2016

The Effect of Tactile and Audio Feedback in Handheld Mobile Text Entry

Christopher L. Edman
Wright State University

THE EFFECT OF TACTILE AND AUDIO FEEDBACK IN HANDHELD MOBILE TEXT ENTRY

A thesis submitted in partial fulfillment of the
requirements for the degree of
Master of Science

By

CHRISTOPHER LAIRD EDMAN
B.A., Wheaton College, 2007

2016
Wright State University

WRIGHT STATE UNIVERSITY

GRADUATE SCHOOL

AUGUST 25^{TH}, 2016

I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY Christopher Edman ENTITLED The Effect of Tactile and Audio Feedback in Handheld Mobile Text Entry BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF Master of Science.

Kevin Bennett, Ph.D.
Thesis Director

Scott Watamaniuk, Ph.D.
Graduate Program Director

Debra Steele-Johnson, Ph.D.
Chair, Department of Psychology

Committee on
Final Examination

Kevin Bennett, Ph.D.

John Flach, Ph.D.

Scott Watamaniuk, Ph.D.

Robert E.W. Fyffe, Ph.D.
Vice President for Research and
Dean of the Graduate School

ABSTRACT

Edman, Christopher Laird. M.S. Department of Psychology, Wright State University, 2016. The Effect of Tactile and Audio Feedback in Handheld Mobile Text Entry.

Effects of tactile and audio feedback are examined in the context of touchscreen and mobile use. Prior experimental research is graphically summarized by task type (handheld text entry, tabletop text entry, non-text input), tactile feedback type (active, passive), and significant findings, revealing a research gap evaluating passive tactile feedback in handheld text entry (a.k.a. "texting"). A passive custom tactile overlay is evaluated in a new experiment wherein 24 participants perform a handheld text entry task on an iPhone under four tactile and audio feedback conditions with measures of text entry speed and accuracy. Results indicate audio feedback produces better performance, while the tactile overlay degrades performance, consistent with reviewed literature. Contrary to previous findings, the combined feedback condition did not produce improved performance. Findings are discussed in light of skill-based behavior and feed-forward control principles described by Gibson (1966) and Rasmussen (1983).

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Table Page

ACKNOWLEDGEMENTS

To those who had a significant role in bringing this project to completion:

Kevin, my benevolent advisor, who helped me push across the finish line,

John and Scott, my wise and accommodating committee members,

Sally, my wonderful mother, who loves me enough to offer support even when it is hard,

Laird, my father-professor and ready resource,

And above all Amanda, my undeserved wife, who suffers and celebrates with me,

Thank you.

An additional acknowledgement is due Jin Ryong Kim and Hong Z. Tan for their provision of additional information requested relevant to their works appearing in the review of literature (Kim & Tan 2014a, 2014b).

The Effect of Tactile and Audio Feedback in Handheld Mobile Text Entry

One of the most prevalent trends in mobile computing over the last decade has been the introduction, and rise to prominence, of the touchscreen interface. The first mobile phone interfaces contained a small electronic display at the top and physical keys arrayed over the majority of the remaining surface area. Over time, the display portion became proportionally larger than the physical controls. Ultimately, the physical controls have been replaced by “soft” controls in a touchscreen interface: Barredo (2014) reports that the percentage of smartphones with physical keyboards dropped from 56% in 2007 (the year of the Apple iPhone™ release) to just 1% in 2014. This trend is expected to continue until at least the year 2022 (Grand View Research, 2015).

This evolution in the market is not difficult to understand. There exist a wide variety of practical benefits to touchscreens (no moving parts, less weight, and far more flexibility -- e.g., the soft keyboard can be removed to free up limited display real estate). The benefits are equally compelling from a theoretical perspective. Two fundamental goals in interface design are direct perception and direct manipulation (e.g., Bennett and Flach, 2011). Touchscreen interfaces empower designers to achieve these goals because they merge the perception (displays) and action (controls) surfaces of the interface (see the classic discussion of “interreferential I/O” by Hutchins et al., 1986). Stated in terms of ecological interface design principles, the perception/action loop (Gibson, 1966) is intact and the interface leverages the powerful skill-based behaviors of the human (e.g., Rasmussen and Vicente, 1989). In less technical language:

> People use their fingers to operate the unique multi-touch interface of iPhone OS-based devices, tapping, flicking, and pinching to select, navigate, and read Web content and use applications. There are real advantages to using fingers to operate a device: They are always available, they are capable of many different movements, and they give users a sense of immediacy and connection to the device that's impossible to achieve with an external input device, such as a mouse. (Apple, 2010, p. 41).

Despite these obvious benefits, the evolution from physical controls to soft controls has introduced some tradeoffs. Buxton, Hill, & Rowley (1985) were perhaps the first researchers to note that touchscreen interfaces lack the feedback of the mechanical controls they replace. They suggest that designers should provide feedback through auditory and visual channels to compensate for this loss. A complementary approach is to add haptic / tactile feedback to the touchscreen interface:

> The loss of tactile or haptic feedback, which users expect from conventional mechanical-input mechanisms, creates problems including higher error rates and user frustration. The solution is to add tactile feedback to the touch-screen interface to secure the best features of both touch screens and conventional controls. (Levin, 2009, p. 18)

The ISO (van Erp et al., 2010) defines the haptic system as being composed of touch (tactile/cutaneous, which includes mechanical, thermal, chemical and electrical stimulation to the skin) and kinesthesis (body force, body position, limb direction and joint angle). The literature on auditory and tactile feedback in touchscreen interfaces generally uses the term tactile to describe interface manipulations. We will adopt this term in the present paper, while noting that the tactile and kinesthetic systems are highly intertwined and co-dependent (e.g., Gibson, 1966). We begin by reviewing this literature.

Literature Review

Tactile Feedback

Researchers and designers have developed and evaluated a variety of methods to provide tactile feedback. While mechanisms for introducing touch-based feedback have varied widely (see Levin, 2009 for a survey of tactile displays for mobile devices), Jones & Sarter (2008) describe three broad categories of tactile displays: vibrotactile (mechanical), electrotactile (electrical), and static (physical). Vibrotactile and electrotactile displays provide “active feedback” (Silfverberg, 2003) utilizing a powered apparatus to stimulate the skin (Brewster et al., 2007; Hoggan et al., 2008; Hoggan et al., 2009; Lee and Zhai, 2009; Hwangbo et al., 2013; Han et al., 2014; Kim and Tan, 2014b; Kim and Tan, 2014a; Han and Kim, 2015; Ma et al. 2015). In contrast, static displays (e.g., a physical computer keyboard) provide “passive feedback” that is naturally derived from contact between the finger and the display surface (Silfverberg, 2003; DeWitte, 2008; Harrison and Hudson, 2009; Kim and Lee, 2012; Odell and Faggin, 2014).

Auditory Feedback

In addition to active and passive tactile feedback, synthetic auditory feedback has been incorporated into touchscreen interfaces. The most common sound mimics the “click” that occurs when a key in a traditional keyboard has been pressed to the point of activation. This provides auditory feedback specifying input to the system. The efficacy of this interface design strategy has been investigated in a number of studies (Hoggan et al., 2009; Lee and Zhai, 2009; Kim and Lee, 2012; Hwangbo et al., 2013; Han et al., 2014; Kim and Tan, 2014b; Kim and Tan, 2014a; Han and Kim, 2015; Ma et al., 2015).

Task Settings

Researchers and designers have evaluated these display types in three general task settings: non-text input, tabletop text entry, and handheld text entry. Non-text input refers to touchscreen interactions that do not constitute text entry, such as the use of a numerical keypad or other virtual buttons in the interface. Tabletop text entry occurs on larger touchscreen devices such as tablets and smart tabletops whose screen size facilitates the use of all ten fingers while the device is supported by another surface. Handheld text entry involves smaller devices (typically less than eight inches diagonal screen size) that are held in the hands while text is entered (as in the popular communications activity known as “texting”).

As alluded to earlier, a concern with touchscreen interfaces is that performance will be degraded relative to physical keyboards. A touchscreen interface lacks physical key boundaries (e.g., their center and edges) that provide tactile feedback that specifies the proper physical positioning of the fingertips. The touchscreen also lacks tactile feedback that specifies the downward movement of a physical key as it is being pressed. Finally, the touchscreen interface lacks the tactile and auditory feedback (i.e., the “click”) that specifies when a threshold is passed and the key is activated. Thus, the theoretical prediction is that adding auditory and tactile feedback to a touchscreen will improve performance because it emulates the information provided by a physical keyboard. How do the results in the literature align with these predictions? A graphical summary is presented in Figures 1 (a key to symbology and a listing of experiments) and 2 (a graphical summary of experimental results).

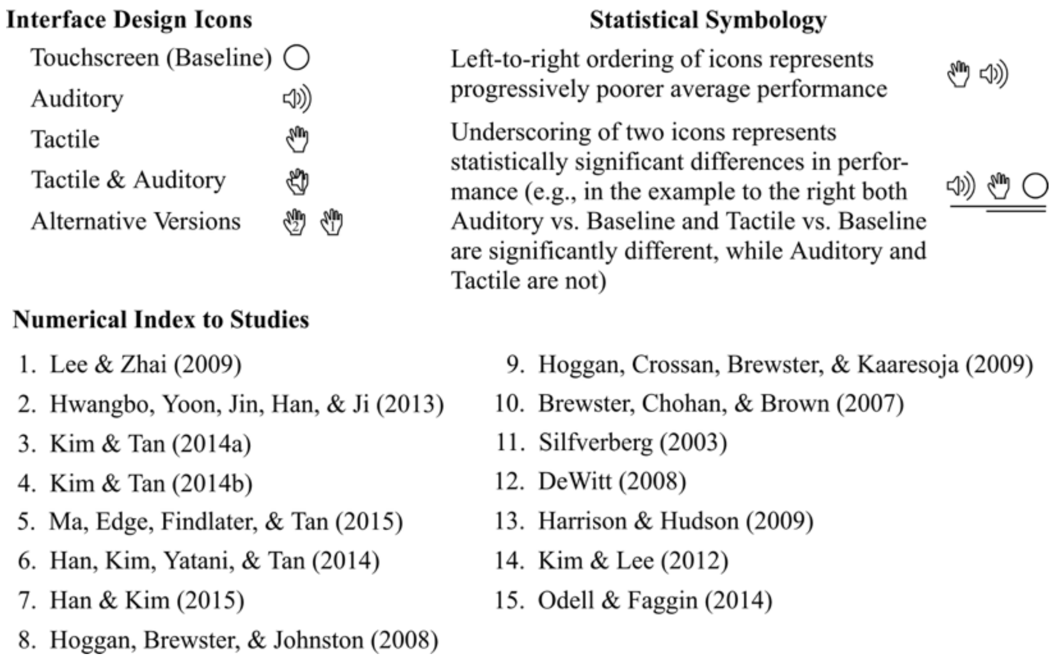

Figure 1. Legend for symbolic conventions used to represent interface designs, statistical results, and studies that appear in the graphical literature review illustrated in Figure 2.

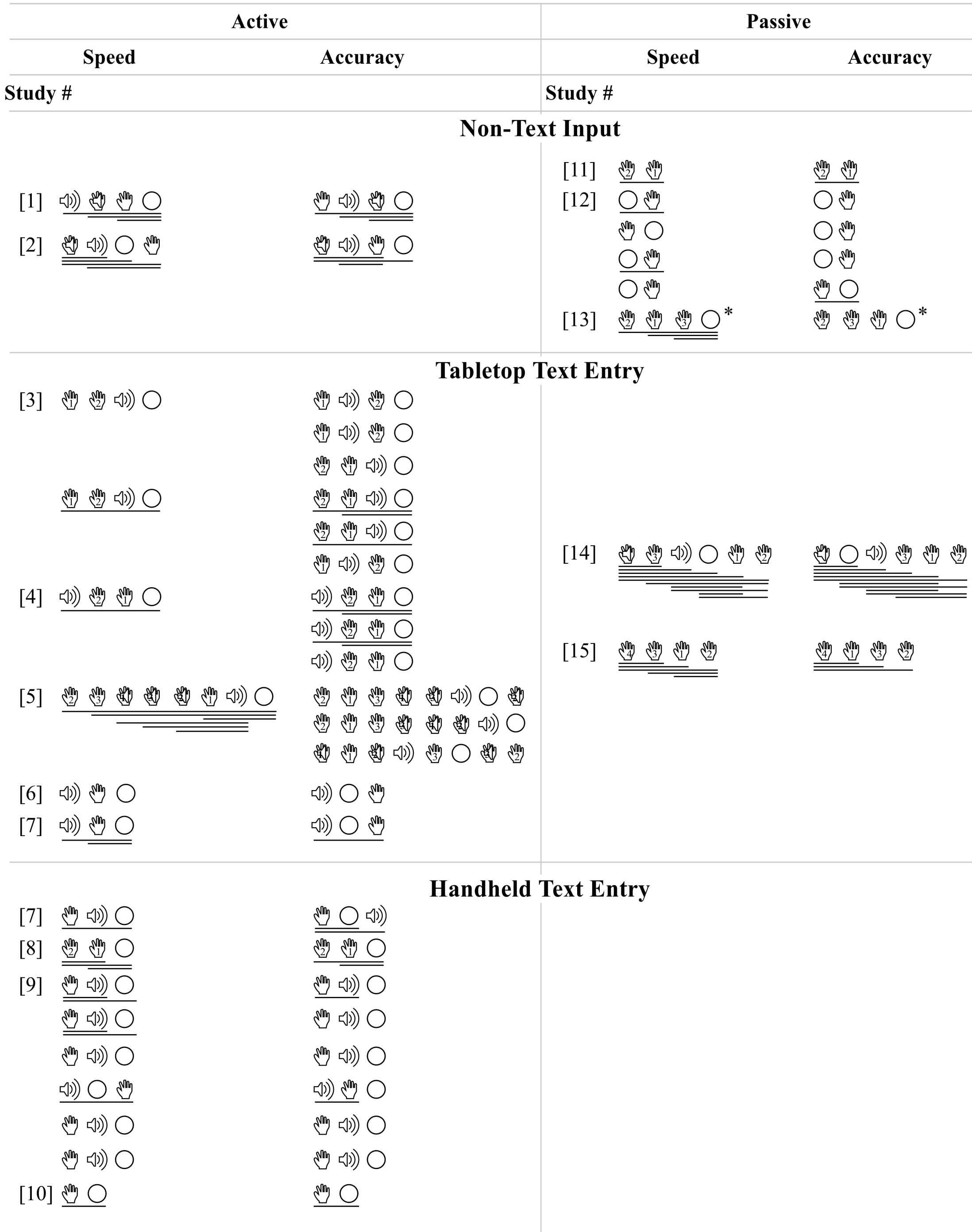

Figure 2. Literature review. This figure presents a graphical illustration of the pattern of results for studies investigating the augmentation of touchscreen interfaces with tactile and auditory feedback. Note: see Figure 1 for legend.

The pattern of results indicate that the addition of auditory feedback generally improves average performance as compared to the baseline touchscreen alone (i.e., auditory icons are normally to the left of the baseline icons in Figure 2). The results for tactile feedback depend upon the nature of that feedback. The studies on the left side of Figure 2 indicate that the addition of active tactile feedback to the baseline touchscreen interface generally improves average performance (i.e., the tactile icons are generally located to the left of baseline icons). In contrast, the studies on the right side indicate that the addition of passive tactile feedback only sometimes improves performance (*note that Harrison and Hudson, 2009 [13] did not measure speed and accuracy).

Present Research

As Figure 2 reveals, there is a gap in the literature: there are no studies investigating the role of passive tactile feedback in handheld text entry. The present study fills this gap by investigating the impact of auditory and passive tactile feedback on text entry performance with an iPhone. Passive tactile feedback (i.e., information about fingertip location relative to keys) was provided through a semi-rigid screen protector placed on the touchscreen. As illustrated in Figure 3, this "tactile overlay" contained raised indentations ("dimples") that physically correspond to the center of each key. Auditory feedback signifying key activation was provided by turning on the "keyboard click" option in the iPhone interface. In addition, we investigated the extent to which the effect of these two interface manipulations was modulated by levels of user experience.

Figure 3. Tactile overlay consisting of a semi-rigid screen protector modified with braille-like bumps to provide passive tactile feedback regarding key position.

As outlined earlier, conventional wisdom and the general pattern of results would suggest that both tactile and auditory feedback will improve performance at the text entry task. Tactile feedback will guide the finger towards the correct key by decreasing the discrepancy between the actual position of the finger relative to the target position on the touchscreen. Auditory feedback will improve text entry speed by providing a clear and immediate indication to the user that a key has been successfully activated.

However, closer analysis of the literature review presented in Figure 2 suggests that the predictions may not be quite so straightforward. Figure 4 summarizes the experimental outcomes for all comparisons between a baseline touchscreen and an interface augmented with tactile or auditory feedback. Specifically, does the augmentation (1) improve performance significantly, (2) degrade performance significantly, or (3) not have a significant impact? Note that statistical comparisons between non-baseline interfaces were not counted (e.g., the results of Silfverberg, 2003

[11] and Odell and Faggin, 2004 [15] did not contribute). Note also that in some instances the statistical comparisons that were reported did not provide comprehensive comparisons between all displays (e.g., Ma et al., 2015 [5]) and were similarly not counted.

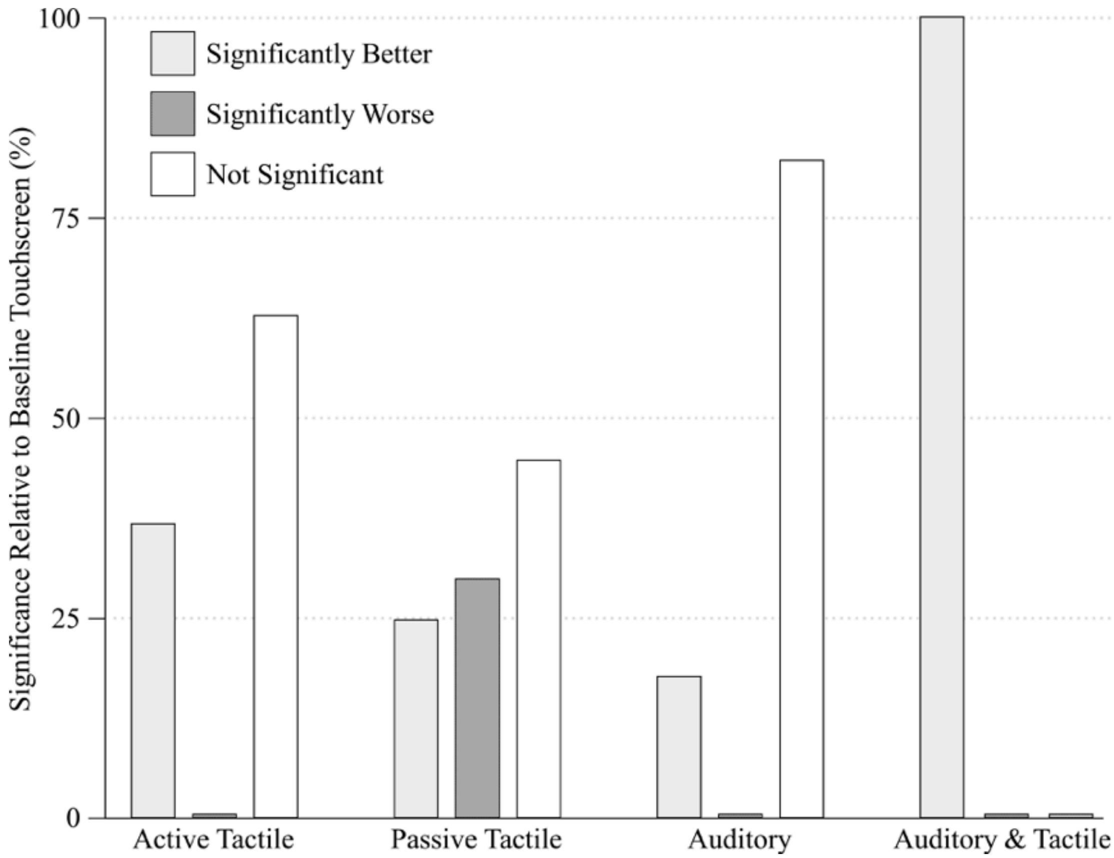

Figure 4. An aggregated summary of experimental outcomes (i.e., statistical significance) between a baseline touchscreen and an interface that was augmented with tactile and/or auditory feedback.

As illustrated in Figure 4, the results for passive tactile feedback (i.e., the type used in the present experiment) are very mixed: the most common finding is no significant differences in performance, but augmentation can produce either significantly better or significantly worse performance at substantial rates. In contrast, while auditory feedback never degrades performance significantly, it also rarely improves performance significantly. Finally, although there are only 6 comparisons to draw upon, the combination of tactile and auditory feedback has always produced significantly better performance. Thus, the pattern of results provide some, but not overwhelming support, for the theoretical benefits of tactile and auditory feedback (see earlier discussion). The present study will reinvestigate these issues while also assessing the impact of user experience levels.

Method

Participants

Participants were 24 volunteers (16 male, 8 female) ages 19-40 (average age 26) who identified themselves as native English speakers. Eligible participants (those enrolled in Wright State University psychology courses) received course credit for their participation.

Apparatus / Interfaces

The handheld device was a mobile phone (Apple iPhone™, model 3GS) with a touch sensitive display (3.5 inch diagonal, 480 by 320 pixels). Four interface configurations were investigated. The Baseline configuration was the standard iPhone interface. The “keyboard click” sound was enabled in the Auditory configuration. The Tactile configuration contained a semi-rigid screen protector (Case-mate IPH3GSP) that was modified by introducing Braille-like protrusions located in the center of each alphabetic key (see Figure 3). Both the click sound and the modified screen protector were present in the Combined configuration.

Stimuli / Text Phrases

Twenty-five phrases were selected from MacKenzie & Soukoreff's (2003) English phrase dictionary (all contained four or five words and either 26 or 27 total characters):

> spill coffee on the carpet; the fire blazed all weekend; it should be sunny tomorrow; the library is closed today; the second largest country; gas bills are sent monthly; our fax number has changed; chemical spill took forever; completely sold out of that; the trains are always late; always cover all the bases; this watch is too expensive; the four seasons will come; well connected with people; every apple from every tree; this library has many books; fall is my favorite season; teaching services will help; the laser printer is jammed; the quick brown fox jumped; all good boys deserve fudge; you are a wonderful example; vanilla flavored ice cream; he was wearing a sweatshirt; tickets are very expensive. (MacKenzie & Soukoreff, 2003)

Procedure

Participants completed a single experimental session lasting approximately 30 minutes. A pre-experimental questionnaire was administered. Participants then completed four blocks of trials using only one interface within each block. The interface presentation order was counterbalanced across participants (i.e., each participant was randomly assigned, without replacement, to one of the twenty-four possible presentation orders). Each of the 25 text phrases was presented once in each of the four blocks of trials; their order was randomized anew within each block. Participants were given a 20 second rest period between each block of trials.

Participants were instructed to complete each trial as quickly and accurately as possible. Participants were required to hold the phone with two hands in a horizontal orientation. An individual trial was initiated by the presentation of a text phrase in a window at the top of the screen, accompanied by a short audible tone; it remained visible until the participant entered their first character, and then was replaced by typed text. Participants were allowed, but not required, to correct erroneous input. Participants were instructed to press the “done” key to signify completion of a trial and initiate the next trial. No performance feedback was provided to participants (except for the appearance of text on the phone as it was typed). The initiation, end time, and final typed phrase were recorded (100 ms accuracy), as well as the character and timestamp of each individual keystroke. A post-experimental questionnaire was administered.

Results

A similar procedure was followed in all analyses. Outliers were identified using the test described in Lovie (Lovie, 1986, p. 55-56): $T1 = (x(n) - x) / s$, where $x(n)$ is a particular observation (one of n observations), x is the mean of those observations, and s is the standard deviation of those observations. Nonparametric tests (Friedman ANOVA) were conducted to determine if the outlier distribution was random across interfaces (none were significant). The overall distributions were tested for normality and all tests were significant, indicating positive skewedness; a log transformation was applied. The first 5 trials in a block served as practice with the new interface; data were averaged across the final 20 trials.

An estimate of the level of handheld text entry experience was obtained for each participant: the frequency of reported use (i.e., number of e-mails and text messages per week) was multiplied by the duration of reported use (i.e., number of weeks interacting with a touchscreen phone). A median split of the resulting scores was used to create a between-subjects factor of experience (i.e., higher and lower experience). A 4 (interface: baseline, auditory, tactile, combined, within subjects) x 2 (experience: less or more, between subjects) mixed-design ANOVA was conducted for each dependent variable. Contrasts were conducted to investigate significant effects.

Overall Completion Time

The overall completion time for a trial was computed by measuring the time interval between the presentation of a text phrase and activation of the final keystroke. The main effect of interface was significant, $F(3,66) = 2.86$, $p < .05$; the average performance levels are listed on the x axis of Figure 5.

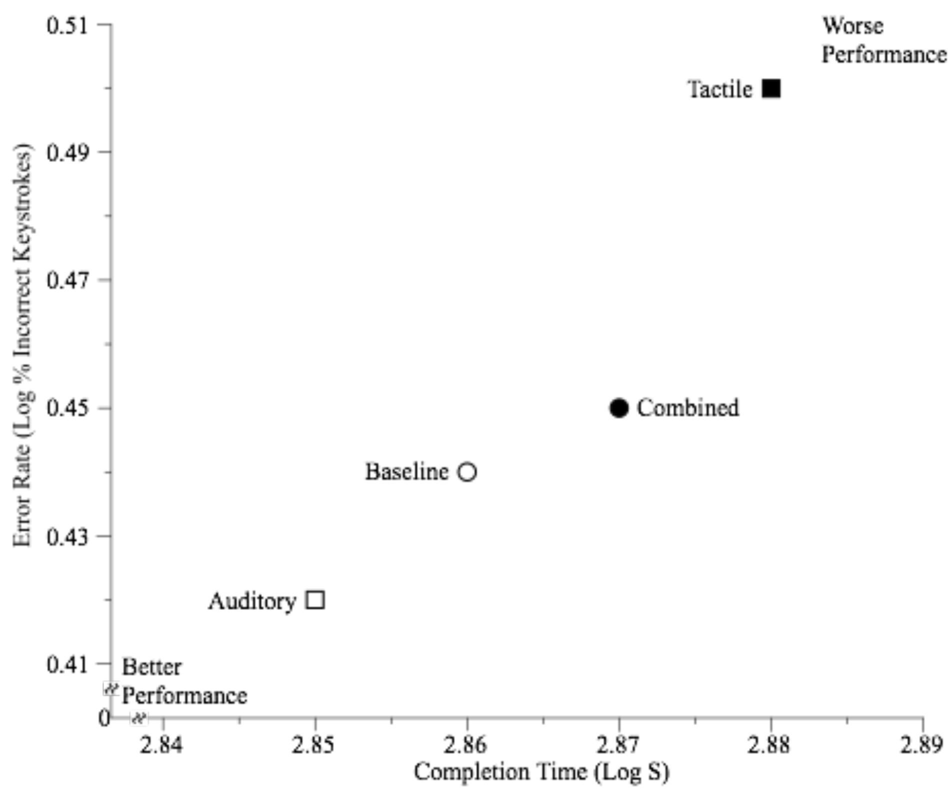

Figure 5. Average speed (completion time in seconds) and accuracy (error rate) in overall text entry performance for the four interface configurations.

Total Error Rate

A Total Error Rate score (Soukoreff and MacKenzie, 2003) was calculated by determining the proportion of erroneous keystrokes relative to total keystrokes in a trial (with corrections excluded). The main effect of interface was significant, $F(3,66) = 3.35$, $p < .03$; average performance levels are illustrated in the y axis of Figure 5. The main effect of experience was also significant, $F(3,66) = 10.03$, $p < .000001$. Participants in the more experienced group produced significantly fewer errors than participants in the less experienced group.

Average Inter-Keystroke Time

Mean inter-keystroke times were computed by averaging the time intervals between successive keystrokes in a response (errors and corrections excluded). The main effect of interface, $F(3,66) = 3.49$, $p < .03$, was significant; average performance levels are illustrated in Figure 6.

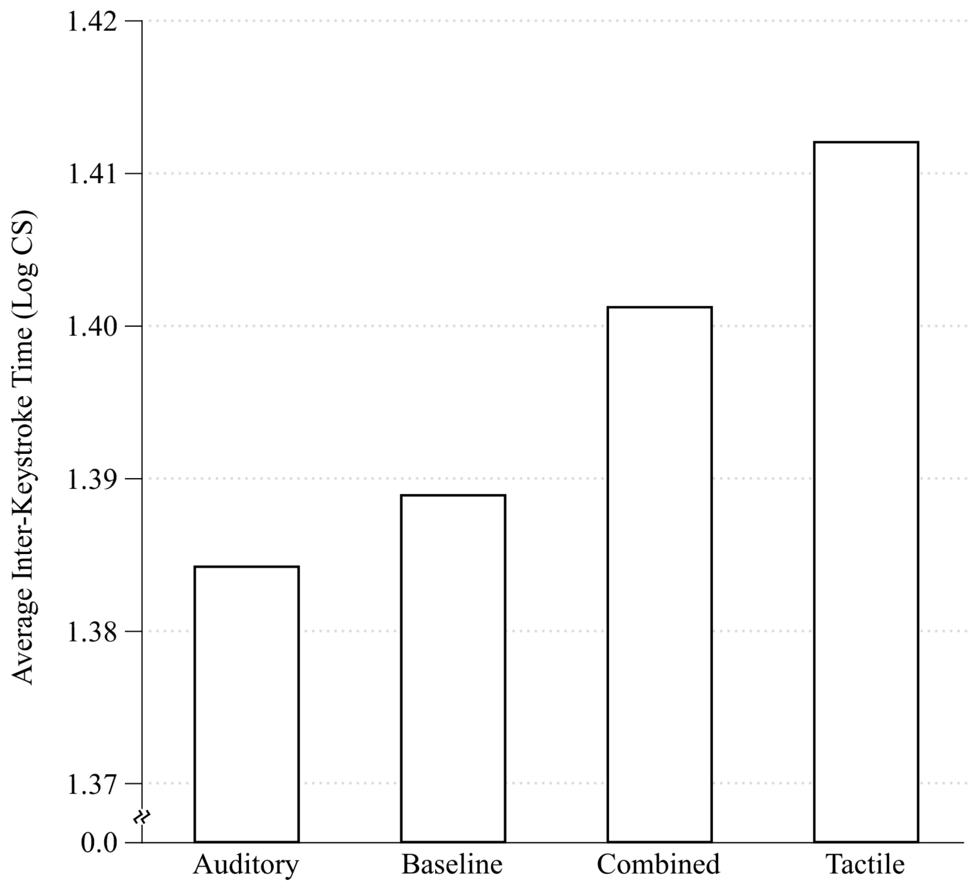

Figure 6. Average inter-keystroke time (1/100ths second) for the four interface configurations.

Inter-Keystroke Variability

Variability scores were computed by calculating the standard deviation of inter-keystroke times. No significant results were obtained.

First Keystroke

The time to first keystroke was computed by measuring the interval between the presentation of a text phrase and the first keystroke of a response. No significant results were obtained.

Summary

The results indicate that the main effect of interface was significant for three of the five dependent variables. As Figures 5 and 6 illustrate, the same general pattern of performance was obtained across interfaces (from best to worst): Auditory, Baseline, Combined, and Tactile. All significant contrasts between interfaces for these three dependent variables are listed in Table 1. These contrasts are also illustrated in Figure 7 with the same symbology of the graphical literature review (see Figure 1). The over-arching pattern is that the two interfaces with the tactile overlay (i.e., Tactile and Combined) produced significantly degraded performance relative to the two interfaces without it (i.e., the Baseline and the Auditory interface).

	Baseline vs. Auditory		Baseline vs. Combined		Baseline vs. Tactile		Tactile vs. Auditory		Auditory vs. Combined		Tactile vs. Combined	
Dependent Variable:	F(1,22) =	P<	F(1,22) =	P<	F(1,22) =	P<	F(1,22) =	P<	F(1,22) =	P<	F(1,22) =	P<
Completion Time							6.26	.03	6.67	.02		
Error Rate					7.67	.02	7.67	.02				
Inter-Keystroke Mean					7.34	.02	7.67	.02				

Table 1. Comparisons between interfaces showing contrasts conducted to analyze main effects of interface.

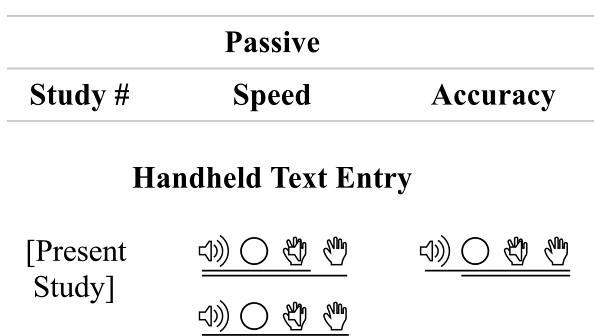

Figure 7. Experimental results of the present study.

Discussion

The results of the present study are generally in line with the trends outlined in the literature review (see Figure 4). This review revealed that although auditory feedback is likely to improve average performance relative to a baseline touchscreen interface, it is not likely to improve performance significantly. This is exactly the pattern obtained in the present study (see Figure 7). The literature review also revealed that passive tactile feedback often produces significantly degraded performance (vs. flat touchscreen interface). This is also consistent with the pattern obtained in the present study: all significant differences involved degraded performance for interfaces with the tactile overlay (see Table 1 and Figure 7). Unlike the trend in the literature review, auditory and tactile feedback together (i.e., the combined interface) did not significantly improve performance. The presence of auditory feedback does appear to offset the negative impact of passive tactile feedback to a degree (see Figure 7). The remainder of the paper will be devoted to an interpretation of the poor performance that was obtained for passive tactile feedback.

Demand Characteristics of Tactile Overlay

The first interpretation is based on the physical characteristics of the tactile overlay, which may have created a sort of user "demand characteristic." Each key of the stock iOS software keyboard occupied approximately 42 x 32 pixels (1,344 total). In contrast, the bump in the tactile overlay for each key occupied a much smaller area (approximately 12 x 12 pixels, 144 total, see Figure 3).

The disparity between the size of a key and the size of a bump may have contributed to degraded performance. Users may have felt the need to reposition their thumb when tactile feedback suggested that it was not perfectly aligned with the center of a key, even though an off-center keypress would still have activated the correct key. This repositioning would clearly have contributed to longer inter-keystroke and overall completion times. Several participants (seven) volunteered comments indicating that they would have preferred a tactile overlay with larger landmarks, closer in size to the virtual keys of the on-screen keyboard itself.

These limitations are not inherent to passive tactile interfaces. New technologies, such as the Tactus Intelligent Surface™ (Tactus Technology, 2012), offer wide ranging possibilities. This design provides a thin, deformable transparent layer that can be inflated to create physical keys of any size and shape over the surface of an on-screen keyboard.

Skill-Based Behavior, Feed-Forward Control

Note that the previous interpretation of poor performance with the tactile interface is based on classic notions of feedback control: the repositioning of the thumb would have been in direct response to the "error signal" between its physical location and the small tactile bump. In fact, throughout this paper we have discussed the predicted benefits for tactile and auditory augmentation of touchscreen interfaces using the concept of perceptual feedback. In reality, the successful performance of this and similar "skill based" (Rasmussen, 1983) perceptual motor behaviors (e.g., texting, walking, riding a bike, writing by hand, swinging a golf club, etc.) are also dependent upon "feed-forward" control (e.g., Gibson, 1966; Rasmussen, 1983). Rasmussen addresses this point in greater detail:

> Only occasionally is performance based on simple feedback control, where motor output is a response to the observation of an error signal representing the

> difference between the actual state and the intended state in a time-space environment, and where the control signal is derived at a specific point in time. Typical examples are experimental tracking tasks. In real life, this mode is rarely used, and only for slow, very accurate movements-assembly tasks, drawing. In most skilled sensorimotor tasks, the body acts as a multivariable, continuous control system synchronizing movements with the behavior of the environment. ... performance is then based on feed-forward control and depends upon a very flexible and efficient dynamic internal world model. (Rasmussen, 1986, p. 100-101)

Rasmussen further elaborates the role of an internal world model in skill-based behaviors like texting:

> The existence of such an internal world model cannot be doubted ... A kind of dynamic world model is necessary in order to account for control of responses to the environment which are too fast to allow control by simple perceptual feedback. Often-cited examples are fast sequences in sport, musical performance, etc., ... To serve this purpose, it is necessary that the internal dynamic world model simulates not only the behavior of the environment, but also of the body; i.e., it simulates the interaction. (Rasmussen, 1986, p. 80)

To summarize, successful execution of skill-based behaviors like text entry depends upon feed-forward control based on a flexible, dynamic internal world model. The smooth and coordinated flow of activity that characterizes skill-based behavior depends upon the successful development of this world model. Furthermore, successful development can be achieved only after a great deal of practice has been invested. For example, countless hours of practice are required to become a professional golf or tennis player (or a proficient texter).

Clearly, the participants in the present study were very skilled at handheld mobile text entry. Questionnaire responses indicated that this skill was built up over extended periods of time (multiple years) and involved considerable amounts of mobile text composition (thousands of messages). This experience is also reflected in the levels of speed and accuracy at which they performed: the average participant in the present experiment was able to produce approximately four accurate keystrokes per second.

Thus, a second interpretation of the poor performance in the present study is based upon the observation that these mobile text entry skills were *not* developed with touchscreen interfaces that contained raised, braille-like bumps similar to those in the tactile overlay. The tactile interface used in the present study was almost certainly a novelty to participants; they did not have enough practice with the tactile overlay (i.e., only 50 experimental trials) to incorporate it into their internal dynamic world model. Instead, its novelty probably brought the interface into conscious awareness, and relegated performance to a less efficient mode of interaction. From the perspective of feed-forward control and skilled performance, a negative impact on handheld text entry performance with the passive tactile overlay comes as no surprise.

Summary

The literature review described earlier revealed that little, if any, research has been conducted on the effect of passive tactile feedback in hand-held devices with touchscreen interfaces. This is an important gap to address, since the marketplace is large for these devices and passive tactile feedback offers a number of advantages relative to active tactile feedback (e.g., simplicity, cost effectiveness, and coverage: they work over the entire interaction surface at once for any number of still or moving fingertips).

The present study was a first attempt at filling that gap. Considering the clear pattern of significant results indicating that the tactile overlay produced decrements in performance, one might be tempted to draw sweeping generalizations. This could be both unfortunate and premature. Our tactile overlay was a very low-tech, simple solution that had certain design characteristics (i.e., low tactile bump to overall key size ratio) that may have contributed to the poor performance that was observed. Participants did not have sufficient practice to internalize this novel interface into their dynamic world model and produce the smooth, coordinated behavior that is characteristic of skilled behavior.

On the other hand, the possibility that passive tactile feedback will never be beneficial for hand-held devices with touchscreen interfaces is one that must be entertained. Consider two successful implementations of passive tactile feedback. Braille has different patterns of protrusions that specify different letters and allow reading through touch. The raised bumps on the F and J keys of a computer keyboard allow a skilled typist to determine the proper physical positioning of their fingers without looking. The construction of the tactile overlay is far more similar to the second example (F and J bumps that specify physical location) than Braille (bumps that differentiate between letters).

Therein lies the problem for ultimate performance gains. Unlike a computer keyboard, one cannot rest one’s fingers on the keys of a handheld touchscreen device to ensure proper spatial positioning. However, it may not be necessary anyway. The spatial location of specific keys on a hand-held device is completely established by the act of holding the device itself (e.g., two hands in a horizontal orientation). Doing so ensures a stable framework for interaction, including key location and the proper physical positioning of the thumbs relative to those keys. Also, text entry on a handheld device rarely requires visually focusing on a surface away from the handheld interface (i.e., transcribing). Physical key location is normally established through visual feedback as opposed to touch (as in a computer keyboard). Under these conditions, it is possible that any bumps and protrusions of a tactile interface may really just serve to get in the way.

References

Apple. (2010). Iphone human interface guidelines (user experience). Cupertino, CA: Apple, Inc.

Barredo, Á. (2014, June 18). Decline of the keyboard. [microblog post]. Retrieved from https://twitter.com/somospostpc/status/479195892323721216.

Bennett, K. B., & Flach, J. M. (2011). *Display and interface design: Subtle science, exact art.* Boca Raton, FL: CRC Press.

Brewster, S., Chohan, F., & Brown, L. (2007). Tactile feedback for mobile interactions. In *Proceedings of the SIGCHI conference on human factors in computing systems* (pp. 159-162). New York, NY: ACM. doi: 10.1145/1240624.1240649

Buxton, W., Hill, R., & Rowley, P. (1985). Issues and techniques in touch-sensitive tablet input. In *Proceedings of the 12th annual conference on computer graphics and interactive techniques*, (pp. 215–224). New York, NY: ACM. doi: 10.1145/325334.325239

Dewitte, A. E. (2008). Investigation of dynamic three-dimensional tangible touchscreens: Usability and feasibility. (Thesis). Rochester Institute of Technology. Retrieved from http://scholarworks.rit.edu/theses/5726

Gibson, J. J. (1966). *The senses considered as perceptual systems.* Boston, MA: Houghton Mifflin.

Grand View Research. (2015). *Touch screen Display Market Analysis, Market Size, Application Analysis, Regional Outlook, Competitive Strategies, and Forecasts, 2015 To 2022* [Online report summary]. Retrieved from http://www.grandviewresearch.com/industry-analysis/touchscreen-display-market

Han, B., & Kim, K. (2015). Typing performance evaluation with multimodal soft keyboard completely integrated in commercial mobile devices. *Journal on Multimodal User Interfaces*, 9 (3), 173-181. doi: 10.1007/s12193-015-0177-4

Han, B.-K., Kim, K., Yatani, K., & Tan, H. Z. (2014). Text entry performance evaluation of haptic soft qwerty keyboard on a tablet device. *Haptics: Neuroscience, devices, modeling, and applications*, 8618, 325-332. doi: 10.1007/978-3-662-44193-0_41

Harrison, C., & Hudson, S. E. (2009). Providing dynamically changeable physical buttons on a visual display. In *Proceedings of the 27th annual CHI conference on human factors in computing systems* (pp. 299-308). New York, NY: ACM. doi: 10.1145/1518701.1518749

Hoggan, E., Brewster, S. A., & Johnston, J. (2008). Investigating the effectiveness of tactile feedback for mobile touchscreens. In *Proceedings of the SIGCHI conference on human factors in computing systems* (pp. 1573-1582). New York, NY: ACM. doi: 10.1145/1357054.1357300

Hoggan, E., Crossan, A., Brewster, S. A., & Kaaresoja, T. (2009). Audio or tactile feedback: Which modality when? In *Proceedings of the SIGCHI conference on human factors in computing systems* (pp. 2253-2256). New York, NY: ACM. doi: 10.1145/1518701.1519045

Hutchins, E. L., Hollan, J. D., & Norman, D. A. (1986). Direct manipulation interfaces. In D. A. Norman & S. W. Draper (Eds.), *User centered system design* (pp. 87-124). Hillsdale, NJ: Lawrence Earlbaum Associates.

Hwangbo, H., Yoon, S. H., Jin, B. S., Han, Y. S., & Ji, Y. G. (2013). A study of pointing performance of elderly users on smartphones. *International Journal of Human-Computer Interaction*, 29 (9), 604-618. doi: 10.1080/10447318.2012.729996

Jones, L. A., & Sarter, N. B. (2008). Tactile displays: Guidance for their design and application. *Human Factors*, 50 (1), 90–111. doi: 10.1518/001872008X250638.

Kim, J. R., & Tan, H. Z. (2014a). Haptic feedback intensity affects touch typing performance on a flat keyboard. In M. Auvray & C. Duriez (Eds.), *Haptics: Neuroscience, devices, modeling, and applications* (pp. 369-375). Springer. doi: 10.1007/978-3-662-44193-0_46

Kim, J. R., & Tan, H. Z. (2014b). A study of touch typing performance with keyclick feedback. In: *Proceedings of IEEE haptics symposium* (pp. 227–233). Houston, TX: IEEE. doi: 10.1109/HAPTICS.2014.6775459

Kim, S., & Lee, G. (2012). Typing on a touch surface: Effect of feedback with horizontal touch keyboard and vertical display setup. In *Proceedings APCHI'12* (pp. 525-530). Matsue-city, Shimane, Japan: ACM.

Lee, S., & Zhai, S. (2009). The performance of touch screen soft buttons. In *Proceedings of the SIGCHI conference on human factors in computing systems* (pp. 309-318). New York, NY: ACM. doi: 10.1145/1518701.1518750

Levin, M., & Woo, A. (2009). Tactile-feedback solutions for an enhanced user experience. *SID Information Display,* 2009 (October) [Online archive]. Retrieved from http://informationdisplay.org/IDArchive/2009/October/MakingDisplaysWorkforYouTactileFeedbackSol.aspx.

Lovie, P. (1986). Identifying outliers. In A. D. Lovie (Ed.), *New developments in statistics for psychology and the social sciences* (pp. 44-69). London, UK: The British Psychological Society and Methuen.

Ma, Z., Edge, D., Findlater, L., & Tan, H. Z. (2015). Haptic keyclick feedback improves typing speed and reduces typing errors on a flat keyboard. *World Haptics Conference (WHC)*, 220-227. IEEE. doi: 10.1109/WHC.2015.7177717

Mackenzie, I. S., & Soukoreff, R. W. (2003). Phrase sets for evaluating text entry techniques. In *CHI '03 extended abstracts on human factors in computing systems* (pp. 754-755). New York, NY: ACM. doi: 10.1145/765891.765971

Odell, D., & Faggin, E. (2014). The typing performance and preference costs of reducing tactile feedback and tactile landmarks in tablet keyboards. In *Proceedings of the human factors and ergonomics society 58th annual meeting* (pp. 1790-1794). SAGE Publications. doi: 10.1177/1541931214581373

Rasmussen, J. (1983). Skills, rules, and knowledge; Signals, signs, and symbols, and other distinctions in human performance models. *IEEE Transactions on Systems, Man, and Cybernetics*, SMC-13(3), 257-266. doi: 10.1109/TSMC.1983.6313160

Rasmussen, J. (1986). *Information processing and human-machine interaction: An approach to cognitive engineering*. New York, NY: Elsevier.

Rasmussen, J., & Vicente, K. J. (1989). Coping with human errors through system design: Implications for ecological interface design. *International Journal of Man-Machine Studies*, 31(5), 517-534. doi: 10.1016/0020-7373(89)90014-X

Silfverberg, M. (2003). Using mobile keypads with limited visual feedback: Implications to handheld and wearable devices. In L. Chittaro (Ed.), *Human-computer interaction with mobile devices and services* (pp. 76-90). Berlin/Heidelberg, Germany: Springer. doi: 10.1007/978-3-540-45233-1_7

Soukoreff, R. W., & Mackenzie, I. S. (2003). Metrics for text entry research: An evaluation of msd and kspc, and a new unified error metric. In *Proceedings of the SIGCHI conference on human factors in computing systems* (pp.113-120). New York, NY: ACM. doi: 10.1145/642611.642632

Tactus Technology. (2012). *A new dimension of touch*. [White paper]. Retrieved from http://tactustechnology.com/wp-content/uploads/2014/08/White-Paper-New-Tagged-PDF.pdf

Van Erp, J. B. F., Kyung, K.-U., Kassner, S., Carter, J., Brewster, S., Weber, G., & Andrew, I. (2010). Setting the standards for haptic and tactile interactions: Iso's work. In A.M.L. Kappers, J.B.F. Van Erp, W.M. Bergmann Tiest, & F.C.T. Van Der Helm (Eds.), *Haptics: Generating and perceiving tangible sensations: International conference, EuroHaptics 2010* (pp. 353-358). Berlin/Heidelberg, Germany: Springer. doi: 10.1007/978-3-642-14075-4_52