Investigating the Effectiveness of Tactile Feedback for Mobile Touchscreens

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ABSTRACT
This paper presents a study of finger-based text entry for mobile devices with touchscreens. Many devices are now coming to market that have no physical keyboards (the Apple iPhone being a very popular example). Touchscreen keyboards lack any tactile feedback and this may cause problems for entering text and phone numbers. We ran an experiment to compare devices with a physical keyboard, a standard touchscreen and a touchscreen with tactile feedback added. We tested this in both static and mobile environments. The results showed that the addition of tactile feedback to the touchscreen significantly improved finger-based text entry, bringing it close to the performance of a real physical keyboard. A second experiment showed that higher specification tactile actuators could improve performance even further. The results suggest that manufacturers should use tactile feedback in their touchscreen devices to regain some of the feeling lost when interacting on a touchscreen with a finger.

Author Keywords
Tactile feedback, multimodal interaction, touchscreens, mobile interaction, fingertip interaction.

ACM Classification Keywords
H.5.2. [**User Interfaces**]: Haptic I/O.

INTRODUCTION

Touchscreen mobile devices are becoming ever more popular with both manufacturers and users. As there is no need for a physical keyboard to take up space on the device, they can have larger screens which can be used more flexibly, meaning a better display of videos, web pages or games, or reconfiguring the display as required, for example rotating from portrait to landscape. A soft keyboard can be displayed when text must be entered. The most popular such device at the present time is the Apple iPhone (Figure 1), but many other manufacturers have also removed the physical keyboards from devices such as PDAs, digital cameras and music players. The use of a touchscreen also allows novel forms of interaction, for example using gestures [14] on the screen to control a device, or more flexible forms of text entry and navigation.

Although the keyboards used on touchscreen devices are based on the original physical mobile keyboards, one important feature is lost: the buttons cannot provide the tactile response that physical buttons do when touched or clicked. Without the tactile feedback, users can only rely on audio and visual cues which can be ineffective in mobile applications due to small screen size, outside noise, social restrictions and the demands of other real world tasks [9]. Studies of touchscreen text entry have shown the difficulties of typing with a stylus on the touchscreen using the standard QWERTY keyboard and have proposed various different keyboard layouts to combat this [11, 16]. Despite these results, the primary method for data entry is still the standard QWERTY keyboard. In an initial, small study [1] we showed that entering text on a touchscreen when on the move can be problematic and that adding artificial tactile feedback can reduce error rates.

Figure 1: The Apple iPhone, a finger-operated touchscreen phone.

A mobile device user's context can be extremely varied, for example, travelling on the train, at a party or in the gym. The user expects to be able to interact effectively with the device in all of these situations. For example, sending emails and browsing the Web on a touchscreen mobile device whilst on the train to work is a common activity. A solution is needed that makes the entry of text efficient and simple in these situations.

One other important issue is that devices like the iPhone have done away with the stylus and just use the finger for input (and in fact multiple fingers for certain interactions). The previous generation of touchscreen phones used a small stylus for interaction. This is advantageous from the device's point of view as the interaction point is very clear and easy for the device to recognise. They are, however, less convenient for users who have to get the stylus out each time they want to interact with the device and the stylus is easy to lose. There has been little study of the effects of using a finger on the screen for interaction. Given the necessary limited size of these devices, widgets are often too small [13] or positioned in an awkward way preventing them from being selected easily with a finger. This makes it even more difficult for users to interact with their devices when, for example, travelling to work on a bumpy train.

In an effort to address these issues, this paper presents a study into the use of tactile feedback for a touchscreen mobile phone QWERTY keyboard where a fingertip is used to press the keys. Our aim was to quantify the effects of tactile feedback in mobile and static settings by comparing a device with a physical keyboard to a touchscreen phone and then to the touchscreen phone with added tactile feedback.

BACKGROUND

The amount of research in mobile tactile feedback for text entry is limited as, up until this point, there have always been physical buttons on the devices providing their own natural tactile feedback. The research has focused on more complex feedback instead such as calendar alerts and navigation cues [2, 4].

Previous research into tactile interaction on mobile devices has often focused on new hardware, for example, a tactile stylus [8] for use on touchscreens and also a piezo-electric display [7, 15] for use with a stylus. These projects have all provided tactile feedback by attaching a physical actuator to the back of the device, or to the stylus, or by building custom device displays. The experiments discussed here involve the use of the standard, built-in mobile phone vibration actuator which can be found in almost all commercially available devices and compare them to specialised external vibrotactile actuators. By using the actuator already in the device, the tactile feedback is not restricted by expensive or rare technology and does not require any hardware to be added to the device which could increase its size or weight which may be inappropriate for mobile devices.

Brewster *et al.* [1] reported a small study investigating the effects of adding tactile feedback to keyboard interactions on a PDA operated with a stylus. They compared a standard PDA soft keyboard to one with artificial tactile feedback presented when the keys were pressed. The artificial tactile feedback in this case was created using a small vibrotactile actuator attached to the back of the device (the same as Figure 10). Results showed that, in a static lab setting, with tactile feedback users entered significantly more text, made fewer errors and corrected more of the errors they did make. In mobile use (on a subway train) they found many of the tactile benefits reduced, but users still corrected significantly more errors. This study was small, but provided the motivation for our work. To fully understand the effects of tactile feedback we need to evaluate both a real physical keyboard and one with artificial tactile feedback to see how they compare. If we can achieve the same level of performance as a real keyboard then we can combine the benefits of touchscreen displays with physical buttons. Our previous study only used six participants in the mobile condition so it is hard to draw any strong conclusions. Also, fingertip use was not tested, only stylus-based interactions. The work reported here builds on this previous study to validate it and to extend its range.

There have been several studies into mobile interaction with touchscreens using styli that do not involve tactile feedback. MacKenzie [11] has conducted various experiments investigating the use of different keyboard layouts to assist in text entry using a touchscreen. However, these different layouts have not become commercially available and are unlikely to, just as the Dvorak [3] keyboard layout has been proven to be superior in numerous cases but has never been widely adopted. For this reason, we looked at augmenting the current QWERTY keyboard layout with tactile feedback.

This paper presents experiments conducted in both a lab setting and mobile environment investigating text entry on a touchscreen device with and without tactile feedback. The aim is to explore the effects of tactile feedback from keyboard events (confirming that the fingertip is touching a button, confirming that the button has been pressed and highlighting whether the fingertip has slipped off the button or not) to see if performance can be improved.

EXPERIMENTAL DESIGN

After initial investigations using currently available mobile touchscreen devices, the Palm Treo 750 and a Samsung i718 (Figure 2) were chosen for the experiment. The Palm Treo was chosen for the control condition as it is a popular device and has a physical keyboard, allowing us to compare typing performance between a touchscreen and real, physical buttons. The Samsung i718 was chosen as it is a new device and has a large touchscreen display, ideal for presenting a full QWERTY virtual keyboard. The i718 phone contains a Samsung Electro-Mechanics Linear Resonant Actuator and Immersion VibeTonz technology to control the actuator and produce sophisticated tactile effects (www.immersion.com). This actuator consists of a moving magnetic mass, an electromagnet and a spring. The system is underdamped with a very high Q (i.e. sharply peaked resonance). The resonant frequency is ~175Hz. The small size of the mass and the strength of the resonance makes this actuator ideal for short, sharp effects (such as are found in mechanical buttons) because it reaches maximum acceleration in 2 to 3 wavelengths (10 to 20ms). This is one of the best vibration actuators available in a standard phone and is much more controllable than a standard motor.

Figure 2: A Palm Treo 750 and a Samsung i718.

Feedback Design

A standard QWERTY touchscreen keyboard was created for the i718 that matched the one on the Treo in terms of button size and keyboard layout. We could then add tactile effects as required using the built in actuator and Immersion's Vibetonz studio (their tactile authoring tool). The exact size and spacing of the physical keys on the Treo were copied when designing the touchscreen buttons on the i718. The Treo keys were 50x35mm with a gap of 3mm between each. The i718 has a 2.8inch touchscreen with 240x320 pixels. The touchscreen buttons we designed for the i718 were slightly larger than its standard soft keyboard, because they were based on the physical Treo keys and were designed for use with the fingertip not a stylus, but in all other respects were exactly the same as standard Windows Mobile buttons: they highlight when pressed.

In this study, a set of simple Tactons [2] was created to represent the different keyboard events and keys that exist on a touchscreen keyboard. A fingertip-over event (when the fingertip has touched a button) used a 1-beat smooth Tacton, a fingertip-click event used a 1-beat sharp Tacton, while a fingertip-slip event (when the fingertip moved over the edge of a button) used a 3-beat rough Tacton. All of the tactile feedback was created using the standard internal vibration actuator in the i718 device.

Fingertip-Over Event

One of the key features lost in a touchscreen keyboard is feeling the edges of the keys. We created a tactile equivalent to this so that users could feel around the display and know when they were on a key or moving between one key and the next. In other work, such as Brewster *et al.* [1] this was not included, but is a key feature of a real keyboard and is important for working out when the fingers are touching the keys and orienting in the display.

In a standard interface, a mouse over event is fired when the mouse pointer is moved over a GUI element such as a button. This was adapted to create a fingertip-over event which is fired when the finger moves over any button in the interface. When the fingertip-over event is triggered, a 1-beat smooth 300ms Tacton is presented. The cue uses a 250Hz sine wave with increasing intensity during the ramp up time and decreasing intensity during the ramp down time to create a smooth rounded feeling button (Figure 3).

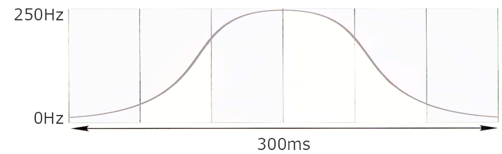

Figure 3: Fingertip-Over Tacton waveform with ramp up and down to make it feel smooth and rounded.

Home Keys

On traditional physical keyboards it is common to find raised ridges on the 'F' and 'J' keys used for orientation. To recreate this on the touchscreen keyboard, when the 'F or J' key triggers the fingertip-over event a different textured Tacton is presented. The Tacton is 1-beat 300ms amplitude modulated 250Hz sine wave, which feels rough.

Fingertip-click Event

Tactile feedback was used to confirm that a button had been pressed. When the fingertip-click event was triggered, a 1-beat sharp 30ms Tacton was presented. The cue used a 175Hz square wave and no ramp up or ramp down time to create a very short and quick 'click' resembling the 'click' felt when depressing a physical button.

Fingertip-Slip Event

An event was triggered whenever the fingertip moved over the edge of any button on the screen, indicating a transition or slip from one to the next (fingertip slips can be troublesome for users and can cause errors that are often undetected). This allowed users to run their fingertips over the buttons feeling all of the edges. When the fingertip-slip event is triggered, a 3-beat rough 500ms Tacton is presented. The rough texture is created using an amplitude modulated 175Hz sine wave. This Tacton was designed to be attention grabbing and to feel very different to the other cues allowing easy identification of a slip by the user.

Methodology

We designed an experiment to investigate the effects of incorporating tactile feedback into mobile touchscreen buttons. The experiment compared user performance on a typical mobile device featuring a real, physical keyboard (Palm Treo), to a touchscreen keyboard with added tactile feedback (Samsung i718) and to the same device with no tactile feedback. The experiment hypotheses were as follows:

1. Participants will be able to enter text with the least errors and greatest speed on the physical keyboard;
2. Tactile feedback will improve speed and accuracy of text entry on touchscreen keyboards;

3. Touchscreens with tactile feedback will achieve comparable accuracy and speed levels to physical keyboards;
4. Tactile feedback will improve the speed and accuracy of text entry on touchscreens when mobile.

We needed participants who had some expertise in text entry on mobile devices, so before beginning the experiment participants were required to complete a questionnaire on their text entry habits. We chose participants who send, on average, 1 - 10 text messages on a QWERTY mobile device per day as they can be considered moderate users who have experience of using physical keyboards. It was not possible to get enough participants who had experience of touchscreen keyboards as they are not yet common. Users were given training with the keyboards as discussed later.

We used a within-subjects design where the conditions were:

1. Standard mobile device with physical keyboard (the control Physical condition);
2. Touchscreen mobile device with tactile feedback added to soft keyboard (the Tactile condition);
3. Touchscreen mobile device with soft keyboard (the Standard condition).

The phrase set used for the text in the experiment was from MacKenzie [10] and has been used successfully in several studies [11, 17]. It is a 500-phrase set with no punctuation symbols and no upper case letters. Due to time constraints from our experimental design, the full set of 500 phrases could not be used so a random set of 30 phrases was selected for each run of the experiment. This resulted in each condition (Standard, Tactile and Physical) lasting approximately 20 minutes. All conditions were tested in a static lab environment and also on the move on a subway train.

EXPERIMENT 1 – LAB AND MOBILE STUDY

Twelve participants took part in this experiment. All participants were students or staff at the University with an age range of 18 to 38 years. There were 3 female participants and 9 male participants. Two participants were left-handed. All participants were seated during the experiment and asked to hold the device in their hands at all times.

Participants were shown a phrase and asked to memorise it, then type it in using the keyboard for each condition. They were asked to enter it as quickly and as accurately as possible. Each phrase was shown at the top of the screen until the participant began typing at which point the phrase disappeared. The interface used on the i718 is shown in Figure 4. The Treo had the same display, except the onscreen keyboard was not shown; participants hit the physical 'Enter' key to submit a phrase. This method sits in between the text creation method and the text copy method. Text creation (where users come up with their own messages), although most realistic, is difficult to use as errors cannot easily be detected. Text copy (users copy messages on the screen) is not very realistic as most users do not copy their text messages or emails, for example, from a piece of paper onto their device. The method used in this experiment was not text creation, but the participants were not copying text directly onto the device either making it a slightly more realistic scenario (Brewster *et al.* used the copying method in their earlier study). Timing began when the participants hit the first key and stopped when they hit 'Submit' (or Enter on the Treo). They moved on to the next task whether or not the phrase was correct.

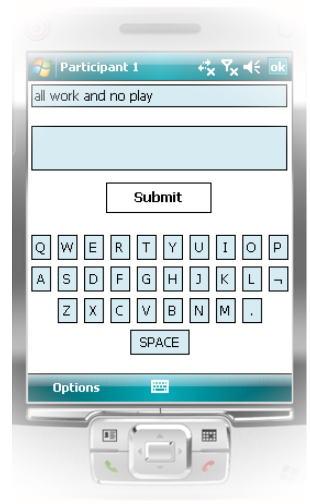

Figure 4: Screenshot of the experiment interface.

The mobile part of the study could have been tested in many different ways, for example, with users walking [14]. This has been shown to be an effective way to generate some of the workload of using a device whilst on the move [1]. We chose to investigate the interaction on a subway train (Figure 5) on the Glasgow Underground. People use PDAs and phones on trains and buses every day whilst commuting. The underground is a good platform for testing as noise levels are very dynamic, being quiet when stopped at a station, but very noisy when the train is in motion. Light levels again vary dramatically. Vibration and movement are also very changeable. When the train is stopped there is little vibration. However, when it accelerates and decelerates people are subjected to lots of forces and vibration from the engine and general movement. Another important factor for this experiment is that the within-subjects design used meant that participants had to use three different keyboards which took around one hour. This would be too far for some of the participants to walk. The subway allowed us to test in a realistic usage situation but without fatiguing the users too much.

Conditions in this experiment were fully counterbalanced. Half of the participants completed the lab-based experiment first while the other half took part in the mobile subway train session first. For both the lab and mobile parts of the experiment, the keyboard conditions were also counterbalanced. The first set of conditions was completed on one day and the second set was completed at least one day later, to avoid participant fatigue. A training period was given before each trial (with five phrases for each keyboard type) to familiarise each user with the interface to be used. Tactile feedback was described and users were given the chance to physically feel the feedback with their fingertips. The dependent variables measured in the experiment were speed, accuracy, keystrokes per character and subjective workload (using the NASA TLX workload assessment [5]). We added an extra factor, annoyance, to the workload analysis to specifically focus on any issues of irritation that the tactile feedback might cause the participants.

Figure 5: The mobile condition of the experiment on the subway train. The experimenter (on the left) takes notes whilst the participant (on the right) enters text.

Results

Accuracy

The Physical keyboard condition had accuracy levels of 88.25% in the lab and 89.6% in the mobile setting. The Tactile condition achieved scores of 82.7% in the lab and 80% on the train, while the Standard touchscreen keyboard produced scores of 69.6% in the lab and 65.8% when mobile (see Figure 6).

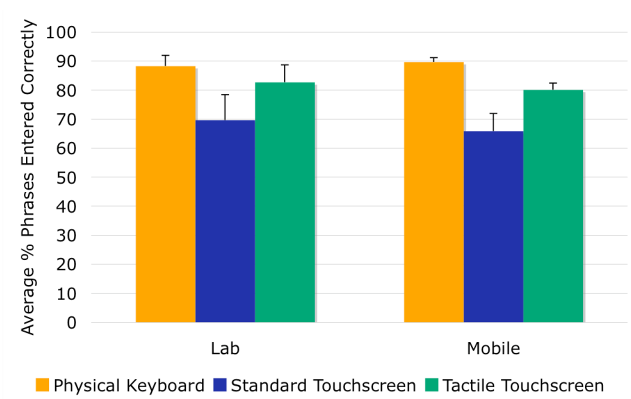

Figure 6: Average percentage of phrases entered correctly (with standard deviations).

A two-way ANOVA was performed on the mean number of correct phrases entered, comparing the effects of mobility (static and mobile) and the three keyboard types (Physical, Tactile and Standard). A correct response in this case was when the entered phrase (when the 'submit'/Enter button was selected) matched the given phrase completely (regardless of whether corrections were made along the way).

The ANOVA showed a significant main effect for keyboard type ($F(2,22) = 96.9$, $p < 0.001$). Using post hoc Tukey's Pairwise Comparisons, it can be seen that a significantly higher number of phrases was entered correctly on both the physical keyboard and the tactile touchscreen than on the standard touchscreen ($p=0.05$). There were no significant differences in the number of correct phrases entered on the physical keyboard and on the tactile touchscreen. The scores are, on average, 5.5% lower on the tactile touchscreen than the physical keyboard in the lab and 9.6% lower when mobile. Only between 1.6 and 2.8 more phrases were entered incorrectly in the tactile condition, suggesting that the performance is comparable with the real keyboard.

There was no main effect for mobility ($F(1,11)=1.79$, $p=0.18$) and no interaction between keyboard type and mobility ($F(2,22)=1.58$, $p=0.21$. This suggests that users did not type less accurately when on the move.

These results show that participants were still able to enter text accurately when on the move, even with the disturbances caused by the train. It also shows the addition of tactile feedback can overcome some of the problems caused by the Standard touchscreen keyboard and enable people to notice and recover from errors they make (which confirms the result of Brewster *et al.* [1]).

Keystrokes Per Character (KSPC)

The number of keystrokes per character was recorded for each keyboard type. KSPC is the number of keystrokes required, on average, to generate a character of text for a given text entry technique in a given language with the ideal being one per character [17]. Given that accuracy scores were based on whether or not the submitted phrase matched the given phrase exactly and did not include corrections as errors, KSPC was recorded in order to examine how many corrections users had to make before submitting a correct phrase. The average number of KSPC for each condition is shown in Figure 7.

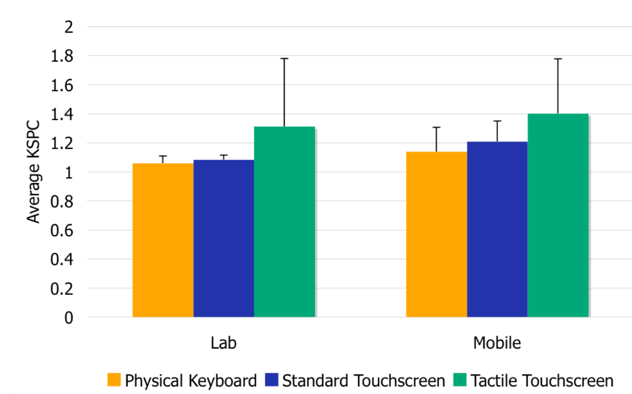

Figure 7: Average KSPC for each setting and keyboard type (with standard deviations).

A two-way ANOVA was performed on the KSPC data comparing the effects of mobility and the keyboard type. A significant main effect for KSPC for keyboard type was found ($F(2,22) = 6.58$, $p<0.0001$). Tukey tests showed that there were significantly more KSPC when typing on the tactile touchscreen than the physical or standard keyboards ($p=0.05$). There was no main effect for mobility ($F(1,11) = 2.53$, $p=0.11$) and no interaction between keyboard type and mobility ($F(2,22) = 0.04$, $p=0.95$).

The standard touchscreen keyboard had a lower KSPC than the tactile one. The reason for this is that participants corrected fewer of the errors they made (as can be seen in Figure 6). In an experiment like this one this is a reasonable tradeoff for participants as they are not penalised for errors (they can continue to the next phrase even if the current one is incorrect). In a real life setting, this would result in many mis-typed email addresses or URLs. The physical keyboard was still the best, with the lowest KSPC value. This suggests that the tactile feedback added helps some aspects of typing but it is not quite at the level of a real, physical keyboard. Further research into the tactile cues would be needed to see if we could improve the results here.

Time to Enter Phrases

Figure 8 shows the average time taken to enter a phrase for each keyboard condition in the lab and mobile settings. Participants using the physical keyboard entered the phrases with means of between 13 and 17 seconds (lab and mobile). The tactile touchscreen allowed participants to enter a phrase of text in 20 seconds (lab) and 22 seconds (mobile) while text entry on the standard touchscreen took longer with rates of between 25 and 27 seconds.

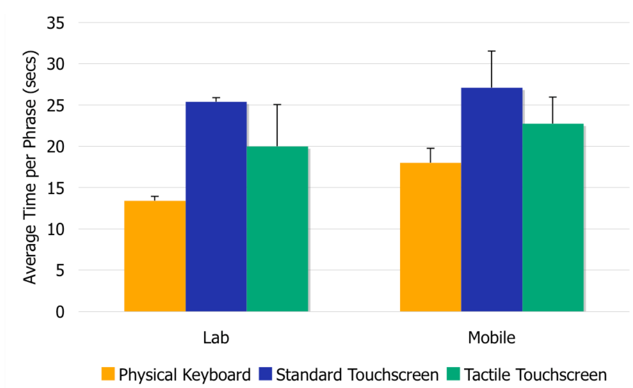

Figure 8: Average time per phrase entered in seconds (with standard deviations).

A two-way ANOVA on time to enter phrases for they keyboard types and mobility showed a significant main effect for keyboard type ($F(2,22) = 69.78$, $p< 0.001$). Tukey HSD tests showed that that the time taken to enter phrases on the physical keyboard and tactile touchscreen were significantly lower than on the standard touchscreen keyboard ($p=0.001$). The physical keyboard was significantly faster than the tactile one ($p=0.05$), indicating that the physical keyboard allows faster typing speeds than the touchscreen even with tactile feedback. This result means that tactile additions to the standard keyboard again had a significant positive effect on the usability of the device. Combining this with the accuracy results suggests that tactile feedback can offer some significant advantages for touchscreen devices.

This time there was a significant main effect for mobility ($F(1,11)=9.48$, $p=0.003$), with the mobile condition increasing the time taken to enter phrases over the lab (there was no interaction, $F(2,22)=2.65$, $p=0.077$). This shows that being mobile does slow down text entry rates due to the movements in the environment even though it did not affect accuracy. This may be because participants chose to maintain accuracy at the expense of input speed.

Subjective Workload

The results of the NASA TLX [5] questionnaires are shown in Figure 9. A two-way ANOVA on overall workload showed a significant main effect (for the standard six factors) for keyboard type ($F(2,22) = 111.35$, $p<0.001$). There was no significant main effect for mobility ($F(1, 11) = 0.19$, $p = 0.66$) and there was no interaction ($F(2, 22) = 0.7$, $p = 0.49$). Tukey HSD tests showed that overall workload when using the standard touchscreen keyboard is significantly higher than when using the physical keyboard or the tactile touchscreen keyboard ($p=0.05$). There was no significant difference between the Physical and Tactile conditions.

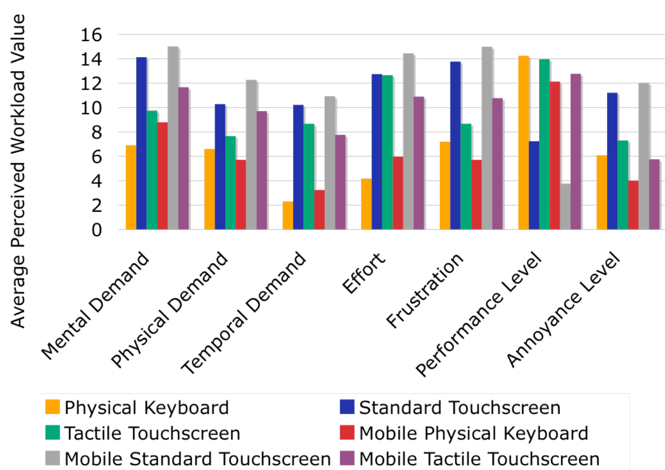

Figure 9: Average scores from NASA TLX questionnaires.

Further analysis using a single factor ANOVA on each of the workload factors showed a significant difference in all seven factors of the workload analysis with $p<0.001$. A Tukey HSD test confirmed that the mental demand, physical demand, frustration and annoyance levels when using the standard touchscreen are significantly higher than when using the other keyboard types. It also showed that perceived performance levels are significantly lower on the standard touchscreen.

The analysis of each workload factor also showed that temporal demand and effort is significantly higher when using the standard or tactile touchscreen than when using the physical keyboard.

Some participants commented that the standard touchscreen was frustrating as they did not receive feedback when their fingertip had moved off the edge of the button. Any visual feedback was masked by the fingertip over the button. A few also commented that they resorted to using their fingernails to tap the button in order to be more accurate but that this was uncomfortable.

Discussion
Hypothesis 1 can be accepted as it has been shown that using the physical keyboard produces significantly fewer errors and the greatest input speed with phrases being entered up to 10 seconds faster than the on the standard touchscreen. The greatest input speed results apply in both the lab and mobile settings.

Hypotheses 2 and 4 can also be accepted as the results show that touchscreen keyboards with tactile feedback produce fewer errors and greater speeds of text entry compared to standard touchscreen keyboards without tactile feedback both in the lab setting and in the mobile setting. This can be seen clearly in the mobile setting where phrases were entered up to 6 seconds faster with tactile feedback and accuracy scores were as high as 74% compared to the poor accuracy scores on the standard touchscreen keyboard. These results indicate that when in a mobile situation on a bumpy noisy train, it becomes even more difficult to use a standard touchscreen keyboard but tactile touchscreens still perform significantly better despite the dynamic environment.

Given that text entry on the tactile touchscreen only took 4 seconds longer on average than the physical keyboard and the accuracy results between both keyboards are comparable, hypothesis 3 can be partially accepted. These results suggest that tactile feedback should be added to touchscreen phones as it can significantly improve performance over a phone without such feedback.

EXPERIMENT 2 - TACTILE TOUCHSCREEN VERSION 2
Given the promising results obtained in the first experiment suggesting that tactile feedback could significantly improve the usability of fingertip touchscreen text entry, it was decided that this should be further investigated using an alternative, higher specification actuator incorporating spatial location to see if performance could be improved even further. Therefore, the same experiment was run again in the lab and mobile environments, but this time using a Dell Axim PDA. The Dell PDA was used as the new vibrotactile actuators could not be connected to the proprietary audio connection in the i718. The aim of this experiment was to investigate whether an alternative, more expensive, specialised actuator providing localisation could increase performance and get closer to that of the real physical keyboard.

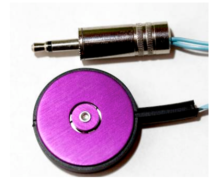

Figure 10: A C2 Tactor from Engineering Acoustics Inc.

Hardware
The C2 Tactor from EAI (Figure 10) was used for this study. It is a small wearable linear vibrotactile actuator, which was designed specifically to provide a lightweight equivalent to large laboratory-based linear actuators [12]. The contactor in the C2 is the moving mass itself, which is mounted above the housing and pre-loaded against the skin. This provides localised feedback as only the contact point (the sliver dot in the centre of (Figure 10) vibrates instead of the whole surrounding (which occurs in a typical mobile phone like the i718 where the whole device shakes). The C2 is resonant at 250Hz but is also designed to be able to produce a wide range of frequencies unlike many basic mobile phone actuators which have a limited frequency range.

In the experiment, a standard Dell Axim PDA was augmented with two C2 actuators attached to the back (Figure 11) so that they rested under the user's hand when it was held. One pressed against the palm of the hand, the other the middle of the fingers.

Figure 11: The Dell Axim PDA with 2 C2 actuators on the back.

Feedback Design
The tactile feedback used in this experiment was identical to that provided in Experiment 1 in that the manipulated tactile parameters are the same. However, the feedback felt very different due to the higher quality of the actuators: they ramp up faster and modulation is clearer. The only other difference was that the actuators provide localised feedback to the hand holding the device as opposed to shaking the whole device. By placing the two actuators on the left and right sides of the device, spatial location could be incorporated into the feedback to give some indication of which button was giving the feedback. Using multiple actuators to provide spatial cues has been used successfully in a previous study investigating vibrotactile progress bars on a PDA [6]. Three actuators were pulsed in turn to give the feeling of movement around a circle to indicate the progress

of a download. The design we used here is similar but uses only two actuators and applies it to text entry.

Whenever a fingertip-over, fingertip-click, or fingertip-slip event was triggered, the actuator placed nearest the button would be used to present the feedback. For instance, if the button 'A' was pressed, the actuator on the left was activated, if the button 'G' was pressed, both actuators were activated and if the button 'L' was pressed, the actuator on the right was activated.

Methodology

The aims and methodology of this experiment were the same as the previous experiment with one additional hypothesis:

5. Vibrotactile feedback from the C2 actuators will provide better results than the built-in actuator in the mobile device.

A new set of 12 participants were recruited from the University. They were presented with 30 random phrases from the MacKenzie phrase set and asked to enter them as quickly and as accurately as possible on the PDA (with and without tactile feedback). Participants used the device in the lab and then on the subway. They only used this device for the tactile touchscreen and standard touchscreen conditions as we could compare back to Experiment 1 for performance on the physical keyboard condition. Once again, speed, accuracy and KSPC were measured.

Results From Experiment 2

Accuracy

The average number of phrases entered correctly is shown in Figure 12 alongside the results from Experiment 1 for comparison. In the lab condition the PDA with actuators scored 23.8 correct answers and mobile 24.5.

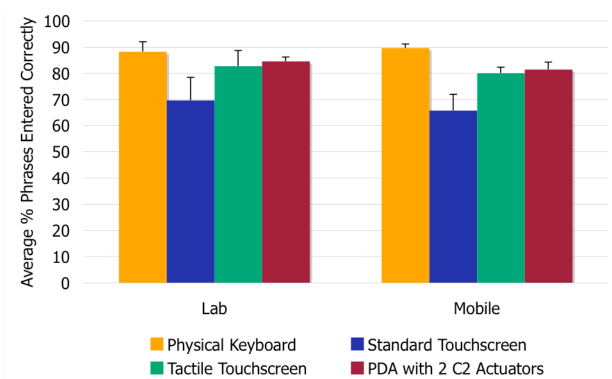

Figure 12: Average percentage of phrases entered correctly (with standard deviations).

A two-way ANOVA with replication was performed on the mean number of correct phrases entered, comparing the effects of mobility (static and mobile) and the four keyboard types (Physical, Tactile and Standard from Experiment 1 and the PDA with 2 C2 actuators). Although participants in experiment 2 had less practice (they only did PDA with no tactile and PDA with tactile in lab and mobile), the first study was fully counterbalanced so that a valid comparison can be made between both sets of data from each experiment. The ANOVA showed there was a significant main effect for keyboard type ($F(3,33) = 84.6$, $p<0.0001$). Post hoc Tukey tests showed that significantly more phrases were entered correctly on the physical keyboard, PDA with 2 actuators and on the tactile touchscreen compared to the standard touchscreen ($p=0.05$). There were no significant differences between the tactile touchscreen, PDA and the physical keyboard. The results show that the average number of correct phrases on the physical keyboard (26.4 in the lab, 26.9 when mobile) and the PDA (25.3 in the lab, 24.4 when mobile) were very similar. There was again no main effect for mobility ($F(1,11)=2.1$, $p=0.144$) and no interaction ($F(3,33)=1.39$, $p=0.24$).

Keystrokes per Character (KSPC)

The KSPC data for Experiment 1 and the PDA with the C2 actuators is shown in Figure 13. The PDA scored a mean of 1.20 in the lab and 1.24 when mobile.

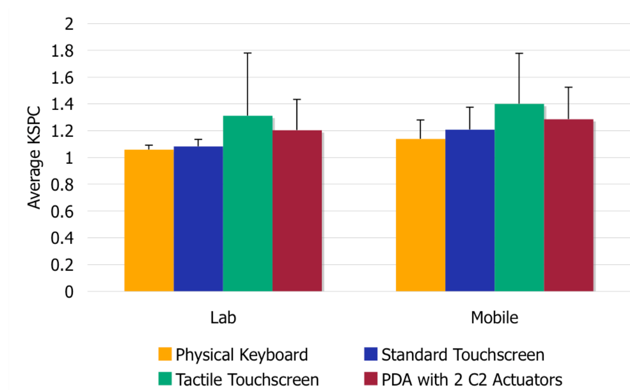

Figure 13: Average keystrokes per character (with standard deviations).

A two-way ANOVA showed a significant main effect in KSPC for keyboard type ($F(3,33)=4.82$, $p=0.003$). Using post hoc Tukey's Pairwise Comparison, it can be seen that a significantly higher number of KSPC occurred when using the tactile touchscreen compared to all three other types of keyboard including the PDA with C2 actuators ($p=0.05$). There were no significant differences in the KSPC on the physical keyboard and on the PDA with C2 actuators or the standard touchscreen. This suggests that the PDA has an advantage over the tactile touchscreen in that KSPC is reduced, meaning that it is closer to the performance of the real keyboard. On the other hand, the KSPC results could be seen as an indication that participants corrected more of their errors on the tactile touchscreen therefore increasing KSPC. Therefore suggesting that the tactile touchscreen helps users to identify errors more easily by providing fingertip-slip feedback while errors could go unnoticed on the standard touchscreen keyboard with no tactile feedback.

There was no main effect for mobility (F(1,11)=3.42, p=0.07) and no interaction between mobility and keyboard type (F(3,33)=0.03, p=0.98).

Time to Enter Phrases

The average time to enter a phrase is shown in Figure 14. A two-way ANOVA on mobility and keyboard type showed a significant main effect for keyboard type (F(3,33)=70.41, p<0.001), for mobility (F(1,11) = 10.24, p=0.001), with a significant interaction between the two (F(3,33)=2.92, p=0.03).

As before, the average time to enter a phrase was significantly affected by keyboard type. Tukey tests showed that the time per phrase on the PDA was significantly lower than on the tactile touchscreen and the standard touchscreen (p=0.05). There was no significant difference between the physical keyboard and the PDA. These results suggest that the more specialised C2 actuator can improve results over the actuator in the Samsung i718 and get closer to the real keyboard. The C2's are too large to be incorporated into a current mobile device, but it does suggest that manufacturers could improve the capabilities of some of the more basic actuators used and gain further performance benefits.

As in Experiment 1 we found that mobility significantly increased the time taken to enter phrases, but this time there was a significant interaction between keyboard type and mobility. The interaction occurred as there was no change in performance in the PDA condition when static and mobile. All other keyboard types performed worse when mobile, but performance with the PDA went from 17.5 to 17.9 seconds per phrase. It is not clear why this occurred and further investigation is needed to see if there is a real effect. It does suggest, however, that the performance with that virtual tactile keyboard is robust, with performance in the mobile condition very close to the real physical keyboard.

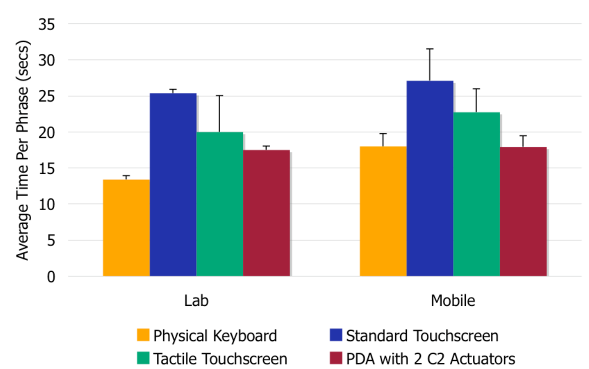

Figure 14: Average time per phrase in seconds (with standard deviations).

Subjective Workload

The results of the NASA TLX questionnaires are shown in Figure 15. A two-way ANOVA on overall workload showed a significant main effect for keyboard type (F(3,33) = 88.62, p<0.001) but no effect for mobility (F = 0.12, p = 0.72) and no interaction between them. A one-way ANOVA performed on each of the seven workload factors followed by Tukey tests showed that mental demand, physical demand, temporal demand, effort, frustration were significantly increased and perceived performance was significantly decreased when using the standard touchscreen.

Unlike Experiment 1, the ANOVA and Tukeys showed a significantly higher level of annoyance for the PDA with C2 actuators than with the physical keyboard or with the original tactile touchscreen (F(2,22) = 35.4, p < .0001). It is not clear why there should be more annoyance in this case, particularly as performance overall was improved. It may be due to the stronger forces that the C2 actuators can apply. We did not allow the users to change the force of the actuators, but that could easily be done in the same way as the volume of the audio can be changed.

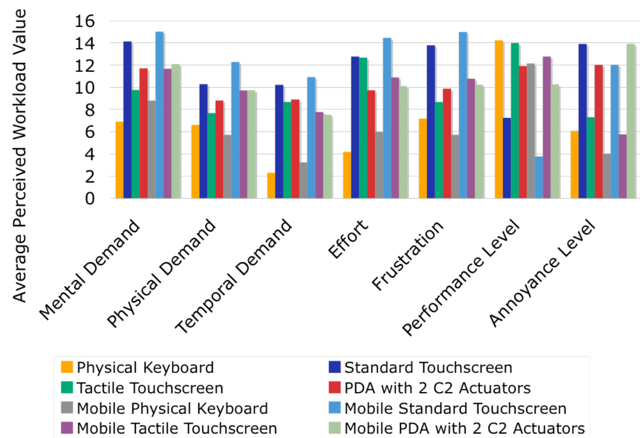

Figure 15: NASA TLX Scores Compared with Experiment 1.

Observed Methods of Finger Input

One interesting observation from these studies was the different ways in which participants chose to use their fingers to press the buttons. All but one of the participants used both thumbs when entering text on the physical keyboard. On the touchscreen, both with and without tactile feedback, participants used several different techniques. Some would go from using their forefinger to the middle finger to the fingernail and back to the forefinger for instance. Two of the participants even attempted using their little fingers to enter the text. At no time did the participants use their thumbs or more than one finger at once on the touchscreens. It appeared as though they were uncomfortable and could not find an easy way to use their fingers with the displays. One participant commented that he felt like he was 'learning to type all over again'. This could simply be due to the relative novelty of touchscreen mobile devices and participants' lack of experience with them or, perhaps, could indicate that a different keyboard layout is required.

DISCUSSION AND CONCLUSIONS

The two studies reported here have shown that tactile feedback can significantly improve fingertip interaction and performance with soft keyboards on touchscreen mobile devices. With the addition of this extra tactile feedback the performance of touchscreen keyboards can be brought close to the level of real, physical keyboards. This means that the benefits of touchscreen displays (such as the flexibility to use the whole screen for games, web pages or photos) do not come at the cost of poorer text or number entry. It has been demonstrated that tactile feedback can benefit touchscreen interaction in both stationary situations and more varying, realistic mobile situations.

Furthermore, a comparison of two different types of tactile actuator showed that text entry on can be further improved by using multiple, specialised actuators which can provide localised feedback as opposed to a single standard actuator which vibrates the whole device. However, the results for both types of tactile touchscreen show that user performance is significantly better than when using a touchscreen with no tactile feedback. Therefore, given that the C2 actuators used are expensive and not currently found in standard devices, it would appear to still be beneficial and easier to augment touchscreens with tactile feedback provided by the actuator already present in the phone.

Given these promising results, it is probable that tactile feedback will aid in all interactions with touchscreen buttons, not just text entry, and future studies will examine fingertip interaction with other types of touchscreen widgets such as progress bars, icons, menus and sliders.

The results of our studies suggest that manufacturers should include tactile feedback in new touchscreen devices. There were no drawbacks from including it, only benefits. Furthermore, such feedback is likely to be of benefit to stylus interaction as well as fingertip interaction (shown also in [1]). Our results strongly suggest that using either the built-in vibrotactile actuator already present in most mobile devices or more specialised actuators to produce tactile feedback can improve the usability of touchscreen keyboards.

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