Characteristics of Pressure-Based Input for Mobile Devices

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ABSTRACT
We conducted a series of user studies to understand and clarify the fundamental characteristics of pressure in user interfaces for mobile devices. We seek to provide insight to clarify a longstanding discussion on mapping functions for pressure input. Previous literature is conflicted about the correct transfer function to optimize user performance. Our study results suggest that the discrepancy can be explained by different signal conditioning circuitry and with improved signal conditioning the user-performed precision relationship is linear. We also explore the effects of hand pose when applying pressure to a mobile device from the front, the back, or simultaneously from both sides in a pinching movement. Our results indicate that grasping type input outperforms single-sided input and is competitive with pressure input against solid surfaces. Finally we provide an initial exploration of non-visual multimodal feedback, motivated by the desire for eyes-free use of mobile devices. The findings suggest that non-visual pressure input can be executed without degradation in selection time but suffers from accuracy problems.

Author Keywords
Pressure input, tactile feedback, haptic feedback, mobile device, interaction technique, pressure-based interaction

ACM Classification Keywords
H.5.2 Information Interfaces and Presentation: User Interfaces—*Input devices and strategies, interaction styles, haptic I/O*

General Terms
Design, Experimentation, Human Factors

INTRODUCTION
This paper investigates finger-based pressure input for mobile devices. In contrast to previous work we focus on finger-based, rather than stylus-based input. This interaction design choice is motivated by the increasing popularity of mobile technologies that use finger input.

Pressure is an integral component of natural interactions with the environment. Holding, twisting, turning, typing among many more manual interactions all are deeply connected with sensing pressure. We learn from the sensation how good our grip is, how heavy objects are or how much resistance an object offers when acted upon. Pressure plays a direct role in many familiar situations, for example in music, pressure leads to expressivity in playing stringed instruments. In current interfaces pressure often plays a more discrete role. Sufficient pressure needs to be applied to make keys of a keyboard register, or to perform clicks on a multi-touchpad.

On mobile devices pressure-sensitivity has numerous applications such as in expressive music applications [5] and in drawing applications [31] but also promises to enrich traditional input such as typing [3]. In general, pressure adds another dimension that can be accessed continuously without large hand motions and hence can be used in subtle ways such as pressure-based access control and providing depth to 3D object manipulations.

We conducted a series of experiments to understand fundamental aspects of pressure interaction with one and two-sided pressure-sensitive mobile devices. First we are looking to answer an unsolved question posed in the literature regarding the functional characteristic of pressure input. It is unclear from the results shown in the current literature, if known deficiencies in pressure input are a result of human performance, sensor behavior, or a mixture of both. We aim to clarify how linear sensor behavior improves the ability of users to control pressure input. Furthermore we wanted to address the question of hand pose and interaction type. That is, is there a difference in performance between pressure input against a solid surface or when an object is hand-held, and is there a difference between single-sided (pointing type) input and two-sided (grasping type) input. The results indicate that grasping outperforms single-sided input and is competitive with pressure input against solid surfaces. This suggests that pressure input in a mobile setting is best delivered through a two-sided interaction paradigm. Finally, an initial exploration of multimodal feedback to support non-visual pressure input is presented. This allows for pressure input on mobile devices with reduced visual presentation capacity and potentially eyes-free operation. We compare the performance characteristics of visual, auditory, vibrotactile, and combined auditory and vibrotactile feedback.

The paper is structured as follows. In the following section we discuss related work on pressure input. As there are conflicting results in the literature we analyze sensor characteristics and show that it is important to linearize pressure input. Next we investigate various poses for handheld application of pressure and show them to work equally well as pressure applied to a device resting on a table. Finally, we investigate multimodal feedback and chart the performance characteristics of different modalities. We conclude with discussing possible applications, open issues and future work.

RELATED WORK

Pressure-based input with pens and styli has been explored in a substantial body of work. In terms of controllability it has been shown that people do not keep precise pressure levels well without additional feedback [18, 22]. Ramos et al. [22] propose pressure widgets as a form of visual feedback to improve performance of pressure-based input. Ren et al. [24] use pen pressure to improve target selection tasks. They use continuous pressure to control the size of a circular cursor area and the zoom level for small targets.

An advantage of pen-based input is that it is easier to simultaneously apply pressure and move a pen on a screen. With direct touch, friction between finger and touch surface quickly increases with pressure, making simultaneous movement strenuous. Zliding is a joint pen-based manipulation of sliding and zooming at the same time using pressure [20]. Ramos and Balakrishnan [21] propose pressure marks, which are pen strokes with continuously changing pressure, as input for graphical user interfaces. However, a number of popular handheld devices are designed for direct finger input and do not use pens.

Direct finger-based pressure input to a handheld device without a pen as a mediator has been explored as well. The idea of using pressure for embodied interaction with devices has been formulated by Harrison et al. [7]. Gummi [26] uses bending to control gradual transitions between views, transparency, and zooming. Scott et al. [27] investigate force gestures for mobile devices, including bending, squeezing, stretching, and compressing. The iPhone Sandwich [6] is a research prototype for two-sided multitouch sensing with continuous pressure input. It consists of two iPhones and a pressure sensing layer between them (Figure 1). Four force-sensing resistors (FSRs) are located in the corners of an acrylic glass layer between the iPhones.

McCallum [17] et al. present a mobile text input technique in which each key is able to sense a range of pressure values. Three states are distinguished: A soft press invokes the first, a medium press the second, and a firm press the third character mapped to the key. For large-scale finger-based multi-touch surfaces Benko et al. [1] estimate pressure from the screen width of the finger image in video-based multi-touch surfaces to preview click selections and to improve precision of selection. This simulates pressure input but is not as precise as a pressure sensor such as a force-sensitive resistor (FSR).

Most pressure-based input techniques rely on continuous visual feedback. However tactile and audio feedback have been used in pen-based interfaces [14, 15]. Rekimoto et al. [23] implemented a three level pressure-based button ("not pressed", "light pressed", and "hard pressed") and provided tactile feedback upon crossing the boundaries of these levels. The effectiveness of tactile feedback in mobile devices has been explored in [2, 9, 16]. EarPod investigated auditory feedback for eyes-free touch-interactions on mobile devices [33].

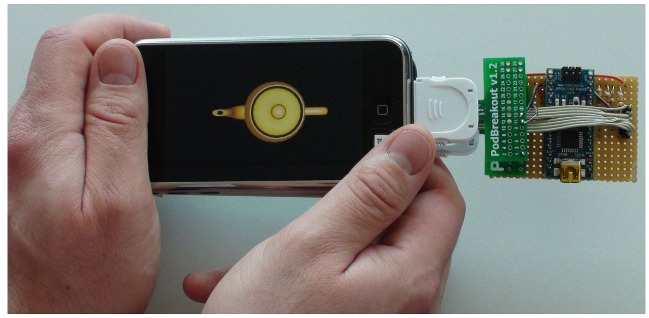

Figure 1. Sandwich prototype for two-sided multitouch sensing with continuous pressure input.

Typical applications for pressure input are widget control [22], menu item selection [4], expressive typing [17], conveying the urgency of phone calls [8], and zooming [20].

CONTROLLING PRESSURE INPUT

In the literature there are conflicting reports on what transfer functions from sensor values to input values yield best results for pressure input. For example, Ramos et al. [22] report that for a linear transfer function participants demonstrated less control for low pressure levels and described the pressure widget as "very sensitive" at these levels. They suggest choosing an adequate transfer function to counter this effect. Cechanowicz et al. [4] evalutated different discretization functions for a pressure-sensitive mouse and found that a quadratic mapping centered at the lower range works best. In [20], Ramos and Balakrishnan use a parabolic-sigmoid transfer function. Shi et al. [29] use a fisheye discretization function and found it to superior to other mappings. Ren et al. [24] use a sigmoid transfer function. McCallum [17] et al. use a logarithmic discretization function to map key pressure to character. These results are in conflict with those reported by Srinivasan and Chen [30]. They performed a basic experiment on human performance in controlling normal forces of contact with rigid objects. In contrast to other work they found that when visual feedback is present the error for keeping pressure at a certain target level remained approximately constant for all measured target forces. However, it needs to be noted that it is difficult to make comparisons due to the wide range of different hardware being used.

Experiment: Pressure Controllability

In order to investigate controllability of pressure at different levels we conducted an experiment in which users had to keep pressure at a certain level for five seconds. Users had to move to the target pressure level and then had to keep pressure at that level as precisely as possible. The goal was to estimate the variability of pressure input for each of the levels. In this first experiment we used a voltage divider to measure the sensor input.

Apparatus

As a pressure input device we used an iPhone Sandwich [6]. In order to get as precise sensor readings as possible we attached two additional force-sensing resistors (FSRs) to the top and bottom display surfaces of the iPhone Sandwich. All measurements in the experiments are based on readings from these two sensors. We did not use the FSRs in the layer between the devices. FSRs are not suitable for precision measurements, but the FSRs from Interlink [12] that we used in our experiments have good hysteretic properties and show sufficiently stable behavior over time such that their limitations do not play a role at the scale of our experiments. The external FSRs are connected to the analog input pins of an Arduino[1] board via a voltage divider or an opamp-based circuit described below. For the voltage divider the resistor was tuned to provide the best dynamic range and sensitivity for the pressure readings. The Arduino board provides the digital sensor output via a serial connector to the iPhone Sandwich. The update rate was set to 30 Hz with a resolution of 8 bits. Users held the iPhone Sandwich in landscape orientation. The FSRs were vertically centered and attached about 3 cm from the right edge of the devices to be easily reachable with the thumb and index finger, respectively, of the right hand (Figure 7). The raw sensor values were slightly filtered using a Savitzky-Golay filter [25] to reduce noise.

The target pressure was represented as a value ranging from 0.1 (corresponding to 0.5V) to 0.9 (corresponding to 4.5V) where 0 means no pressure and 1 corresponds to maximum pressure. The maximum pressure was empirically determined in pilot tests to be easily reachable. The target pressure was visualized as a vertical bar on a horizontal scale displayed on the screen (Figure 7, top). The left edge of the screen represented zero pressure; the right edge represented maximum pressure. The horizontally moving pressure cursor provided continuous visual feedback on the current pressure input. The target pressure was set in increasing order in steps of 0.1. The duration of one step was 5s, after which the pressure target advanced to the next step. We allowed 2s to move to the next level and computed the variation of pressure input around the target during the remaining 3s. The standard deviation was used as a measure of pressure stability. Pressure was presented in increasing order to have fixed pressure deltas from one to the next step. We were not interested in the time to transition to the next level, but in how precisely users could hold up pressure at a particular target level.

Participants and Design

Six right-handed users (3 male, 3 female) participated in this initial study, ranging in age from 26 to 45 years (mean 33, sd 6.8). The task was to follow the pressure target and to keep the cursor on the pressure target as precisely as possible.

[1] http://www.arduino.cc

The experiment used a 2×2×9 within-subjects factorial design. The factors and levels were:

- Pose: front-on-table, grip
- Mapping: linear, quadratic
- Target pressure: 9 levels (0.1 to 0.9)

With three repetitions per trial, users had to perform 2×2×9× ×3 = 108 trials. In the "front-on-table" condition the device lay on the table and users operated the pressure sensor with their index finger. In the "grip" condition users operated the pressure sensor by holding the device with their left hand and applying pressure with thumb and index finger of their right hand. The order of presentation for mapping was counterbalanced. Half of the participants started with front-on-table, the other half with grip.

Results

Five of the six participants preferred the grip condition to the front-on-table condition, stating, e.g., that grip was more precise for lower pressures and that it allowed them to more easily reach high pressure levels. One participant had no preference. Four of six participants mentioned that pressure was more difficult to control for low pressures. Two participants found it strenuous to hold pressure over several seconds at the higher pressure levels. The quantitative results are shown in Figure 2. The graphs show the median variability over the last 3s of each 5s step. This was computed as the median of the standard deviations for each condition. These results clearly show that variability increased at lower pressure levels and these results are similar to those reported by [4, 22, 29].

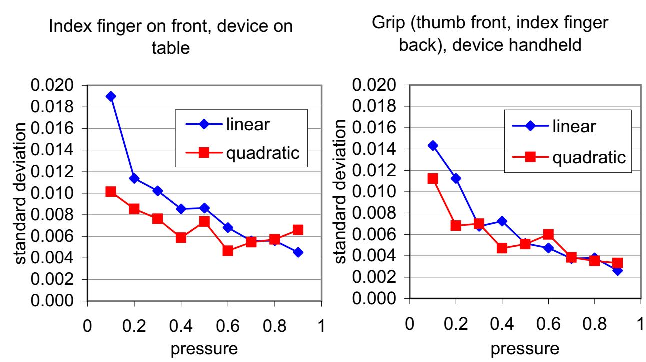

Figure 2. Standard deviation for different pressure levels during 3s intervals. Variability is high for low pressure levels. The FSRs are attached to voltage dividers.

Sensor Characteristics and Signal Conditioning

In order to investigate why variability increased at low pressure levels, we looked at the weight-to-sensor value mapping introduced by our setup. We placed the FSR on an electronic scale, placed a piece of rubber the size of a fingertip on top of the FSR, and put a range of weights on top (a glass filled with different amounts of water). We then noted the reading of the electronic scale and sampled the sensor output over two seconds. The resulting curves are shown in Figure 3.

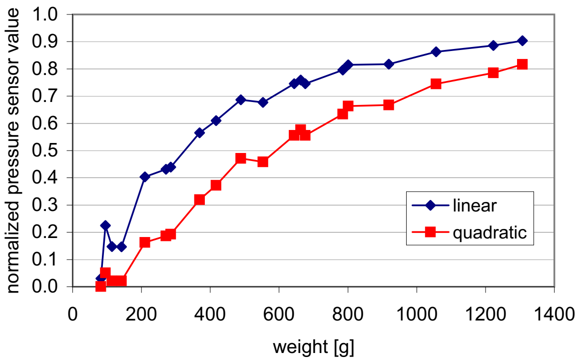

Figure 3. Combined characteristic of FSR response curve and voltage divider.

The blue curve shows the pressure range linearly rescaled from 0 to 1 (linear mapping in the experiment), the red curve shows the result of the quadratic mapping. It can clearly be seen that the blue curve is not linear but steeper for lower pressure values, i.e. the sensor reading is not a linear function of the pressure value. The data has a good fit to a logarithmic function ($p = 0.3144 \ln(x) - 1.3116, R^2 = 0.98$). The quadratic mapping shows a flatter slope for low pressure values. For the linear mapping this means that user input variability at a low pressure value will be translated into a larger variability in the sensor output than the same input variability at a higher pressure level. In order to compensate for this characteristic of the FSR and voltage-divider circuit one would have to use a mapping that is the inverse function of the resulting logarithmic characteristic, which would be an exponential function, in this case $x = \exp((p + 1.3116)/0.3144)$.

As we wanted to use the resolution of the sensor to its full capacity we decided to build a new hardware setup in which the hardware already provides linear sensor input. We used an opamp-based current to voltage converter (Figure 4). The transfer function of the voltage divider is $V_{out} = \frac{R}{R+R_{FSR}} \cdot V_{in}$, hence a voltage divider does not simply create a linear relationship between resistors R or R_{FSR} and the output voltage [10, 19]. This is also noted in documentation of the force sensing resistor [12], who propose a current-to-voltage circuit to achieve a linear relation. The operational amplifier has two defining characteristics. One is that the impedance between the two inputs is very high and theoretically often treated as infinite. This has the effect that there is minimal load on any circuit placed left of the opamp. The second characteristic is that the output impedance is very low which makes the circuit insensitive to load or energy demand at the output. The operational amplifier will amplify the output as needed to achieve these properties. This makes this element very versatile for building a range of analog circuits [10]. To understand the current-to-voltage converter of Figure 4 note that the input impedance is such that practically no current will flow into the input. Hence all current at the negative input will instead flow across the resistor connecting to the output. Hence the output voltage simply obeys Ohm's law taking the negative polarity of the input into account. Thus we arrive at a relationship of $V_{out} = -I_{in} \cdot R_{FSR}$ and if the input current is held constant, the output will be linear with respect to R_{FSR} for a large range of output loads [12, 19]. The characteristic of the opamp circuit was measured in the same way as described above. Figure 5 shows the normalized linear mapping as well as the quadratic mapping. The linear mapping now has a good fit to a linear function ($p = 0.0008x + 0.0339, R^2 = 0.97$).

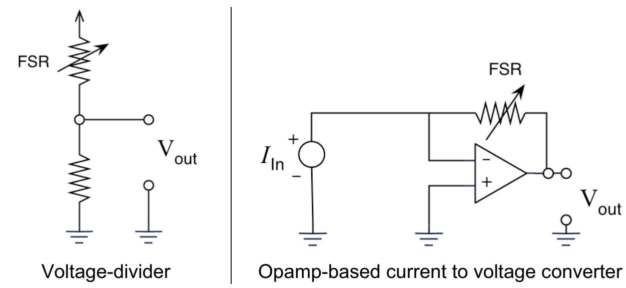

Figure 4. Voltage divider (left) and opamp-based circuit (right). The latter provides linearized sensor input.

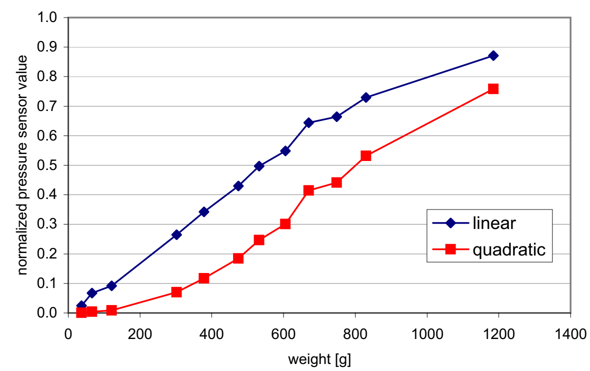

Figure 5. Combined characteristic of FSR response curve and opamp-based circuit.

Pressure Controllability with Linearized Sensor Input

We repeated the above experiment – holding a particular pressure level for 5s – with 6 participants, this time only using the grip pose. We compared both hardware setups in this test. For the voltage divider hardware we used the exponential function derived above to linearize the input before applying the transfer function. For both hardware conditions we tested a linear and a quadratic transfer function. The experimental factors thus were hardware (voltage divider and opamp-based) and transfer function (linear and quadratic). Otherwise the experimental task was identical to the one described above.

The results of the input variability are shown in Figure 6. For both the old hardware (voltage divider linearized by exponential correction function) and the new hardware (opamp-based) the linear transfer transfer function works better than the quadratic transfer function. The reason is probably that the quadratic function over compensates the already linearized sensor input. Moreover, comparing the linear mappings for the old and new hardware, one can observe that there is an advantage of the new hardware. This is probably due to the better use of the dynamic range of the setup.

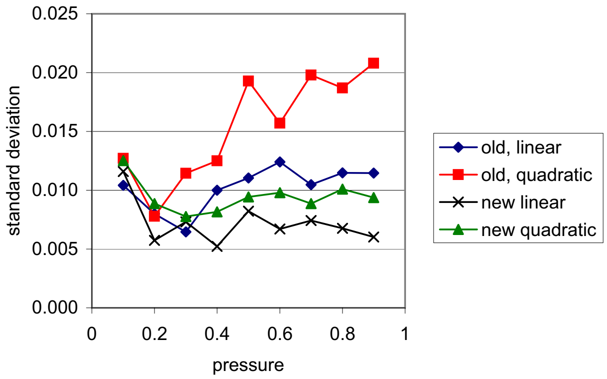

Figure 6. Standard deviation for different pressure levels during 3s intervals. Overall variability is better for the new hardware and the linear mapping.

Overall these results are in line with Srinivasan and Chen's [30] findings in that human ability to control pressure seems to be uniform for a wide range of pressure levels. The test subjects performed significantly better with a linear sensor than with a non-linear sensor. A linear transfer function works better than a quadratic transfer function if the sensor data is a linear mapping of the input force. The results reported in the literature may be due to the use of non-linear pressure sensors.

POSES FOR PRESSURE INPUT

Traditionally, pressure-based input assumes that the device to which pressure is applied is resting on a stable surface. Examples are pressure-sensitive pen input to tablet PCs or graphics tablets. Pressure-based input for stationary devices has been explored, for example, in [22]. Applying pressure to mobile devices when handheld is a challenge and has not been extensively researched. Moreover, many pressure-based interfaces assumed a pen or stylus to apply pressure (for example [18, 22]). However, many current mobile devices allow direct finger input.

Experiment: Handheld Device Poses

We therefore investigated direct finger-based pressure input for handheld devices. The objective was to find out which ways of holding the device when applying pressure, i.e. which device poses, are most suitable for handheld pressure input. As a baseline, we also compared a device resting on a table with a device held in hand. We were interested in how quickly and accurately users can control pressure they exert with one or more fingers on the device and what pressure range is useful for interaction. In particular, we investigated user performance of pressure-based input under the following poses (Figure 7):

- Index finger on front of device, device resting on table ("front-on-table")
- Thumb on front and index finger on back of device, device handheld ("grip")
- Thumb on front of device, device handheld ("front")
- Index finger on back of device, device handheld ("back")

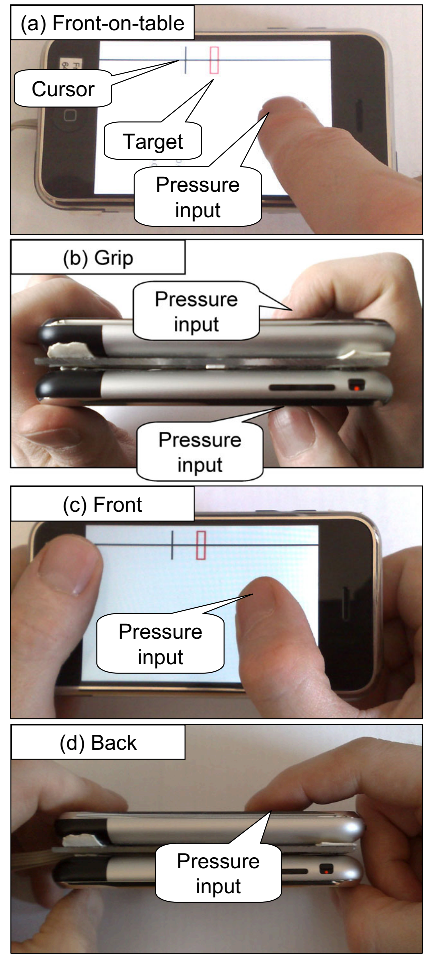

Figure 7. Device poses tested for handheld pressure input: (a) index finger on front, device resting on table (baseline); (b) grip with thumb and index finger; (c) thumb on front; (d) index finger on back. Changing pressure moves the cursor on the horizontal line. The red rectangle indicates the target pressure and target width.

Apparatus

As above, the target pressure was represented as a value ranging from 0.1 to 0.9 where 0 means no pressure and 1 corresponds to maximum pressure. The target widths on this scale were 0.02 and 0.04. The pressure input was linearized using the hardware described in the previous section. The pressure was measured using two FSRs, one attached to the front and one to the back display of the iPhone Sandwich. The device was held in landscape orientation. The FSRs were vertically centered and attached about 3 cm from the right edge of the devices to be easily reachable with the thumb and index finger, respectively (Figure 7). The raw sensor values were slightly filtered using a Savitzky-Golay filter [25] to reduce noise.

Participants and Design

Twelve participants (8 male, 4 female) ranging in age from 15 to 36 years (mean 26.6, sd 6.7) participated in the experiment. All of them were right-handed. The experiment used a 4×9×2 within-subjects factorial design. The factors and levels were:

- Pose: front-on-table, grip, front, back
- Target pressure: 9 levels (0.1 to 0.9)
- Target width: narrow (0.02) and wide (0.04)

The task involved sequentially selecting targets that appeared at random positions on a horizontal bar (see Figure 7, top). The left end of the bar corresponded to zero pressure, the right end to maximum pressure. Continuous visual feedback was provided on the device display. As the user increased pressure a vertical line cursor moved along the bar. The target was shown as a red rectangle on the bar. The target was selected by keeping the cursor within the target rectangle for the dwell time of 1s. Selecting the target ended the trial and the target moved to the left end of the bar (zero pressure). The user had to release pressure and wait for one second after which the next trial would be started at the new target position.

The order of presentation of the four device poses was counterbalanced using a latin square design. The order of target widths was counterbalanced within the poses. The distances were presented in three blocks. Within each block the nine distances (0.1 to 0.9) were presented in random order. This amounts to 4 poses × 2 widths × 3 distance blocks × 9 distances per block = 216 trials per user.

Results

We measured the time required for selecting a target and logged the pressure sensor values over time. The mean selection times (1s dwell time subtracted from these values) are: 3.14s for front on table, 2.91s for grip, 3.74s for front, and 3.42s for back (Figure 8). The selection times are roughly log-normally distributed. A repeated-measures ANOVA on the log-transformed data shows that these differences are statistically significant ($F_{3,33} = 9.11, p < 0.001$). Bonferroni corrected post-hoc comparisons between all pairs show a difference between front and the other poses, but not among the other poses. The mean values suggest that handheld pressure application, specifically for the grip posture is not disadvantaged compared to pressure application against a solid surface. The average selection time was 4.46s for the narrow target and 2.14s for the wide target ($F_{1,11} = 152.08, p < 0.001$). Wide target selection more strongly differentiates the results. Front hand-held shows up to a factor of 3 degradation in time-to-target compared to grip for low pressure values (Figure 9). The median selection time showed a linear relationship with pressure, ranging from 1.5s at 0.1 to 3.4s at 0.9 ($t = 2.277p + 1.261, R^2 = 0.95$). The results show a significant effect of target pressure on acquisition time ($F_{8,88} = 50.88, p < 0.001$). We also asked users which of the poses they preferred. Six of twelve users preferred grip, 3 index finger front-on-table, 2 index finger on back, and 1 user preferred thumb on front.

The results show that pressure-based selection is possible in reasonable selection times, even with 9 targets equally distributed on the pressure range and with fairly narrow target widths. All handheld poses, except front, are on par with the

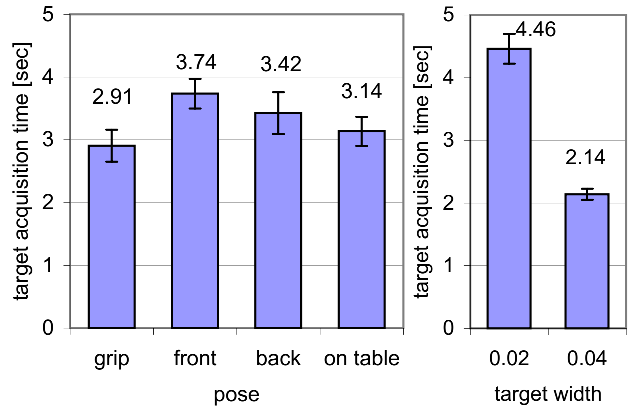

Figure 8. Target acquisition times for the four device poses. (Error bars show 95% confidence intervals.)

front-on-table pose, in which the device is supported by a table surface.

MULTIMODAL FEEDBACK FOR PRESSURE INPUT

Physiologically the sensations of touch and pressure are due to the deformation of mechanoreceptors located in the skin. While many types of mechanoreceptors exist and are involved in touch sensation, Merkel nerve endings are specifically involved in the sensation of pressure [13]. Pressure input for interfaces is difficult as humans are not adept at distinguishing absolute pressure values [18]. When the hand is pressed against an object the just noticeable difference (JND) in contact force is about 7% [30]. The JND for distinguishing among different weights is about 10% [30]. The performance for memorizing absolute pressure levels is even lower. Therefore additional feedback of applied pressure needs to be given to allow users to exert control over pressure-based input.

Currently visual feedback is preferred for pressure-based interfaces as it is the feedback modality that offers the most communication bandwidth between the user and interface. However the use of visual feedback in mobile scenarios may cause users to be less aware of the visual cues alerting them to dangers in their environment. EarPod [33] is an example of a system designed to alleviate the use of visual feedback. Additionally, eyes-free interaction using pressure input can reduce the amount of screen space that is required for traditional widgets. While non-visual feedback has been examined for pen-based pressure input [15], much remains unknown about the design and application of non-visual feedback for pressure input. Hence we chose to examine a variety of multimodal feedback consisting of audio feedback, audio presented with additional tactile feedback, and tactile feedback by itself.

Continuous visual feedback has been identified as being important for fine control over pressure-based widgets [22]. However the design of continuous non-visual feedback is difficult as users adapt to stimuli and thus become less sensitive to changes [28, 32]. Additionally, initial trials using continuous audio and vibrotactile feedback suggested that

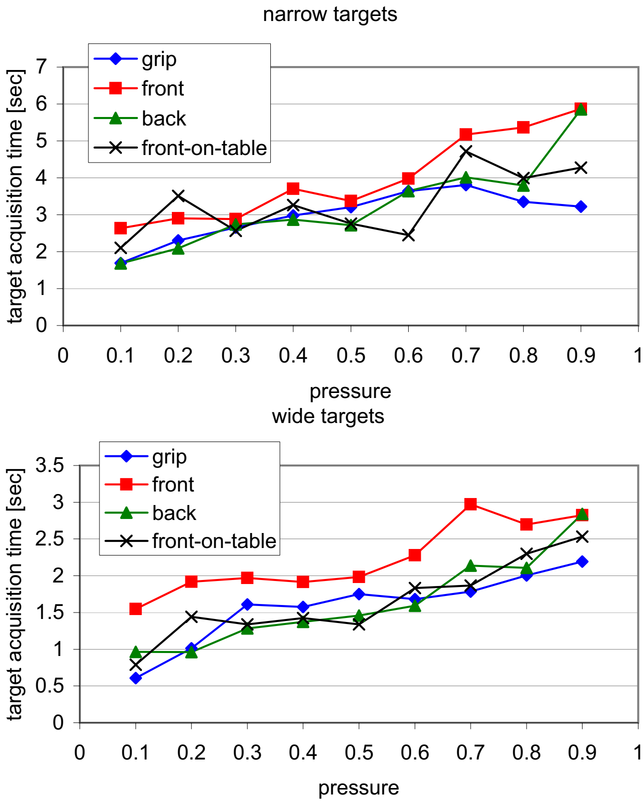

Figure 9. Target acquisition times by target pressure for the four device poses. The top graph shows the results for narrow, the bottom one for wide targets.

subjects found the use of continuous cues irritating. This observation coincides with annoyance of persistent exposure reported in [15]. Therefore, we reduced the amount of feedback presented to the user. Feedback is only given on the transition from one pressure level to the next (Figure 10) rather than continuously with changes in the pressure input. With this constraint on feedback it was felt that it would be unfair to test the non-visual feedback with a large number of pressure levels. Previous studies such as PreSenseII [23] or PressureText [17] also chose a relatively small set of distinguished pressure levels. In certain applications this is justifiable. Mode selection, for example, typically only needs a few distinct states.

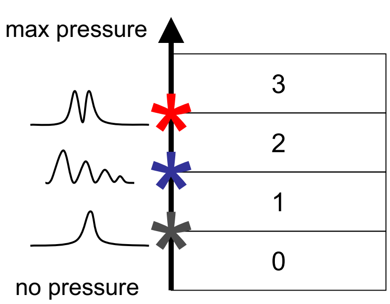

Figure 10. Three different kinds of vibrotactile feedback were played on the transition between the pressure levels.

Feedback Design

Sensor modalities have their particular characteristics. While it is difficult to control for these differences, we aimed to design feedback across different modalities is such a way that exposure time is normalized. That is, sensory stimuli should be presented for roughly the same duration in all cases.

Visual

The visual design is very similar to the previous experiments. However, the target location became hidden once the user started to move the cursor. This change was made in order to normalize exposure time for the different types of feedback.

Audio

Each pressure level was mapped to a particular musical pitch to be played by a plucked string sound. As pressure level increased the note of the pitch also increased. We used the notes C3# (138.59 Hz), F3 (174.61 Hz), and F4 (349.23 Hz).

Audio and Vibrotactile

The audio feedback condition was expanded by adding small short vibrations from the pager motor of the SK6 Shake device [11]. When each note was played a small vibration lasting 40 milliseconds was played alongside the audio cue. This bimodal approach has been used by [9] to increase user performance when interacting with on screen keyboards.

Vibrotactile

Using pager motors to create distinguishable vibration patterns is difficult. Having only intensity control of the vibrations reduces the design space to make vibrations that are both short in the time it takes to play them and that are easily distinguishable. After informal testing we decided on the following 3 vibration patterns; one short pulse, a series of pulses with decreasing intensity and two short pulses (Figure 10). Each vibration pattern lasted 40, 130, and 120 ms, respectively. This had the effect of a sharp sensation for the first pressure level, a soft, pulsing sensation for the middle pressure, and two sharp sensations for the final level.

Experiment

12 participants (5 male, 7 female) ranged in age from 18 to 36 years (mean 25.8, std 5.1). All of them were right-handed. The task was to reach a certain target pressure level, with the target pressure level presented in the modality being tested. The subject was tasked with matching the target feedback given with the feedback produced when they moved from one pressure level to the next. For example, in the vibrotactile condition this meant that for target level 1 at the beginning of the trial the sharp short pulse would be played (cf. Figure 10). Then the subject would apply the pressure that produced the matching short pulse feedback. For each modality we tested each pressure level in ten separate occasions. The target pressure levels were presented in a randomized order. The subject would select the pressure level by holding the cursor in the same position for 1s.

The pressure sensor was placed underneath the thumb of the subject. For the visual condition it was placed on the top bezel of an iPhone and for the non-visual conditions it was placed on the top of the Shake device (Figure 11) in order to ensure good physical coupling to the vibrations.

Figure 11. Shake device for vibrotactile feedback with FSR on top.

During initial tests subjects found it difficult to recognize the note presented for both the audio and bimodal conditions. To alleviate this issue the target note was played five times in quick succession in the final experiment. No other issues about presentation of the target feedback were reported or observed.

Results

We measured both the discrete pressure levels and raw sensor values along with the time taken to select the target for each trail. A two-factor repeated-measures ANOVA was performed on the accuracy (Figure 12) and selection times (Figure 13) for each condition and for each pressure level. Accuracy is the rate of correct selection. For accuracy (Figure 12) the modality of feedback was found to be significant ($F_{3,108} = 13.9, p < 0.001$). The target pressure level (1, 2, or 3) also had a significant effect on accuracy ($F_{2,108} = 7.21, p = 0.001$). A significant interaction effect was not found ($F_{6,108} = 1.49, p = 0.189$). A Bonferroni post-hoc multiple comparison revealed a significant difference in accuracy between target pressure levels 2 and 3 (p = 0.001). Furthermore, the accuracy of visual feedback differed significantly from audio (p $<$ 0.001), audio+vibrotactile (p $<$ 0.001), and vibrotactile feedback (p = 0.011). There was also a borderline significant difference between audio and vibrotactile feedback (p = 0.064). Time to select the target (Figure 13) was not found to be significant for neither feedback type ($F_{3,948} = 2.07, p = 0.103$) nor the target pressure level ($F_{6,948} = 1.18, p = 0.315$).

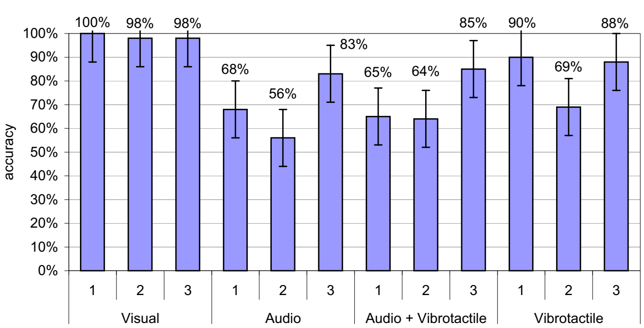

Figure 12. Accuracy is near-perfect for the visual condition and drops significantly for the non-visual modalities. (Error bars show 95% confidence intervals.)

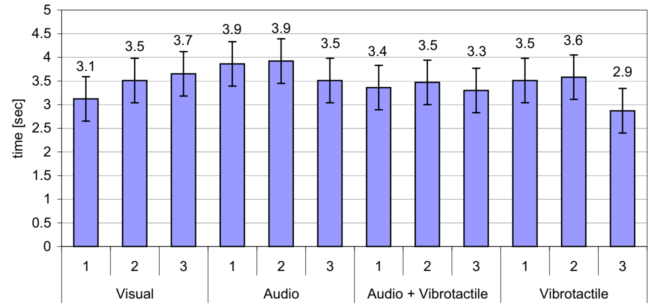

Figure 13. There is no significant difference for pressure-based selection time under different feedback modalities. (Error bars show 95% confidence intervals.)

Visual

Presented \ Selected	1	2	3
1	**126**	0	4
2	1	**111**	5
3	0	3	**127**

Audio and vibrotactile

Presented \ Selected	1	2	3
1	**67**	29	6
2	20	**58**	15
3	4	11	**87**

Audio

Presented \ Selected	1	2	3
1	**67**	21	11
2	23	**49**	14
3	6	11	**81**

Vibrotactile

Presented \ Selected	1	2	3
1	**77**	6	3
2	15	**51**	10
3	1	9	**75**

Table 1. Confusion matrices of the presented and selected pressure levels.

Discussion

From the study we see that users do not generally slow down in their interactions when using other modalities, however this is to the detriment of accuracy. Looking at the confusion matrices (Table 1) we see that the center condition is more prone to errors than the states at the extremities. In the case of the maximum pressure level this can be explained by being able to lock into the level by exceeding the upper threshold. So this condition is indeed easier, independent of the feedback modality. It is noteworthy that we do not see any strong effect when mixing modalities. The design of the experiment did now allow a learning effect to occur from the outcome of each trial. Beyond the tactile feedback we did not provide feedback on whether the correct target was selected. In the experiment learning could only occur from the users' exploration of the pressure range and the feedback that was played on the level transitions. The accuracy of the results stated above are a lower limit that can be improved by providing feedback on the outcome of the task and by optimizing the distinguishability of the feedback.

FUTURE WORK

One key issue in creating pressure-based interfaces is the tight coupling between pressure applied by the user and the feedback given. Our results suggest that with an improved sensor, yielding a linear relationship between pressure applied and sensor readings, the issue of non-visual feedback can be properly addressed in relative isolation. The results show that vibrotacile feedback with a relatively simple pager motor is not sufficient to achieve high accuracy rates. One avenue for future work is better haptic feedback, which might be achieved by non-rigid materials. If the object upon which pressure is exerted slightly changed its shape when pressed, this might serve as additional feedback that helps users to estimate the amount of exerted pressure. We intend to study various deformable materials and compare their pressure input characteristics with rigid materials.

This work suggests a number of future directions. For one, pressure adds a further dimension to be represented in graphical user interface elements. Pressure widgets [22] already go in this direction but finger-based localized two-sided input suggests further expanding this idea. We are interested in the development of squeezable widgets, which we call "squidgets," that combine the information provided by pressure widgets with the high degree-of-freedom of local two-sided interactions. Such interactions include local rotations and two-sided sliding. An advantage of the use of pressure is that it requires very little motion and hence does not lead to dynamic change in occlusion of the display. For example UI elements can be placed in the periphery of the display and through the pressure dimension still allow continuous input. We also intend to investigate two-handed pressure input, in which one hand performs the tasks of holding the device and performing "grip" pressure input, while the other hand performs touch input. This can lead to an interesting division of labor of both hands in two-handed tasks.

While design issues still need to be addressed, the concept of using pressure input is appealing. One key property of pressure input is the difficulty of observation by onlookers. This suggests that pressure may be a good input modality for applications in the domain of privacy and safety. For example one can envision authentication to be executed via pressure gestures, which we call "prestures." We suggest the use of subtle tactile feedback while the device is in the user's hands will be much harder to observe than the finger motions required to select keys for alpha-numeric password entry on a keyboard or touchscreen.

CONCLUSION

In this paper we addressed finger-based pressure input on mobile devices. Pressure input offers an additional local dimension to touch input and hence offers an array of interaction possibilities. Because the interaction can be performed without moving the fingers it is a particularly attractive dimension to use when screen real estate is precious or when finger-motion is not desirable. Pressure sensors can invisibly be embedded below the device casing but can still help to emulate the experience of a physical button. We conducted a number of experiments to explore several fundamental properties of these finger-based pressure interactions.

The results on transfer functions for pressure input clarify a longstanding discussion in the area. Literature explored various functions such as linear, quadratic, fisheye, and parabolic-sigmoid. We show that it is important to consider the sensor characteristics first before picking mapping functions and show that with proper sensor use through load-decoupling with an operation amplifier, linear mapping works best in experiments. The discrepancy in the reported previous results might be explained by the difference in sensor conditioning circuits.

Mobile devices can be operated on with different hand poses. Also, the particular touch input paradigm may dictate which of these poses are desirable or ergonomically likely. We may interact with the device from the front, or the back or from both sides at once. Comparing these possibilities and also pressure applied to a device laying on a solid surface, we show that two-sided interaction has a slight advantage in selection time and is preferred by the users.

We investigated auditory and tactile feedback to chart the performance for eyes-free use of pressure input. Non-visual modalities are beneficial in mobile situations, since they allow the user to keep visual attention to cues in the environment. The study shows no degradation in selection time but a loss of accuracy for these modalities, which we quantify in our study.

Overall, pressure input via force-sensing resistors is linear if properly conditioned. Two-sided "grip" interactions work best for handheld pressure input and non-visual feedback does have performance degradation against the visual modality.

With these foundations established, we are working to develop higher-level applications and constructs for pressure input. In particular we are preparing pressure-based gesture vocabularies similar to motion-based gestures. These can be used in subtle, unobservable ways, suggesting a use in authentication or privacy-sensitive applications. Furthermore we are interested in expressive use, such as mobile music performance with mobile devices and pressure is an attractive dimension in this setting. Finally, pressure adds to the dimensionality of input and hence is attractive for applications where many dimensions are manipulated at once, such as 3D editing environments.

Acknowledgments

Craig Stewart's work is partly funded by EPSRC EP/E042171/1 and an internship at Deutsche Telekom Laboratories.

REFERENCES

1. Benko, H., Wilson, A. D., and Baudisch, P. Precise selection techniques for multi-touch screens. *Proc. CHI '06*. ACM (2006), 1263–1272.
2. Brewster, S., Chohan, F., and Brown, L. Tactile feedback for mobile interactions. *Proc. CHI '07*. ACM (2007), 159–162.
3. Brewster, S. A., and Hughes, M. Pressure-based text entry for mobile devices. *Proc. MobileHCI '09*. ACM (2009), 73–76.
4. Cechanowicz, J., Irani, P., and Subramanian, S. Augmenting the mouse with pressure sensitive input. *Proc. CHI '07*. ACM (2007), 1385–1394.
5. Essl, G., and Rohs, M. Interactivity for Mobile Music Making. *Organised Sound 14*, 2 (2009), 197–207.

6. Essl, G., Rohs, M., and Kratz, S. Squeezing the sandwich: A mobile pressure-sensitive two-sided multi-touch prototype. *Demonstration at UIST '09*. ACM (2009).
7. Harrison, B. L., Fishkin, K. P., Gujar, A., Mochon, C., and Want, R. Squeeze me, hold me, tilt me! an exploration of manipulative user interfaces. *Proc. CHI '98*. ACM (1998), 17–24.
8. Hemmert, F., Löwe, M., Wohlauf, A., and Joost, G. Tactful calling: Urgency-augmented phone calls through high-resolution pressure input on mobile phones. *Proc. Extended Abstracts CHI '09*. ACM (2009), 3187–3192.
9. Hoggan, E., Brewster, S. A., and Johnston, J. Investigating the effectiveness of tactile feedback for mobile touchscreens. *Proc. CHI '08*. ACM (2008), 1573–1582.
10. Horowitz, P., and Hill, W. *The Art of Electronics*, 2nd ed. Cambridge University Press, Cambridge, 1989.
11. Hughes, S. *Shake – Sensing Hardware Accessory for Kinaesthetic Expression Model SK6*. SAMH Engineering Services, Blackrock, Ireland, 2006.
12. Interlink. FSR – force sensing resistor integration guide and evaluation parts catalog. Version 1.0, 90-45632 Rev. D, Available at Interlink Electronics, `http://www.interlinkelectronics.com`.
13. Kandel, E. R. *Principles of Neural Science*. McGraw-Hill Education, 2000.
14. Lee, J. C., Dietz, P. H., Leigh, D., Yerazunis, W. S., and Hudson, S. E. Haptic pen: A tactile feedback stylus for touch screens. *Proc. UIST '04*. ACM (2004), 291–294.
15. Liao, C., Guimbretière, F., and Loeckenhoff, C. E. Pen-top feedback for paper-based interfaces. *Proc. UIST '06*. ACM (2006), 201–210.
16. Luk, J., Pasquero, J., Little, S., MacLean, K., Levesque, V., and Hayward, V. A role for haptics in mobile interaction: Initial design using a handheld tactile display prototype. *Proc. CHI '06*. ACM (2006), 171–180.
17. McCallum, D. C., Mak, E., Irani, P., and Subramanian, S. PressureText: Pressure input for mobile phone text entry. *Proc. Extended Abstracts CHI '09*. ACM (2009), 4519–4524.
18. Mizobuchi, S., Terasaki, S., Keski-Jaskari, T., Nousiainen, J., Ryynanen, M., and Silfverberg, M. Making an impression: Force-controlled pen input for handheld devices. *Proc. Extended Abstracts CHI '05*. ACM (2005), 1661–1664.
19. Putnam, W., and Knapp, R. B. Input/data acquisition system design for human computer interfacing. Unpublished Lecture Notes, October 17, 1996, `www.cs.princeton.edu/~prc/MUS539/Sensors.pdf`.
20. Ramos, G., and Balakrishnan, R. Zliding: Fluid zooming and sliding for high precision parameter manipulation. *Proc. UIST '05*. ACM (2005), 143–152.
21. Ramos, G., and Balakrishnan, R. Pressure marks. *Proc. CHI '07*. ACM (2007), 1375–1384.
22. Ramos, G., Boulos, M., and Balakrishnan, R. Pressure widgets. *Proc. CHI '04*. ACM (2004), 487–494.
23. Rekimoto, J., and Schwesig, C. PreSenseII: Bi-directional touch and pressure sensing interactions with tactile feedback. *Proc. Extended Abstracts CHI '06*. ACM (2006), 1253–1258.
24. Ren, X., Ying, J., Zhao, S., and Li, Y. The adaptive hybrid cursor: A pressure-based target selection technique for pen-based interfaces. *Proc. Interact '07*. Springer (2007), 310–323.
25. Savitzky, A., and Golay, M. Smoothing and differentiation of data by simplified least squares procedures. *Analytical Chemistry 36*, 8 (1964), 1627–1639.
26. Schwesig, C., Poupyrev, I., and Mori, E. Gummi: A bendable computer. *Proc. CHI '04*. ACM (2004), 263–270.
27. Scott, J., Brown, L. M., and Molloy, M. Mobile device interaction with force sensing. *Proc. Pervasive '09*. Springer (2009), 133–150.
28. Sherrick, C. E., and Cholewiak, R. W. *Cutaneous Sensitivity*. Wiley and Sons, New York, 1986, ch. 12, 1–58.
29. Shi, K., Irani, P., Gustafson, S., and Subramanian, S. PressureFish: A method to improve control of discrete pressure-based input. *Proc. CHI '08*. ACM (2008), 1295–1298.
30. Srinivasan, M., and Chen, J. Human performance in controlling normal forces of contact with rigid objects. *Proc. Advances in Robotics, Mechatronics, and Haptic Interfaces*. American Society of Mechanical Engineers (1993), vol. 49, 119–125.
31. Threinen-Pendarvis, C. Customizing a wacom tablet key to control brushstroke. Corel Painter – Tips & Tricks. Available online at http://www.corel.com/servlet/Satellite/us/en/Content/1181934056653?trkid=tpc0607wow, retrieved on January 9 2009.
32. Van Erp, J. B. F. Guidelines for the use of vibro-tactile displays in human computer interaction. *Proc. Eurohaptics 2002*. University of Edinburgh (2002), 18–22.
33. Zhao, S., Dragicevic, P., Chignell, M., Balakrishnan, R., and Baudisch, P. earPod: Eyes-free menu selection using touch input and reactive audio feedback. *Proc. CHI '07*. ACM (2007), 1395–1404.