Evaluation of Haptically Augmented Touchscreen GUI Elements Under Cognitive Load

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ABSTRACT

Adding expressive haptic feedback to mobile devices has great potential to improve their usability, particularly in multitasking situations where one's visual attention is required. Piezoelectric actuators are emerging as one suitable technology for rendering expressive haptic feedback on mobile devices. We describe the design of redundant piezoelectric haptic augmentations of touchscreen GUI buttons, progress bars, and scroll bars, and their evaluation under varying cognitive load. Our haptically augmented progress bars and scroll bars led to significantly faster task completion, and favourable subjective reactions. We further discuss resulting insights into designing useful haptic feedback for touchscreens and highlight challenges, including means of enhancing usability, types of interactions where value is maximized, difficulty in disambiguating background from foreground signals, tradeoffs in haptic strength vs. resolution, and subtleties in evaluating these types of interactions.

Categories and Subject Descriptors

H5.2 [**Information interfaces and presentation**]: User Interfaces - *graphical user interfaces, haptic I/O*.

General Terms

Design, experimentation, human factors, performance.

Keywords

Haptic feedback, multimodal, touchscreen, mobile device, piezoelectric actuators, usability, multitasking, GUI elements.

1. INTRODUCTION

Adding computer-controlled haptic (i.e., tactile) feedback to mobile device interfaces has considerable potential to improve their usability [15]. Mobile devices such as handheld computers and smart phones are small by nature, which limits their screen real estate and space for physical input controls. Mobile devices are also portable, which encourages their use in many contexts including those where the user's visual and/or auditory attention is required or where visual or auditory feedback is not appropriate (e.g., library, business meeting). In addition, mobile devices are often used while the user is performing some other task (looking up online information during a presentation as in Figure 1, or using a map on a mobile device while walking down a busy sidewalk), and these tasks compete for the user's cognitive resources [11]. Adding another interface modality, such as haptic feedback, allows more channels for a mobile device to communicate with its user. Mobile devices are especially suitable for haptic feedback as these devices are often held by the user or carried in close bodily contact.

Figure 1. An example of multitasking using a mobile touchscreen device (Nokia 770 tablet); haptic feedback could enable the user to pay more visual attention to the presenter

However, little is known about how to *usably* design this type of feedback, especially for multitasking situations where the user is cognitively loaded. One challenge is the limited expressiveness of haptic technology in most current mobile devices, which employ actuators capable only of simple binary vibratory feedback (on/off). Technology that can produce richer haptic feedback is needed to research and develop effective interaction techniques that make the most of this underused channel.

New technologies such as piezoelectric ceramic actuators are emerging as suitable technologies for rendering more expressive haptic feedback (e.g., [8],[9],[15]). Piezoelectric actuators are suitable for mobile devices as they are fast, strong, thin and light. Furthermore, one can control their amplitude and frequency, allowing a variety of tactile waveforms. Thus it can generate small discrete pulses or a variety of prolonged signals, felt through the stylus and by the hand holding the device.

Using a handheld platform consisting of a piezoelectric actuator with a touchscreen, we sought to better understand whether haptic feedback produced by this technology improved device usability under different cognitive loads. Specifically, we haptically

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augmented a variety of GUI elements (e.g., buttons, progress and scroll bars) and evaluated their use in multitasking situations.

In this paper, we first survey existing work on haptically augmented GUI elements and briefly describe the mobile haptic touchscreen technology that we used. We then present our design approach, our haptic augmentations and two iterations of a user evaluation. We conclude by discussing our experimental results' implications for designing haptic feedback in mobile contexts.

2. RELATED WORK

Haptic feedback has been added to GUI elements using a variety of technologies (e.g., force-feedback, vibration motors) and many usability benefits have been found. For example, Dennerlein et al. [4] found that providing haptic channels in GUI steering tasks using a force feedback mouse (with *DC motor actuation*) led to >50% movement time improvements; however, this implied system knowledge of user goals. Oakley et al. [10] used a PHANToM force-feedback device (*DC motor actuation*) to haptically augment scrollbars. Two haptic effects (recess and gravity well) were added to scroll bars to help users scroll while keeping their eyes on the scrollable text. They found that although haptic effects did not lead to improved task completion times, their participants made significantly fewer errors when haptic feedback was enabled and perceived many aspects of workload to be significantly lighter. Fukumoto and Sugimura [5] evaluated Active Click, an example closer to the mobile domain; it used a *voice coil actuator* mounted to the body of the handheld computer to convey haptic information to the user's hand that held the device. They compared haptic and audio augmentations of touchscreen buttons. They found that compared to their audio augmentation, performance with haptic feedback was 5% faster in quiet environments and 15% faster in noisy environments. Although the reported benefits of adding haptic feedback to GUI elements using force-feedback devices or vibration motors are encouraging, they often cannot generalize to other haptic technologies because the haptic feedback generated by each type of actuation is unique.

More recent research has focused on haptically augmenting GUI elements on piezoelectric enabled mobile touchscreens. Poupyrev et al. conducted a number of studies using a haptic touchscreen on a Sony Clié handheld computer [14], which appears to use similar *piezoelectric actuators* technology as the prototype in our study. In their work, they explored various design spaces associated with haptic feedback, including tactile notifications, tactile monitoring, rendered tactile textures, and haptic feedback for GUI interfaces [13,14]. In the latter area, Poupyrev et al. [13] haptically augmented a variety of buttons, scroll bars and menus. In implementing this feedback, they categorized GUI touchscreen interactions into 5 generic types (i.e., touch down, hold, drag, lift off in the element, lift off outside the element) and designed haptic signals for each of them. They ran an informal usability study with 10 colleagues and found that the haptic feedback was well received, and was most effective when the GUI elements needed to be held down or dragged across the screen.

Some preliminary research work has also been conducted on the prototype used in our study. Kaaresoja et al. [7] developed and demonstrated haptically augmented buttons, scrollbars, and text selection. Tikka et al. [17] looked at the integration of audio and haptic feedback and found that audio can bias the perceived intensity of the prototype's haptic feedback. Although the current work to date on haptically augmenting GUI elements using piezoelectric touchscreen technology have demonstrated its promise as a usable mobile haptic technology, few formal experimental evaluations that have explored its performance and perceived benefits, particularly in multitasking conditions, have been reported.

Little has been reported on understanding the benefits of multimodal GUI feedback on mobile devices in multitasking or cognitively demanding conditions. Subjects' ability to learn informative haptic icons and utilize them under workload has been investigated in a variety of application domains (e.g. [1],[9]) and these experiments form the basis for the evaluation paradigms employed here. Other studies have looked at the general benefits of multimodal input. For example, Oviatt et al. [12] investigated how people interacted, under different task difficulties, with a map-based interface that supported speech input, pen input or a multimodal combination of both. They found that users' multimodal interactions increased significantly as the tasks became more difficult. Although [12] did not look at whether task performance improved when multiple output modalities where used, their results suggest that there is increased benefit to using multiple modalities under higher cognitive load. Our study explored this hypothesis, specifically focusing on visual and haptic feedback.

3. HAPTIC TOUCHSCREEN PROTOTYPE

In this study, we used a prototype mobile device based on the Nokia 770 handheld tablet, that has a large touch display (Figure 1). This first-generation prototype, which has been used in other studies, uses piezoelectric actuators to deliver haptic feedback by vibrating the touchscreen perpendicular to its surface. This prototype was tethered to a laptop, where Java applications were developed and executed. Applications initiated haptic pulses of varying durations (longer pulses felt stronger) through a `doFeedback(duration_value)` command. *Duration values* sent to the prototype ranged from 0 to 255 (corresponding to a range of durations up to 10ms), where a value of 5 was enough to generate a perceivable haptic pulse. Continuous signals of frequencies up to 1kHz could be produced at piezo amplitudes up to a few hundred micrometers [8]. For more technical details on the prototype hardware, see [7] and [8].

Users interacted with the prototype through a stylus. Even though the whole touchscreen moved up and down, users perceived the feedback to originate from the contact point between the stylus and the screen. This perceptual illusion could be used, for example, to simulate button clicks, to the dominant hand, that feel like they come from individual buttons and not the entire screen. Users also felt the haptic feedback in the palm of the non-dominant hand holding the device. Pulses could be heard audibly.

4. EXPERIMENTAL METHODS

4.1 Preliminary Value Assessment

Before proceeding with the development and evaluation of haptically augmented GUI elements, we employed focus groups and questionnaires to better understand typical mobile device use cases, associated cognitive loads and usability-related challenges. We also sought to learn users' attitudes towards our proposed haptic feedback signals for various GUI elements (e.g., buttons, scroll bars, window borders, pull-down menus). Participants – 5 university students with varying computer experience and skill levels – stated that they generally performed relatively simple tasks on their mobile devices, such as scheduling, setting alarms, and playing media. Other more complex tasks included text messaging, web browsing and gaming. Tasks tended to be of short duration and interruptible, and participants reported a low regard for drag-and-drop interactions. They listed a variety of other activities which they tended to perform in parallel with their mobile device use.

Participants were receptive to the idea of haptic augmentation, especially for buttons, progress bars and scroll bars. Further, they reported a preference for moderate and selective use of haptic stimuli, and felt that haptically augmented GUI elements would be much more useful in multitasking situations.

4.2 Evaluation Approach and Hypotheses

Based on our preliminary assessment, we chose to focus on adding haptic feedback to buttons, progress bars and scroll bars, as we felt they had the most potential for increased usability. We focused our research to test the following two hypotheses:

1. *Haptically augmented* buttons, progress bars, and scroll bars are *more useful* than their non-augmented counterparts.
2. Haptically augmented buttons, progress bars and scroll bars are *more useful under cognitive load* than under no load.

We aimed to assess usefulness by examining objective task performance data and subjective self-report data.

We designed the haptic feedback signals redundantly; they provided only information available visually through the GUI, so that any benefit associated to the haptic feedback could be attributed to the addition of a haptic channel and not extra information. For example, haptic feedback was produced when a button was pressed and released, and also rendered graphically; it did not provide *extra* information such as guidance on which button to press next. Thus, for the purposes of our experimental study, the amount of added haptic information was conservative.

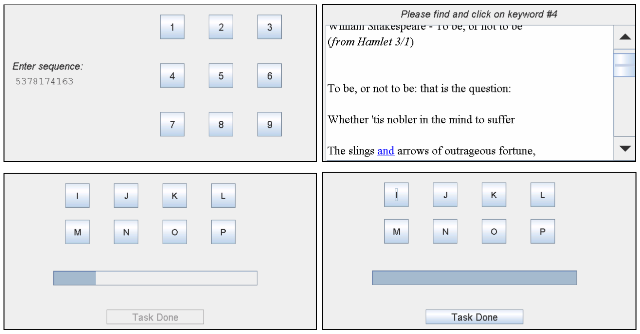
Using this approach, we conducted two iterations of an experiment to test our hypotheses. The first iteration evaluated the effect of adding haptic feedback to buttons, progress bars and scroll bars, with and without additional cognitive load (4.3). When technical problems made the Scroll Bar task results inconclusive, we ran a second similar iteration focused solely on scroll bars (4.4).

4.3 Methods – General

4.3.1 *Touchscreen Tasks and Haptic Augmentation*

One test application was developed for each of the three GUI elements that we augmented haptically. The same visual feedback was given regardless of whether haptic feedback was turned on or off. Participants held the prototype hardware in the non-dominant hand.

Button Task. Participants were asked to input a randomly generated 10-digit number sequence, digit by digit using the on-screen keypad (Figure 2a) and to continue entry in the event of a mistake. The target number sequence and text instructions were presented on-screen. In haptic conditions, a haptic pulse was produced upon each button press (`duration_value` (dv)=250) and release (dv=200); i.e. each digit entry resulted in two pulses. The same haptic feedback was produced by each of the buttons.



Enter sequence:
5378174163

Please find and click on keyword #4

William Shakespeare - To be, or not to be
(*from Hamlet 3/1*)

To be, or not to be: that is the question:

Whether 'tis nobler in the mind to suffer

The slings and arrows of outrageous fortune,

Figure 2. a) Button task; b) Scroll Bar task; Progress Bar task before (c) and after (d) progress bar completion.

Progress Bar Task. The bar's progress began at the task's start (Figure 2c), and participants pressed a "Task Done" button upon its completion (Figure 2d). Duration varied randomly between 5 to 10 seconds. Participants carried out a distracter task (which was to press buttons corresponding to letters they heard in the headphones; described below) while waiting for the progress bar. In haptic conditions a series of haptic pulses were rendered, increasing in force and frequency ("start": dv=1, ~1Hz; "end": dv=255, ~10Hz) and terminated at completion.

Scroll Bar Task. Participants were asked via on-screen instructions to scroll to and click on the *n*th instance (where *n* was randomly chosen in each of the trials) of a single keyword, "and", in a text (Shakespeare's *Hamlet: Prince of Denmark Act III Scene 1*) (Figure 2b). Ten instances of "and" were located throughout the text and were marked (underlined and blue) as potential targets. The same text and keyword instances were used in both iterations.

In haptic conditions, a haptic pulse (dv=100 in Iteration 1) was produced whenever a keyword appeared onscreen as the participant scrolled up or down. In the first experiment iteration, our augmented scroll bar lagged noticeably and became unstable when the user attempted to scroll quickly; this was corrected in the second iteration. The haptic feedback was also revised slightly in Iteration 2; a stronger pulse (dv=150) was given when a keyword appeared from the bottom of the screen, and a weaker pulse (dv=30) was given when a keyword appeared from the top.

4.3.2 *Cognitive Load Tasks*

Two auditory tasks were used to cognitively load participants in the experiment. Purely auditory tasks were chosen to avoid interference with the visual and gestural/haptic components of the touchscreen task, and were carefully designed to be cognitively demanding but not overwhelming. A third non-load condition was used as a control.

Both tasks required participants to listen to a stream of pseudo-randomly ordered letters between I and P that were presented at approximately 2 letters per second. The *Letter Sequence Task* required participants to verbally report when they heard the sequence "NMKL", which appeared on average 4 times a minute at random intervals. The *Identical Letters Task* required participants to verbally report 3 identical letters in a row (e.g., "III", "PPP"). These letter triplets appeared at pseudo-random intervals, on average 5 times a minute. We expected, before conducting the experiments, the 3-identical letters task to require more cognitive processing because they occurred more frequently and could consist of any letter. In the third non-load control condition, participants listened to a stream of letters but did not have to listen for any particular sequence.

The streams of letters from all three cognitive load tasks were delivered through noise-cancelling headphones. The headphones also blocked the sound that the haptic touchscreen prototype emitted when haptic pulses were rendered.

4.3.3 Subjective Data

Two questionnaires were used to collect subjective data. In preliminary profiling, we solicited information about the participant's experience with computers, mobile devices and haptic feedback devices. Post-experiment, we asked participants how they felt about the haptic feedback (e.g., noticeable, useful, annoying), how easy it was to multitask between the touchscreen and cognitive load tasks, and how well they thought they performed.

4.3.4 Data Analysis

We used *Signal Detection Theory* (SDT) to quantify how heavily participants were loaded by the cognitive load tasks. SDT is a commonly used method to quantify the effort of discriminating a signal in the presence of information noise [6,16]. One key value calculated by SDT is the *discriminability index*, d', which is an estimate of the strength of the signal relative to the surrounding noise. The d' calculation uses both signal hit and false alarm percentage values, with the underlying assumption that better signal identification performance (that results in a higher d' value) is due to a stronger signal and/or more devoted cognitive resources to the identification task. d' values were used to calculate the difficulty of each of the two cognitive load tasks and gauge how much participants were cognitively loaded while performing each of the touchscreen tasks.

Analysis of Variances (ANOVA) on the touchscreen and cognitive load task performance data were performed separately for each of the three touchscreen tasks, since it would not be meaningful to compare their relative performance. Before calculating each participant's mean score for an experimental condition, outliers (i.e., scores greater than two standard deviations from the mean score of that condition) were replaced with the next highest value in that experimental condition. Outliers across participants' scores within an experimental condition were similarly adjusted. The alpha level, α, was set to 0.05 for all statistical tests. Homogeneity of variances and sphericity assumptions for all ANOVAs were checked. Post-hoc pair-wise contrasts were used when statistically significant interactions were found.

4.3.5 Procedure

Each participant was given an introduction to the study and asked to fill out the profile questionnaire. Participants were then asked to perform the two cognitive tasks without the touchscreen task, to allow us to assess their *baseline* cognitive load task performance. Participants were then introduced to the touchscreen tasks (Iteration 1: all three tasks; Iteration 2: Scroll Bar task only) and given the opportunity to perform the tasks until they were comfortable with them. We sought to minimize learning effect by encouraging participants to take as much time as they wanted to familiarize themselves with the task and interaction. Participants then completed 3 blocks of tasks where they performed an auditory and touchscreen tasks at the same time. Participants were instructed to do their best on the auditory task, even at the expense of the touchscreen task. After each block of tasks, participants were asked about how well they thought they performed on the touchscreen tasks, and given a rest. At the experiment's end, participants completed the *Post Experiment Questionnaire*. Total session duration averaged 1 hour for the first experiment iteration and 45 minutes for the second.

4.4 Methods - Iteration 1

4.4.1 Participants

Seventeen volunteers, university graduate and undergraduate students with and without significant mobile computer experience, were recruited from the university community. Results for two participants were discarded because hardware problems prevented one participant from finishing and the other stated that he had Attention Deficit Disorder and was not able to perform the touchscreen and cognitive load tasks at the same time. Therefore only data from 15 participants (2 left-handed) were analyzed.

4.4.2 Design

The experiment for the first iteration was a 3 (touchscreen tasks) x 2 (haptic feedback conditions) x 3 (cognitive load task) within-subjects design. Touchscreen tasks were conducted 5 times for each condition (i.e., 5 trials), in order to get more accurate scores after averaging. Only trial times where the task was performed accurately (i.e., Button task: entire number sequence correctly entered; Scroll Bar task: correct keyword selected) were used to obtain an average time score.

Dependent variables consisted of touchscreen task performance (response time, accuracy), cognitive load task performance (accuracy), and self-reported performance, opinions and comments.

Randomization was used throughout to mitigate learning effects. Task sets were blocked on cognitive load task (3 blocks) and block order was counter-balanced. For each block, the touchscreen task order, presence/absence of haptic feedback, and touchscreen task parameters (i.e., Button task number sequence, Progress Bar duration, Scroll Bar task keyword instance) were randomized.

4.4.3 Technical Problems: Scroll Bar

Some minor problems associated with the scroll bar augmentation implementation were found after the first experiment iteration, which made those particular results inconclusive. In addition, the Scroll Bar task difficulty was inconsistent; in each condition, participants acquired 5 *randomly chosen* keyword locations (i.e., instances). Because targets near the text start / finish were easier to acquire, more trials were needed to accurately estimate performance. We addressed these problems in the second iteration.

4.5 Methods – Iteration 2

The second experiment iteration only involved the Scroll Bar task but was otherwise very similar to the first experiment.

4.5.1 Participants

Twelve volunteer university graduate and undergraduate students (1 left-handed) were recruited. Three had participated in the first experiment; since the second experiment took place 10 weeks later, we felt cross-over effect would be negligible.

4.5.2 Design

The experiment was a 2 (haptic feedback) x 3 (cognitive load task) within-subject design. The experiment task was identical to that described in 4.3.1, with the following exceptions. Each participant now performed 20 trials per condition, and each received the *same* set of keyword (always "and") locations (9 unique locations were used), for every condition, in a randomized order. This keyword location set was designed such that in half of the trials (10/experimental condition) the target was located near the middle of the text, requiring participants to make most use of the visual and/or haptic feedback to find them. Instances of the other targets, which were located closer to the top or bottom of the text and required less counting to find, were employed to increase variety and thus minimize learning. To obtain an average performance time score, we used only trial times associated with the two middle keywords, and when they were accurately selected.

5. EXPERIMENTAL RESULTS

We first present the audio cognitive load task results, and then the touchscreen task performance results. Results associated with the first experiment iteration's Scroll Bar tasks are omitted; Scroll Bar task results come only from the second iteration.

5.1 Cognitive Load Task Performance

We expected the *Identical Letters Task* to produce a higher cognitive load than the *4-Letter Sequence Task*, and indeed there was a difference in their d' values in absence of the touchscreen tasks (Iteration 1: 23%, significant difference; Iteration 2: 11%). However, the performance *d'* scores of the two auditory tasks were not significantly different when performed with any of the touchscreen tasks (Figure 3; Button: $F_{1,14}$=0.102, MS_{err}=0.509; Progress Bar: $F_{1,14}$=4.03, MS_{err}=0.509; Scroll Bar: $F_{1,11}$=3.19, MS_{err}=0.23), which implied that participants were loaded similarly in both experiments by the auditory tasks. Thus, we cannot say whether participants were more heavily loaded by one cognitive task than the other, and cannot use this to analyze how touchscreen performance might have differed under no, medium, and higher cognitive loads.

We are, however, confident that participants were under considerable cognitive load when performing either of the two auditory tasks. Touchscreen task performance scores, presented below, generally suffered to some degree from having to multitask. In addition, almost all participants from the first experiment iteration (93%) and all participants from the second reported needing to compromise between the auditory tasks and the touchscreen tasks throughout the experiment.

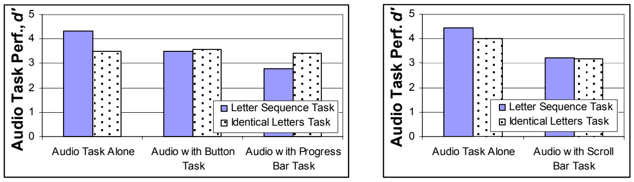


Figure 3: Audio Cognitive Load Task Scores, *d'*, for Iterations 1 (left) and 2 (right).

5.2 Touchscreen Task Performance

Touchscreen task performance (response times, task completion times, and accuracy) are summarized in Figure 4 for the Button and Progress Bar tasks (Iteration 1), and the Scroll Bar tasks (Iteration 2). Error bars show the Standard Deviations.

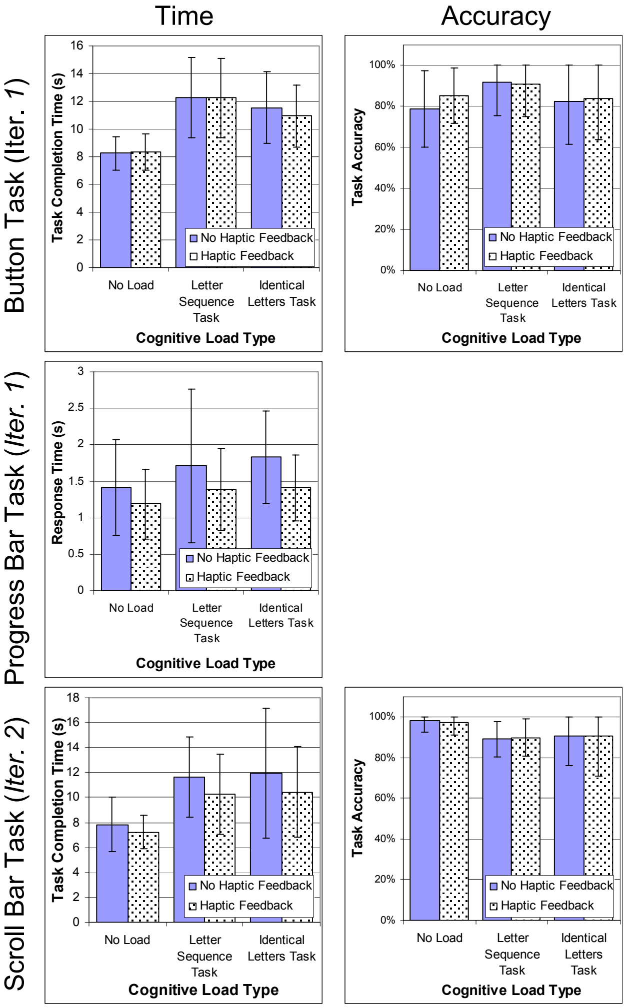


Figure 4: Touchscreen Task Performance Scores.

Table 1: Effect of Haptic Augmentation on Touchscreen Task Performance Over All Cognitive Load Conditions.

Measure	No HFB M (SD)	HFB M (SD)	*F*	MS_{err}	*p*
Button Task (Iter. 1)					
Completion Time	10.7s (3.0s)	10.5s (2.8s)	$F_{1,14}$=0.40	2.12	*ns*
Accuracy	84% (18%)	87% (15%)	$F_{1,14}$=0.59	0.02	*ns*
Progress Bar Task (Iter. 1)					
Response Time	1.65s (0.8s)	1.33s (0.5s)	$F_{1,14}$=11.42	0.21	0.004
Scroll Bar Task (Iter. 2)					
Completion Time	10.5s (4.2s)	9.3s (3.3s)	$F_{1,11}$=14.18	1.70	0.003
Accuracy	93% (10%)	93% (11%)	$F_{1,11}$=0.00	0.01	*ns*

Note: HFB = Haptic Feedback

Table 2: Percentage of Participants who Reported the Opinions Regarding Haptic Feedback Below.

Task	HFB *useful* and/or *helpful*	HFB *annoying* and/or *interfering*	Relative perceived performance with HFB *better*	*same*	*worse*
Button (*Iter. 1*)	67%	7%	27%	71%	2%
Progress Bar (*Iter. 1*)	60%	27%	44%	56%	0%
Scroll Bar (*Iter. 2*)	100%	8%	39%	55%	6%

Note: Values were averaged across the three cognitive load conditions

For each touchscreen task, an ANOVA was conducted on task completion/response time and accuracy scores (outliers removed) to determine whether the addition of haptic feedback had a significant effect on performance scores, and whether this effect was influenced by added cognitive load.

5.2.1 Usefulness of haptic feedback:

Experiment Iteration 1: ANOVA results show that when considered across all cognitive load tasks, the addition of haptic feedback to our Progress Bar task significantly improved response times; however, significant performance benefits were not found when haptic feedback was added in the Button task. Table 1 shows response times associated with the Progress Bar task that are significantly lower with haptic feedback than without. No other statistically significant effect of haptic augmentation was found on performance time or accuracy for these two tasks.

The majority of participants reported on the questionnaires that they found the haptic feedback for buttons and progress bars to be useful and/or helpful (Table 2). In addition, almost half of participants felt that they performed better in the Progress Bar task with haptic feedback (consistently with performance data).

Experiment Iteration 2: The ANOVA results show that the addition of haptic feedback to our Scroll Bar task significantly improved task completion times (Table 1). No statistically significant effect of haptic feedback on accuracy was found.

All participants reported that they found the haptic feedback to be useful and/or helpful (Table 2). Over a third felt they performed better on the Scroll Bar task with haptic feedback.

5.2.2 Usefulness of haptics under cognitive load:

Differences between touchscreen performance time scores when haptic feedback was present, and when it was absent, were on average greater for both cognitive load conditions than no the load condition (Figure 4, Button: 3% vs. -1%; Progress Bar: 24% vs. 17%; Scroll Bar: 13% vs. 8%), but this difference was not significant.

However, neither experiment iteration revealed a statistically significant improvement in performance due to haptic feedback when participants were under *more* cognitive load (i.e. intended variation in load due to the two load tasks). To determine this, we looked for a significant interaction between cognitive load levels and the presence/absence of haptic feedback on touchscreen performance scores. None was found in touchscreen task performance (Button completion time: $F_{2,28}$=0.50, MS_{err}=2.06; Button accuracy: $F_{2,28}$=0.51, MS_{err}=0.02; Progress Bar response time: $F_{2,28}$=0.31, MS_{err}=0.24, Scroll Bar completion time: $F_{2,22}$=0.67, MS_{err}=2.10; Scroll Bar accuracy: $F_{2,22}$=0.06, MS_{err}=0.01). In addition, no significant interaction was found in either experiment iteration for perceived task performance.

6. DISCUSSION

6.1 Hypotheses

We begin our discussion of the experimental results by revisiting our two hypotheses for this study.

6.1.1 Hypothesis 1

Haptically augmented buttons, progress bars, and scroll bars, are more useful than their non-augmented counterparts.

In overview, the haptic augmentations we provided to these touchscreen GUI elements did provide statistically significant performance and subjective enhancements *in some cases,* and for *some types of performance*; in no case did they detract from performance or preference. It is therefore informative to examine in detail both the positive and neutral cases and to consider practical significance (6.2).

Buttons: Adding haptic feedback to our buttons did not lead to significantly better touchscreen task completion times or accuracy. Most participants reported feeling that they performed about the same with and without the haptically augmented buttons, thus supporting the objective performance results.

Progress Bars: Our progress bars were more useful when augmented with haptic feedback, as measured by significantly better response times. A 20% improvement (0.32s) in response time was found. About half the participants felt that the haptic feedback from progress bars helped them to perform better on the task, while the other half felt that their performance was about the same with and without haptic feedback.

Scroll Bars: Our results from the second experiment found that the addition of haptic feedback to our Scroll Bar task led to significantly lower task completion times, with 11% improvement (1.2s) in task completion time, but no significant differences in mean accuracy. Over a third of participants felt that they performed better in the Scroll Bar task with haptic feedback while another half felt they performed about the same.

6.1.2 Hypothesis 2

Haptically augmented buttons, scroll bars and progress bars are more useful under cognitive load than under no load.

Our results did not find our three haptically augmented GUI elements to be more useful (in terms of significant performance and subjective enhancements) under cognitive load than under no load. Further, no significant interactions between cognitive load levels and the presence/absence of haptic feedback were found.

6.2 Implications for Design

6.2.1 Usefulness of haptic feedback on touchscreen

Practical value of performance and subjective improvements: Our results suggest that augmenting GUI elements with haptic feedback can provide both performance and subjective benefits. Lower task completion/response times were found when our haptic augmentations were added to progress bars and scroll bars, but performance was unaffected by augmenting buttons. The performance time gains (323 ms in Progress Bar task response, and 1159 ms in Scroll Bar task completion) caused by added haptic feedback are practically meaningful when considered as a percentage of overall time, and in view of the cumulative effect that results from repeated use of GUI elements even in a single task, such as navigating a website in search of some information (progress bars display the page load status). In addition, we found that our participants generally liked additional haptic feedback, as long as it was not overwhelming and obtrusive. Subjective factors are increasingly viewed as important in heavily used interfaces.

Need for learning: The majority of participants found the haptic feedback to be helpful, but a few of them reported that effort was required to learn how to use the scrollbar haptic feedback. For example, one participant commented that he found them "hard [to use] at first, but once [he] started to learn the rhythm, rather than trying to count the individual bumps it was better". Another commented that "it would take time for [the participant] to find [the scroll bar haptic feedback] totally useful". Participants did not report any difficulty in learning to use the haptic feedback from the buttons or progress bars, which could be considered more intuitive. Although our haptically augmented scroll bars required some learning, participants were still able to perform similarly, if not better, when haptic feedback was added. Furthermore, our study used a first-generation prototype, and subsequent prototypes are expected to produce better and potentially more useful haptic signals.

6.2.2 Usefulness of haptic feedback under load

If the addition of haptic feedback were found to lead to better (actual or perceived) task performance under cognitive load, then one might argue that haptic feedback be added whenever a mobile device is used in multitasking situations. However, the usefulness of haptic feedback under greater cognitive load still remains an open research question after this study. On one hand, we did not find that actual or perceived performance was significantly greater with haptic feedback under cognitive load compared to no load conditions. On the other hand, a trend in the data was observed that suggests that all three of our haptically augmented GUI elements were more useful (in terms of reduced time scores and perceived performance) than their non-augmented counterparts under cognitive load than under no load (Figure 4).

These results reveal a limitation to our study. Although our audio tasks definitely loaded our participants cognitively, it produced considerable noise in the touchscreen performance data. One source was the participants' *primary focus on the audio task,* at the expense of performing the touchscreen task, which we specified to promote continuous cognitive loading. However, an unexpected noise source may have come from the high difficulty and target stimulus frequency associated with the audio tasks. Many participants found the 4-Letter Sequence task more difficult than we expected because the first two letters in 'NMLK' sounded so similar. Further, the period between target letter sequences and patterns in the audio tasks (12-15 seconds) was longer than the average time that participants took to complete touchscreen tasks (~10 seconds), and participants may not have been as cognitively loaded on tasks that were completed more quickly. With this noise, 5-10 trials per experimental condition and 15 participants was not enough, even with outliers adjusted, to find statistically significant performance differences between our two haptic feedback conditions under different cognitive loads.

Given the trends we observed, it seems entirely possible that statistically significant performance benefits would be found for haptic augmentation under cognitive load, given: more frequent, easier, and perhaps shorter, target sequences/patterns for the load task; more participants; and, more trials per condition.

6.2.3 Beneficial vs. redundant haptic feedback

Why did haptic feedback for our progress bars and scroll bars lead to improved performance times, but not for our buttons? When designing the three types of haptic feedback, we deliberately included only information that was also provided visually. In light of this, we believe that the difference in haptic feedback benefit that we observed for these different GUI elements was heavily influenced by how much the user was able to operate the haptically augmented GUI element without looking at the screen. When using the progress bar, the additional haptic feedback freed the user from having to look at the touchscreen; the user only had to look at the touchscreen to touch the "Task Done" button. When using the scroll bar, the haptic feedback also freed the user from looking at the screen while scrolling and before clicking on the keyword. In the case of buttons, the user had to look at the touchscreen to use them, even when the buttons were augmented with haptic feedback; the haptic feedback's redundancy reduced its usefulness (many participants, however, reported that they liked the confirmation of button presses that the haptic feedback provided). Participants commented that they could rely "almost entirely on haptics [*sic*]" in performing the Scroll Bar and Progress Bar tasks, which supports this conclusion.

Adding more non-redundant information: We believe that including more information in the haptic signal, *beyond* what is provided visually, could potentially provide even more performance benefits to GUI elements than allowing users to interact with the element without looking at it (Section 7).

6.2.4 Background vs. foreground interactions

Although participants generally responded faster in the Progress Bar tasks, 27% reported that they found the progress bar haptic feedback confusing and/or annoying. Our Progress Bar task required participants to press non-haptic buttons while waiting for the bar to reach completion. Some of the progress bar's haptic feedback may have felt as though it originated from the buttons with which the participant was interacting, which might have led to some confusion. One limitation of the piezoelectric actuators technology used here (and of other technology as well) is that it can provide haptic feedback only serially, through the stylus and non-dominant hand. We also believe that this reported annoyance uncovered a mismatch between the background nature of the progress bar and its strong haptic feedback.

These observations highlight a design challenge with most haptic technology appropriate for mobile devices: How can haptic feedback, associated with an element running in the background, be designed to not interfere with using "foreground" GUI elements (which may or may not be haptically augmented)? This need for disambiguation may entail revisiting visual design aspects as well.

6.2.5 Haptic signal strength vs. resolution

Piezoelectric actuator technology, coupled with a touchscreen, is a novel alternative to using vibration motors to produce haptic feedback in mobile devices, as well as other novel haptic display technologies. When is one more suitable than the other?

Existing vibration motors can produce strong signals but have very limited expressiveness – there is less variation and richness in the signal they convey. Piezoelectric actuators, on the other hand, can produce high-definition haptic signals but at reduced strength. Although most participants noticed the haptic feedback during the touchscreen tasks, two participants claimed that they could not feel it when they were multitasking. Thus, haptic feedback may be harder to perceive when distracted [11].

We therefore conjecture that higher-definition haptic signals, such as those provided by piezoelectric actuators, may be more suitable when the user is actively engaged in the mobile interaction. Conversely, strong, coarse haptic signals may be appropriate when the user is not engaged with the device and needs to be notified, and when information detail is less important.

7. CONCLUSIONS AND FURTHER WORK

Incorporating haptic feedback from piezoelectrics shows promise for improving the usability of mobile touchscreens. Building on previous work, we designed and experimentally evaluated haptic signals to augment GUI elements. Despite using first-generation hardware and haptic signals that offer no more information than what was provided visually, participants were able to complete given tasks *significantly faster* with haptically augmented progress and scroll bars. They also *perceived an increase in performance* with the added haptic feedback. In terms of practical significance of performance improvements, scroll bars and progress bars are often used multiple times in a task and *performance benefits are cumulative*. We also found evidence suggesting that our haptically augmented GUI elements may have been more useful than their non-augmented counterparts under cognitive load than under no load.

From this research, we gained many insights into designing haptic feedback for mobile touchscreens:

- Haptic feedback is often unfamiliar and users may not find it useful during the initial learning period.
- Adding haptic feedback to certain GUI elements allow their use without vision, which can make them more usable.
- Higher definition haptic signals may be more suitable when the user is actively interacting with the mobile device, while stronger coarser signals may be better when the user is not engaged with the device.

There is much exciting work that remains to explore the potential usability benefits of piezoelectric-touchscreen technology:

- Designing haptic feedback for GUI elements running in the background that does not interfere with using other GUI elements.
- Exploring the usability benefits of adding informative, non-redundant haptic feedback to touchscreen GUI elements.

In related work, some recent research has explored the usability of *haptic icons* on similar technology used in this study [2,9] and on other technology (e.g., [1],[3]). Haptic icons incorporate more encoded information (e.g., spatial location, order, urgency, etc.) from which users can benefit. However, using this richer feedback requires users to learn how to process the encoded information and distinguish between haptic icons. Thus we are exploring whether the benefit of this extra information outweighs the cost of processing the extra information.

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