Designing Haptic Feedback for Touch Display: Experimental Study of Perceived Intensity and Integration of Haptic and Audio

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Abstract. We studied the subjectively perceived intensity of the haptic feedback and the effects of the integration of the audio and haptic feedback. The purpose of the study was to specify design principles for haptic feedback on a piezo actuator enhanced mobile touch display device. The results of the study showed that the best corresponding physical parameter to perceived feedback intensity was the acceleration of the haptic stimulus pulse. It was also noticed that the audio stimuli was biasing the perception of the haptic stimuli intensity. These results clarify the principles behind haptic feedback design and imply that the multisensory integration should be stressed when designing haptic interaction.

1 Introduction

Mobile hand-held devices are getting smaller while the number of functions incorporated in a single device is growing. This trend sets high requirements for user interfaces that should simultaneously fit in a compact size and enable versatile use in an intuitive way. One possibility to tackle this challenge is to develop devices with touch displays that save space on the surface of a mobile device and allow variable configurations of buttons. The extreme of this development could be a device that is basically comprised only of the touch display and has no physical buttons at all.

At the moment there are many mobile devices on the market with touch displays, but generally they do not support two-way haptic interaction. Without the haptic feedback on touch display the user can only rely on audio and visual feedback, which breaks the metaphor of direct interaction [1]. Thus by adding the haptic feedback to the touch display, it would be possible to improve the usability of traditional use cases of touch displays [2] as well as create totally new effective modes of interaction in mobile devices without physical buttons.

Haptic feedback is a vital part of human perception and it is also fundamental for physical user interfaces. Through touching we convey effectively functional signals as well as emotion [3]. Even if touch may not be as rich as vision we have an amazing range of haptic sensations and touch displays should be able to take full advantage of them [1].

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The piezo actuators have been noted to be the best choice for providing haptic feedback for mobile touch display devices because they can be miniaturized, are durable, and most importantly offer efficient and versatile actuation for effective user interaction. The piezo actuators also produce natural sound and this can be utilized when designing feedbacks for mobile touch display interaction.

Although the importance of the haptic feedback is generally realized, there is limited amount of formal studies of how to design the haptic feedback on touch displays. There are no studies that we are aware of that would have researched how the intensity of the different haptic waveforms is perceived nor how the haptic feedback intensity is perceptually integrated with the visual and auditory feedback during the touch display use.

2 Background

The psychological perceptual studies have been exploring the issue of multisensory integration and how haptics are related to other sensory modalities. However, there is only sparse information how haptic and auditory modalities are integrated and how this integration affects perceived intensity.

The sensory integration depends on various factors both on perceptual and on higher cognitive level. The division between perceptual and higher cognitive level is usually called the processing level issue and it refers to the question whether the observed interactions originate in automatic perceptual processes or in later decisional ones. That is important because human responses are relevant to the intermodal coordination only if they reflect basic perceptual processes, rather than specific decisional strategies [4]. Generally the studies concerning multisensory integration have claimed to deal with perceptual processes and not with higher post-perceptual processes [5].

In perceptual studies vision has generally been noticed to bias the perceived location of touch [6] and perceived location of audio [5]. Also touch has been noticed to bias the perceived location of audio [7]. Consequently when pressing virtual buttons on a touch display the haptic and auditory feedbacks are perceived on the location of pressed virtual buttons even if the sound is coming from piezo actuators that are moving the whole display.

However, the question of modality dominance is not that clear when discussing how auditory and haptic modalities are affecting each other and how does this integration affect perceived feedback intensity. Typically the perception of surfaces is dominated by the haptic component of perception [8] but many studies have noticed that audio can bias and can concretely affect the haptic perception [9, 10, 11].

The integration between audio and touch has been studied also from attentional viewpoint and the studies suggest that there are no crossmodal links in attention between these modalities [7, 12]. Thus the users' attention to either of the audio or the haptic feedback is presumably not affecting the perceived intensity. This is contrary to the strong crossmodal links in attention reported both between audio and vision and between vision and touch [13].

However, it has been reported that auditory and haptic modalities are integrated when perceiving the intensity of the stimuli [14] and therefore it could be assumed that these two modalities are affecting each other in touch display use but the exact direction and effects of the integration are not known.

3 Aim of the Study

In this study we focused on researching the perceived intensity of the haptic feedback that was generated by piezo actuators. In particular, we studied the use of a virtual button on touch display because it is the most common use case of a mobile touch display device. The selected piezo technology intrinsically produces both haptic and audio feedback and thus we also studied the effect of the integration of these modalities on haptic feedback intensity perception.

We did two separate studies in order to find out how feedback intensity is perceived and how the perception of intensity is affected by the modality integration. In the first study, subjects evaluated feedbacks that consisted of both haptic and audio feedback. In the second study subjects evaluated only haptic feedbacks as audio feedback was excluded.

Our hypotheses were that the rise time and form of the haptic waveform would correspond with the perceived feedback intensity and that the audio feedback would integrate with the haptic feedback and bias the perception of the haptic feedback intensity.

4 Device and Stimulus Design

Device used in the study was a mockup handheld device with large touch display similar to the Nokia 770 tablet (Fig. 1). The haptic stimulus was generated by piezo actuator solution, which enables the production of various pulse shapes with displacement amplitudes on a scale of several hundred micrometers. The piezo actuator solution is similar to those that have been introduced by Tuovinen [15] and Poupyrev [16], but optimized to the requirements of mobile devices and use contexts.

The stimuli were generated with a robust and simple bending bimorph placed under the touch display module. The stimulus pulse magnitudes and dynamics can be controlled accurately with these actuators [17]. The pulse derives from the energy the piezo actuator supplies in a form of actuator deflection and the associated force subjected to loads [18]. The loads by device mechanics consist of masses and spring loads and are fixed in mechanical design whereas the loads produced by user interaction may vary.

The energy required for haptic stimuli production (force times amplitude) was at a level that inevitably causes a counter pulse to the opposite surface of the device by the

Fig. 1. Nokia 770 tablet with touch display

laws of conservation of momentum, although actuation is targeted at the immediate touch interface. This is characteristic of mobile devices that are small and lightweight by nature.

The modulation of the stimuli was done by controlling the driving voltage and the current of the piezo actuator and thereby altering two parameters, namely the rise time and the displacement amplitude (Fig. 2). This way it was possible to create virtually any kind of one-dimensional haptic stimuli with a relatively large dynamic range. In the context of the present device the range of the amplitudes varied from a few micrometers to a few hundred micrometers. The rise time of the stimulus pulse was varied at a range of 3-7 ms and the displacement amplitude range for stimuli was 3-180 µm. The fall time of the single pulse was fixed at 5 ms for all stimuli.

The piezo actuator also produces sound while actuating. The audio feedbacks were not separately designed, but the intrinsic sounds generated by the piezo actuator were

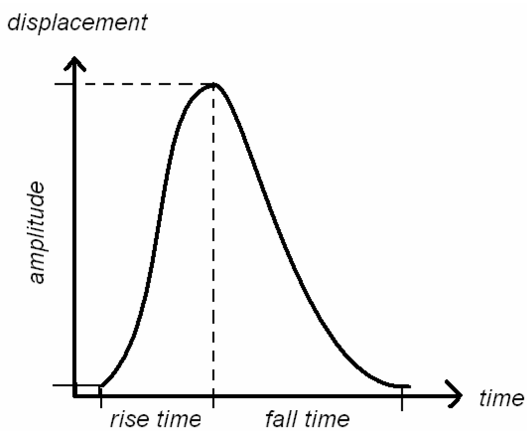

Fig. 2. The stimuli were generated by changing rise time and displacement amplitude. The fall time was fixed to 5 ms.

used as stimuli. As the sound originated from piezo actuator surface instead of touch display surface, the user interaction did not have significant effects on audio stimuli. The maximum sound levels associated with stimuli varied between 28-60 dB at 35 cm distance from the device.

The characteristics of the stimuli pulse were measured with Laser Vibrameter and the displacement amplitude was measured in respect of the displacement time without any load applied by the users. The damping force and its dynamics produced by user interaction were measured and recorded by the resistive touch display.

5 Procedure

We did two separate studies, one with haptic and auditory stimuli, and one with haptic stimuli only where the auditory stimuli were excluded by using earplugs and hearing protectors. 8 naïve participants took part in each of the studies. In both studies there were three females and five males participating and the average age of the subjects was in the first study 33 years and in the second study 27 years. All participants were staff members of Nokia Research Center.

Altogether 16 different physical stimuli were tested. The stimuli were generated altering amplitude and rise time of the stimulus pulse. The stimuli consisted of these 16 different stimuli that were repeated three times in a randomized order resulting to total 48 stimuli.

During the experiment subjects were holding the device perpendicularly in one hand and pressing the key number 5 on the virtual keypad on touch display with the other hand's thumb. In both studies users were told to rate the perceived haptic stimulus intensity without any notion of the purpose of the experiment. Each stimulus was rated verbally on a 1-to-5 rating scale right after each key press, where 1 was *clearly too weak,* 3 *moderate*, and 5 *clearly too strong*. Before starting the experiment users were able to try out the different stimuli.

6 Results

During the experiments, data was collected on the subjective evaluations of the stimulus intensities. In order to find out how the physical haptic pulses are correlated with subjectively evaluated stimulus intensities, the data sets from the two studies and physical parameters of the stimuli pulse were analyzed with linear regression analysis. To explore the integration between haptic and audio stimuli pairwise comparisons were made for the two data sets with Mann-Whitney U test.

The results suggest that the simple correspondence exists within the scale and accuracy used in the device and needed in general in virtual button applications. The average acceleration of the rising edge of the haptic pulse was found to offer the closest correspondence between the physical parameters of the stimulus pulse and the subjective evaluations of stimulus intensity. This was the case both with *haptics and audio* stimuli and with *haptics only* stimuli. The coefficient of determination that represents the percent of the data that is closest to the line of the best fit, was 0.92 ($p<0.01$) for *haptics and audio* (Fig. 3) and 0.90 ($p<0.01$) for *haptics only* (Fig. 4). There were no correlations between the perceived intensity and the input force or the time the users were pressing the touch display.

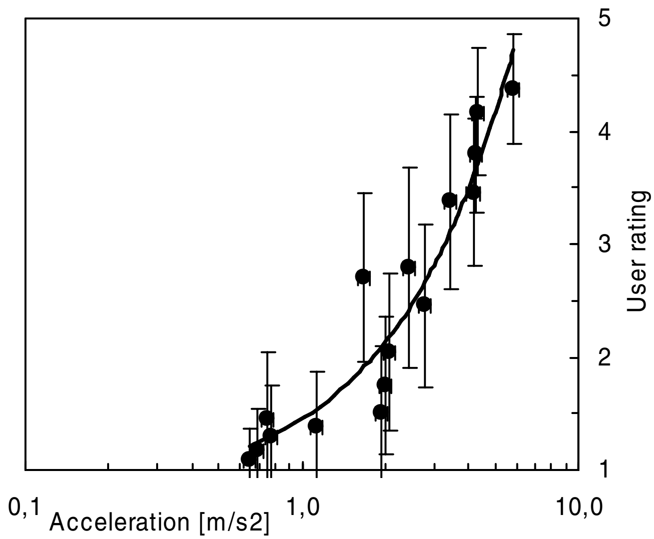

Fig. 3. The scatterplot shows the mean values and standard deviations for subjective evaluations of stimulus intensities for the *haptics and audio* stimulus and the average accelerations and error bars of the haptic stimulus pulses. The linear regression fits the data with a coefficient of determination $R^2=0.92$ ($p<0.01$).

The pairwise comparisons of the data sets from the *haptics and audio* and *haptics only* studies shows that there was difference in the stimulus intensity evaluations between the two studies. In the *haptics only* study three stimuli were evaluated weaker than in the *haptics and audio* study (Fig. 5). These differences imply that audio has an effect to perceived intensity of the haptic stimulus within the stimuli range used in the study (28-60 dB in audio and 0,6-8 m/s^2 acceleration) and it biases the perception and increases the perceived strength of the haptic stimulus.

This result was according the hypotheses although the biasing effect was not as clear as it was expected. The level of biasing was related to the level of audio as the stimuli that have higher sound levels were biased more than the stimuli that have lower sound levels.

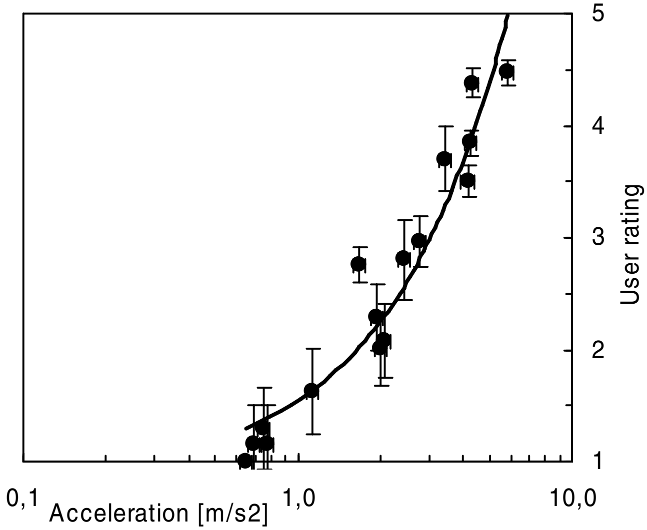

Fig. 4. The scatterplot shows the mean values and standard deviations for subjective evaluations of stimulus intensities for the *haptics only* stimulus and the average accelerations and error bars of the haptic stimulus pulses. The linear regression fits the data with a coefficient of determination R^2=0.90 ($p<0.01$).

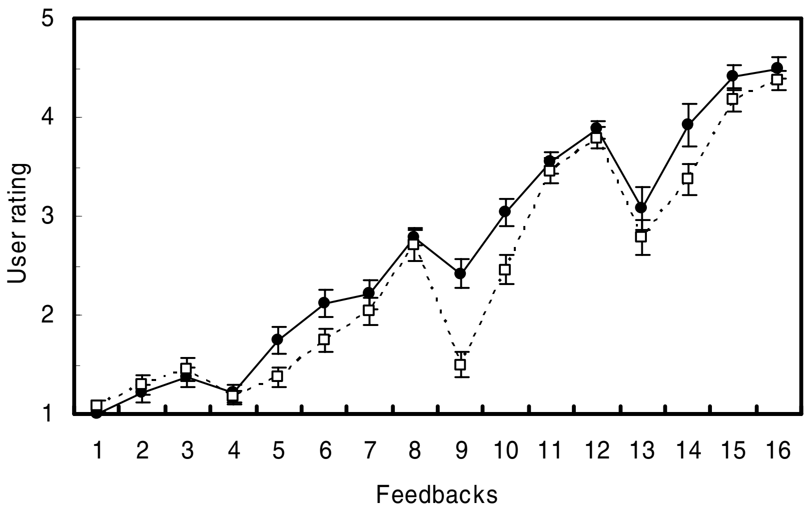

Fig. 5. The figure shows the mean values and standard error of means for subjective evaluations of stimulus intensities both for the *haptics and audio* (*continuous line*) and *haptics only* (*dotted line*) stimuli. The pairwise comparisons between the two studies show that there are statistically significant differences between the two studies in stimuli number 9 ($p<0.01$), 10 ($p<0.05$), and 14 ($p<0.05$).

7 Discussion

In the study it was found out that the displacement dynamics of the touch display correlated with the perceived intensity. The acceleration of the rising edge of the haptic stimulus pulse had the closest correspondence to the perceived intensity of the stimulus within the scale and the accuracy that is needed in mobile touch display devices in general and particular in virtual button applications. The displacement of the touch display surface was inadequate to explain the perceived intensity and there were no correlations between the perceived intensity and the input force or the time the users were pressing the touch display. These results were quite similar between the *haptics and audio* and *haptics only* conditions.

The pairwise comparisons between the two conditions suggest that audio stimulus has some effect on stimulus intensity perception. It was noticed to bias the stimulus intensity evaluations in a way that stimuli that have higher sound levels were biased more than stimuli that have lower sound levels. This was predictable but generally the biasing effect was weaker than expected. It could be partially explained by the small sample size and in a study with more subjects the difference would probably be more evident. However, it was noticed that the sound is affecting perceived haptic stimulus intensity and thus the effects of sound should carefully be taken into account in haptic feedback design in mobile devices.

There were also observable differences in stimulus evaluations between the subjects. It was noticed that some of the subjects preferred stronger stimuli as some of the subjects liked the weaker ones. This implies that different people and perhaps different cultures could have distinctive tastes for haptic feedbacks.

The challenges in designing haptic feedbacks are not only technological ones but also relate to broader research and design issues. First of all the haptic perception is affected by the simultaneous visual and auditory perception and therefore the haptic design should be linked to visual and audio design. Secondly the haptic perception is context dependent and application, device, and environment are probably affecting to the experience of the expedient feedback. Finally the personal and cultural differences are underlining the diversity of the haptic design issues. The haptic preferences presumably vary between individuals and between cultures and there is need of adjustability or even adaptivity in haptic design.

These above-mentioned issues are great challenges when developing and designing haptic user interfaces. Further studies are planned to tackle these challenges in a mobile context and study how to design both effective and pleasant haptic interaction for touch display devices.

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