2017 IEEE World Haptics Conference (WHC)
Fürstenfeldbruck (Munich), Germany
6–9 June 2017

Effects of Visual and Haptic Latency on Touchscreen Interaction: A Case Study Using Painting Task*

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***Abstract*— This paper reports a user study on the effects of latency in visual and haptic feedback on touchscreen interaction for a painting task. Our work was motivated by recently emerging multimodal use of touchscreens and electrostatic friction displays with high-quality 3D graphics. We designed and implemented a painting application on a touchscreen that enabled users to paint a 3D sculpture with their finger pad while perceiving haptic feedback through electrovibration. Software-induced latency was varied from 0 to 120 ms for both visual and haptic feedback. Participants' task was to paint on the 3D sculpture as quickly and accurately as possible. For performance assessment, we measured task completion time and execution error. We also obtained subjective responses to four questions (easiness, responsiveness, pleasantness, and the sense of control) related to user experiences. Experiment results indicated that visual latency is critical for both task completion time and task execution error whereas haptic latency is for task execution error, but not for task completion time. Both latencies affected the subjective responses, but visual latency had more apparent effects.**

I. Introduction

Touchscreen devices are pervasive, and the need for programmable haptic feedback in touchscreen interaction is ever increasing to provide a variety of natural touch sensations to the user's fingertip. An area researching such technology is called surface haptics. This technology enables a user to see and feel the content at the same time with rich haptic information, yielding better usability and user experiences.

One approach in surfaces haptics is called electrovibration and it relies on the electrostatic force induced between the user's finger and an insulated surface on the touchscreen by supplying high AC voltage, which effectively increases the surface friction [1], [2], [3], [4], [5], [6], [7]. Electrovibration was first discovered by Mallinckrodt et al. [8], who accidently experienced rubbery sensations on an insulated surface when the surface was connected to an AC voltage source. Later, Strong et al. developed the first electrovibration display using an array of small electrodes [1]. This technology has been recently revived by the release of TeslaTouch [2], the first touchscreen with a transparent insulating film overlaid on it for collocated visual and haptic feedback. TeslaTouch controls the electrostatic friction between surface and finger pad to create diverse haptic sensations on top of visual content. Electrostatic friction displays have great merits such as seamless integration onto a touchscreen, uniform sensations across the touchscreen, and no need for mechanical actuators. Since then, researchers have shown increasing interest in developing improved electrostatic friction displays [3], [4] and associated applications, e.g., primitive 3D shape rendering [5] and texture rendering [6] both displayed on a touchscreen, and reverse electrovibration for haptic augmented reality [7]. There also exist a few startup companies that are commercializing electrostatic friction displays for touchscreens, e.g., Senseg [9] and Tanvas [10].

The 3D content for touchscreens is also proliferated with advanced GPU technologies on mobile platforms, and users frequently interact with 3D objects. However, complicated 3D graphics and user interaction may significantly increase latency in visual rendering, leading to poor user performance and experiences. Maintaining a high frame rate is crucial, but the frame rate frequently drops when interacting with heavy 3D mesh data. This computational burden also exacerbates haptic feedback latency.

In fact, the detrimental effects of latency in multimodal interaction has been a well-recognized issue. For example, research has addressed the effects of visual delay on the performance of a 1D target acquisition task [11], those of visual and haptic network delay on rendering artifact perception [12], those of the time difference between visual and haptic stimuli on a 1D collision task [13], and those of visual and haptic delay in collaborative virtual environment [14], [15], [16], virtual reality [17], [18], [19], [20], and teleoperation [21], [22]. In general, most of these studies reported that latency in visual feedback significantly affects human performance and minimizing haptic feedback latency improves the performance. Good control of latency in multisensory feedback is critical for improving user performance and experiences. However, it is difficult to specify the range of tolerable latency in visual and haptic feedback since acceptable feedback latency is critically depends on the user's task and the system's environment.

Several studies covered the effects of tactile feedback latency in touchscreen interaction, and they are more relevant to our work. Lee et al. [23] reported that visual stimuli have to lead vibrotactile stimuli by approximately 40 ms in order for the optimal perception of synchrony in the touchscreen button press task. Karaaresoja et al. [24], [25] studied the

*This work was supported by a Cross-Ministry Giga Korea Project (GK16C0100; Development of Interactive and Realistic Massive Giga-Content Technology) of the Ministry of Science, ICT and Future Planning, Korea.

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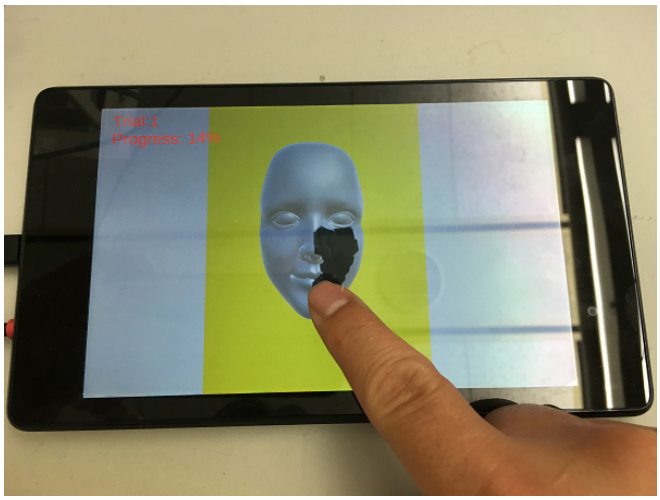


Fig. 1: Experimental application.

effects of tactile feedback delay on touchscreen keyboard and keypad usage. They reported that the task performance (i.e. speed and error rate) was not significantly affected when latency was added to tactile feedback for buttons, but the subjective ratings were significantly dropped with the increment of haptic feedback latency.

In this paper, we report a case study that investigated how latency in visual and haptic feedback affects user performance and experiences when users interact with a 3D object displayed on a touchscreen while exposed to variable surface friction feedback. Since previous latency studies on touchscreen interaction [24], [25] only focused on the simple button press task and did not find any strong relationship between multimodal feedback latency and human performance, it is important to explore the impact of multimodal feedback latency in plausible 3D applications with advanced haptics technology. The task used was a painting task, which had been chosen for several reasons. First, painting is one of the most intuitive activities for touch-enabled 3D modeling data. Second, simulation of painting a 3D object requires a considerable amount of graphic resources and is a good candidate for 3D mobile interactive scenarios with frequent frame rate drops. Last, haptic feedback may facilitate painting by providing different tactile sensations depending on the region being painted.

While varying the software-induced visual and haptic latency in a wide range (0–120 ms), we measured task completion time and task execution error as quantitative performance measures, as well as four subjective measures (easiness, responsiveness, pleasantness, and the sense of control). Experimental results demonstrated rather distinctive effects of visual and haptic latency on the task performance and the qualitative measures.

II. Methods

A. Participants

Thirty volunteers (20 male and 10 female; age M 24.0 years old, SD 5.3 years) participated in this study. All had normal visual and tactile sensory ability by self-report.

B. Apparatus

As a device, we used a Feelscreen development kit from Senseg [9]. This device extends a commercial tablet (Google Nexus 7, 2013 version; 7.0 inches with 1200×1920 pixels; refresh rate 60 Hz) with an electrostatic friction display overlaid on the touchscreen. The device can render strong and clear electrovibrations.

C. Task and Experimental Conditions

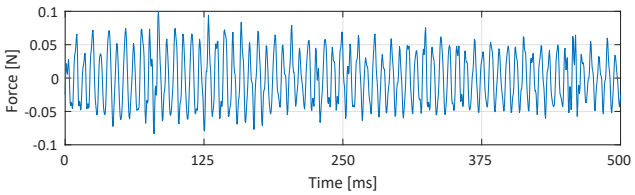
Figure 1 shows an experimental application implemented on the Feelscreen development kit. The application was built using the Unity3D game engine (version 5.3.2) [26] and the Senseg haptic library. The application displayed a 3D mesh model of a Nymph sculpture on the screen. Participants' task was to paint within the 3D model by touching the screen with an index finger of their dominant hand. The touched area was then turned to black for visual feedback. The background color was yellow so that participants were easily aware of the background. Note that the larger white background was not for interaction and thus nothing happened when the white area was touched.

Haptic feedback was also provided. When participants were painting within the 3D model, a haptic effect named `AREA_EVEN` available in the Senseg haptic library was rendered using the electrostatic friction display. When painting in the yellow background, a haptic effect called `AREA_SMOOTH` was rendered. Figure 2 shows example force profiles of the two haptic effects that were measured with a rotary tribometer [5]. The tribometer was equipped with a six axis force/torque sensor and Feelscreen was placed underneath the sensor to collect the lateral frictional forces when its touchscreen surface was being scanned by a rotating touch pen. The normal pressure on the surface and the rotational scanning velocity were adjusted (470 g and 6.5 cm/s, respectively) to mimic human hand scanning.

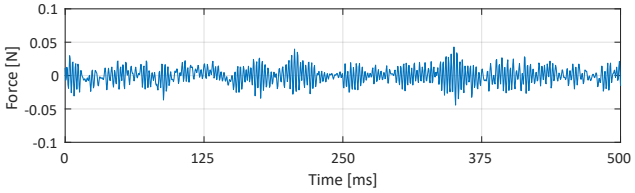
`AREA_EVEN` conveys bumpy, rough, and even sticky sensations, while `AREA_SMOOTH` imparts smooth and high-pitch feeling. This design of haptic feedback was to facilitate the painting task by giving feedback as to the region being painted and tactile cues as to boundary crossing.

Participants were asked to paint the Nymph sculpture as quickly as possible while not painting the background, i.e., minimizing the error, to their best ability. The application considered the task completed when participants painted more than 95% of the Nymph sculpture.

Visual latency V_L is the time difference from the instant at which a user touches on a touchscreen to that at which a visual rendering command is issued. Haptic latency H_L is defined similarly. Since the Feelscreen device had basic latencies for both visual and haptic feedback, we measure those values as follows. The basic latency of visual feedback was obtained using a high speed camera (Phantom v7.3, Vision Research, USA; full frame 4:3 aspect ratio, 800×600, 14-bit image depth, 6,688 fps) by measuring the time difference between the moment of a touch and the moment



(a) AREA_EVEN



(b) AREA_SMOOTH

Fig. 2: Force profiles of two haptic effects.

when visual feedback appeared on the screen. This value was 56 ms on average for our painting application, which includes touchscreen response time, display refresh time, and rendering time. We also obtained the basic latency of haptic feedback by measuring the time difference between the moment of a touch and the moment when haptic feedback was activated using the force sensor and touch pen in our tribometer. The mean basic haptic latency was 40 ms for our painting application.

In addition, we injected software-induced visual latency V_L and haptic latency H_L in this experiment. Their values were 0, 40, 80, and 120 ms for both latencies. Painting task became too difficult with latencies over 120 ms, thus we set the range from 0 to 120 ms. In the full factorial design of V_L and H_L, participants were tested under 16 experimental conditions. The application carefully controlled V_L and H_L and they were added when visual and/or haptic feedback was updated. In the rest of this paper, we use software-induced V_L and H_L to represent the experimental conditions instead of the total latencies.

D. Procedure

Participants completed two blocks of 16 trials. Each trial was for one experimental condition and proceeded as described in Section II-C. The order of the 16 experimental conditions was randomized for each participant. Between two blocks, five minutes of break was forced to avoid participant's fatigue. A practice session was also presented before the main experiment. Each block took about 25 minutes, and the entire experiment required around one hour.

After completing each trial, the experimental program recorded the task completion time T and the painted area A in the background. A was further divided by the area of the Nymph sculpture projected to the touchscreen for normalization, and this value was taken as the task execution error E. We also asked participants to rate the application for the following four questions on a 5-point Likert-type scale from 1 (strongly disagree) to 5 (strongly agree): *Easiness*—It was easy to paint; *Responsiveness*—The application felt responsive to my touch; *Pleasantness*—It was pleasant to use; and *Sense of control*[1] —I felt like I was really painting.

III. Results

All statistical analyses reported below were done using two-way ANOVA with repeated measures.

A. Quantitative Measures

Figure 3 shows the mean task completion times T measured in the experiment. Visual latency V_L had a statistically significant effect on T ($F_{3,87} = 460.42, p < 0.0001$), but haptic latency H_L did not ($F_{3,87} = 0.53, p = 0.66$). The interaction between V_L and H_L was significant ($F_{9,261} = 2.96, p = 0.0023$). These results can be clearly observed in the data of Figure 3. T was increased with V_L almost linearly.

The mean task execution errors E are shown in Figure 4. Here, both V_L and H_L were statistically significant for E ($F_{3,87} = 3.13, p = 0.0299$ for V_L; $F_{3,87} = 4.89, p = 0.0034$ for H_L). The interaction term was also significant ($F_{9,261} = 2.99, p = 0.0021$). Figure 4 shows a general trend that E was increased with H_L, although the data was not as clear as that of V_L for T. When $V_L = 0$ ms, increasing H_L from 0 ms to 40 ms increased E by a noticeable amount.

Based on the above results, we can conclude that: 1) Visual latency increases both task completion time and task execution error; and 2) Haptic latency increases task execution error, but not task completion time.

B. Subjective Measures

The mean scores of the four subjective measures are presented in Figure 5. On easiness (Figure 5a), both visual latency V_L and haptic latency H_L had a statistically significant effect ($F_{3,87} = 179.36, p < 0.0001$; $F_{3,87} = 4.18, p = 0.0081$), but their interaction did not ($F_{9,261} = 0.744, p = 0.668$). Increasing V_L or H_L degraded easiness, but the effect of V_L was more apparent.

Both V_L and H_L had a significant effect on responsiveness ($F_{3,87} = 97.71, p < 0.0001$ for V_L; $F_{3,87} = 5.136, p < 0.0026$ for H_L). However, their interaction term did not ($F_{9,261} = 0.38, p = 0.944$). Increasing V_L clearly decreased responsiveness (Figure 5b).

Pleasantness (Figure 5c) was significantly affected by both V_L and H_L ($F_{3,87} = 143.2, p < 0.0001$; $F_{3,87} = 5.20, p = 0.0024$), but not by their interaction ($F_{9,261} = 0.814, p = 0.604$). Pleasantness was negatively correlated with increasing V_L or H_L, but the degree was generally larger with V_L than H_L by visual inspection.

Lastly, the sense of control was also significantly dependent on V_L and H_L ($F_{3,87} = 85.61, p < 0.0001$; $F_{3,87} = 6.121, p < 0.0001$), but not on their interaction ($F_{9,261} = 1.21, p = 0.289$). The sense of control was decreased by increasing V_L or H_L. The effect of H_L for the sense of control was clearer than those for easiness, responsiveness,

[1]Also called the sense of agency. It refers to the self-awareness that a person has for the ownership and authorship of his/her action [27].

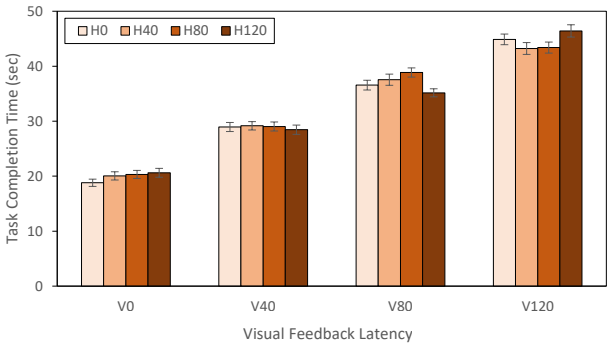


Fig. 3: Mean task completion times. Vx means visual latency of x ms, and Hy means haptic latency of y ms. Error bars represent standard errors.

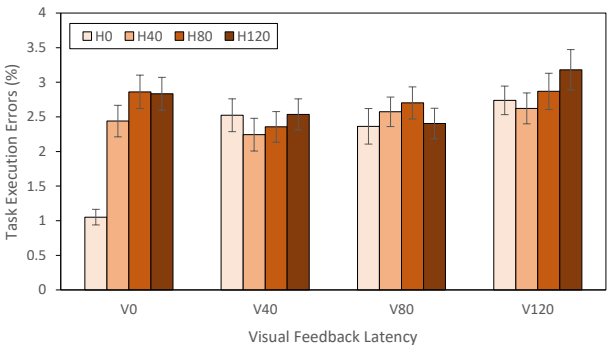
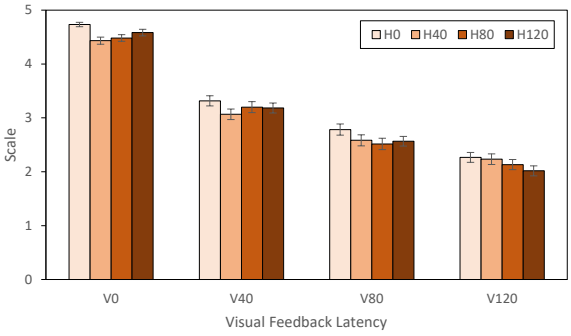
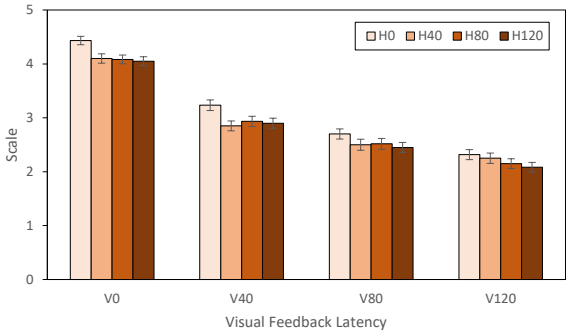


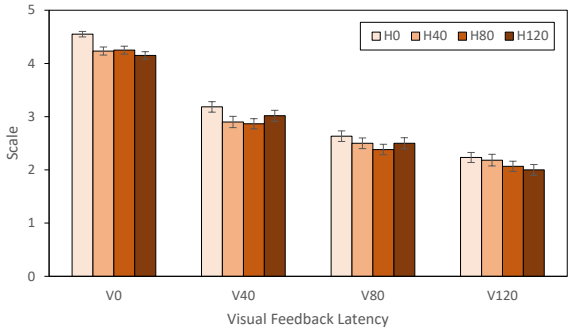
Fig. 4: Mean task execution errors. Error bars represent standard errors.



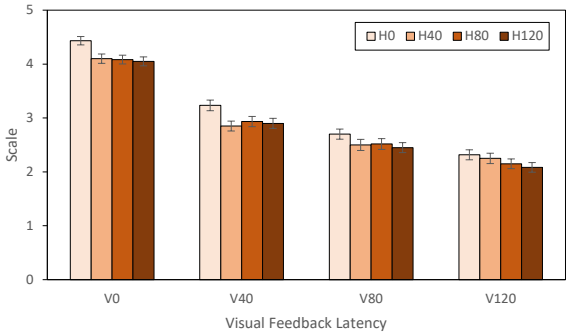
(a) Easiness



(b) Responsiveness



(c) Pleasantness



(d) Sense of control

Fig. 5: Qualitative measurements for user experience. Error bars represent standard errors.

and pleasantness (very low p value; also visually observed from Figure 5d).

The above results can be summarized as follows: 1) Increasing V_L or H_L generally decreased all of the four subjective measures; 2) V_L and H_L had a statistically significant effect on all the subjective measures; and 3) Their interaction term was not statistically significant effect on any of the subjective measures.

IV. Discussion

A. Task Completion Time

The task completion time T measured in the experiment was adversely affected by visual latency V_L, which was expected based on the literature. The mean task completion times for each V_L averaged across four haptic latencies were 19.9, 28.9, 37.0, and 44.4 s. T was almost linearly increased with V_L, even for the smallest $V_L = 40$ ms that is close to only one frame delay. We could observe during the experiment that delayed painting update made participants to either revisit the painting area to repaint the unpainted spots due to visual latency or paint slowly in accordance with visual latency.

In contrast, T was almost independent of haptic latency H_L. This makes some sense considering that most painting was done inside the Nymph sculpture and only the delay in visual update affects the user's painting speed there. It seems

that the role of haptic cues was mostly for the detection of the boundary.

B. Task Execution Error

Haptic latency H_L was detrimental to the task execution error E. The factor means of E for each H_L were 2.17, 2.47, 2.70, and 2.74%, which were consistently increased with H_L. The role of haptic feedback was to inform participants that they were not painting the target when their finger pad was touching outside the sculpture. Haptic latency makes haptic notification of the boundary delayed, and this could have increased the painting errors. This result in turn implies that haptic feedback using two different electrovibration effects was effective in facilitating the painting task in terms of task execution accuracy when there was no haptic latency (H_L=0 ms). However, our finding is contradictory to the results from [25], where there was no significant effect on the speed or errors when haptic feedback latency was applied to the virtual buttons in touchscreen interaction. They suggested that users were tolerant to tactile feedback latency in touchscreen button usage. In our painting task with finger pad scanning over the touch surface, we clearly observed the benefits of haptic feedback added to touchscreen interaction.

We also observed that visual latency V_L and their interaction term affected E significantly. This result suggests that participants relied on both visual and haptic cues in the *crossmodal* sensorimotor task.

C. Subjective Measures

All the four subjective measures (i.e. easiness, responsiveness, pleasantness, and the sense of control) were negatively affected by visual and haptic latency, even with the smallest delay (40 ms). It is important to minimize visual delay to maintain good user experiences in highly responsive applications since visual cues are dominant in most applications. However, we further noticed that latency in haptic feedback plays an important role significantly affecting user experiences. These results as to the subjective measures are consistent with those of Kaaresoja et al. [25]. In their study, the users evaluated the keypad with the shortest haptic feedback latency more pleasant to use. Their results showed that most of the subjective ratings were dropped significantly with the increase of haptic feedback latency in touchscreen interaction, although there were no significant effects on task performance. Hence, latency in both visual and haptic feedback should be handled with great care in interactive touchscreen applications to provide high-quality user experiences.

V. Conclusions

This paper has reported a user study in which the effects of visual and haptic latency on touchscreen interaction were examined using a painting task. The context was user interaction with complex 3D mesh data on a touchscreen with the aid of tactile feedback utilizing electrovibration. The major findings were: 1) Visual latency is critical for decreasing task completion time and task error; and 2) Minimizing haptic latency improves task accuracy. Both latencies had important effects on the user-perceived value of the interaction. These findings can be beneficial to interaction designers for designing and implementing 3D applications on touch-enabled touchscreens with electrovibration. In the future, we plan to extend our investigation to other 3D applications such as 3D mobile games.

VI. Acknowledgments

The authors thank Yongjae Yoo for discussion and support for statistical analysis and Sungho Seo for assistance in conducting the experiment.

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