

Haptic Keyclick Feedback Improves Typing Speed and Reduces Typing Errors on a Flat Keyboard

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Abstract — The present study used a flat keyboard without moving keys and enabled with haptic keyclick feedback to examine the effect of haptic keyclick feedback on touch typing performance. We investigated, with well-controlled stimuli and a within-participant design, how haptic keyclick feedback might improve typing performance in terms of typing speed, typing efficiency and typing errors. Of the three kinds of haptic feedback we tested, all increased typing speed and decreased typing errors compared to a condition without haptic feedback. We did not find significant differences among the types of haptic feedback. We also found that auditory keyclick feedback alone is not as effective as haptic keyclick feedback, and the addition of auditory feedback to haptic feedback does not lead to any significant improvement in typing performance. We also learned that global haptic keyclick feedback simulated through local keyclick feedback on each key (as opposed to haptic feedback all over the keyboard) might have the additional and unexpected benefit of helping a typist to locate keys on a keyboard. Furthermore, the participants preferred auditory or haptic keyclick feedback to no feedback, and haptic feedback restricted to the typing finger alone is preferred to that over a larger area of the keyboard.

I. INTRODUCTION

As mainstream computing devices move beyond the desktop to incorporate mobile devices and tablets, more of our working hours are now spent typing on touchscreens. Typing on a piece of glass with a visual display of a keyboard is difficult and requires increased visual attention to locate the key to be pressed and verify that the correct character has been entered. As a result, typing speed decreases, typing errors increase, and productivity suffers.

Many studies have investigated ways that typing performance can be improved on a touchscreen. Numerous inventions have addressed the two main deficiencies of an onscreen “soft” keyboard: an inability to feel the key locations and a lack of keypress confirmation. They include, for example, TouchFire, a transparent embossed keyboard that can be placed on top of a touchscreen [1], and a pop-up keyboard based on microfluidics (Tactus Technology, Fremont, California, USA). There is now a plethora of external compact keyboards for those of us who care about creating a written document efficiently while on the go.

We asked the question of whether restoring some of the sensory feedback that is typically available on a physical keyboard with moving keys might help with typing on a flat

keyboard without moving keys; and if so, how. Specifically, we were interested in how haptic sensory feedback could enhance typing performance. We further included in our investigation a comparison of the relative benefits of haptic keyclick feedback as opposed to audio keyclick feedback. We reasoned that typing is a manual task and having haptic keyclick feedback may be a more natural way for the typist to receive keypress confirmation than audio keyclick feedback. Furthermore, silent haptic feedback has the additional benefit of not requiring a typist to wear headphones, have headphone music interrupted, or annoy people nearby; all of which are real concerns for mobile device use. Given the additional materials and cost required to incorporate haptic feedback into a flat keyboard with no moving parts, we were also interested in different types of haptic keyclick feedback and in comparing how each option would affect typing performance.

Such an investigation would require an experimental apparatus that looks and feels like a keyboard and can provide well-controlled sensory feedback. Building such an apparatus on a touchscreen would be difficult due to the need to preserve the transparency of the visual display. We therefore opted to build our apparatus by instrumenting an external keyboard already in use as a portable tablet keyboard. Our apparatus was based on the Microsoft Touch Cover, a thin (3 mm) cover for Microsoft Surface tablets that serves the double duty of a flat keyboard. The result is a one-of-a-kind keyboard that can provide keyclick feedback to one key only (*local-H*), to all keys (*global-H*), and to any combination of keys (*partial-H*, to be explained later). The apparatus provides a flexible experimental platform for us to assess and compare different haptic feedback options. To the best of our knowledge, our study provides one of the first investigations directly comparing typing performance using local vs. global haptic keyclick feedback on a keyboard without significant tactile key boundaries. Our results have important implications for the design of future keyboards that seek to restore sensory feedback that was lost in the transition from physical keyboards to soft keyboards.

The contributions of this study are three-fold. First, we developed a keyboard with no moving keys and with well-controlled haptic keyclick feedback on any combination of keys. Second, we found that haptic keyclick feedback significantly improves typing speed and reduces total typing errors, and that audio keyclick feedback does not significantly affect typing speed or typing errors when haptic feedback is provided. Third, we found that even though global haptic feedback was not more effective than local or partial feedback in terms of improving typing performance, half of the participants commented that it helped with locating the keys on the keyboard.

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II. RELATED WORK

Common input methods for mobile devices can be classified into external text-entry methods and on-screen methods [2]. Different techniques are used to improve typing speed and accuracy for the two input methods.

For external text-entry methods, reducing the size of keyboards is a continuing trend. Designers aim for smaller, thinner and lighter keyboards to make them more portable. Some make them foldable and others even go to the extreme of removing keys completely. For example, the Canesta Keyboard uses a projector and a sensor module to create a projected keyboard on a flat surface and detect finger movement, respectively [3]. User studies on the keyboard showed that although the input speed on this keyboard was lower than that on a physical keyboard, it was nonetheless higher than that of using a Graffiti or thumb keyboard. Another example is the UbiK that combines a printed keyboard pattern and a mobile device with microphone array to detect finger tapping position, with a finger localization accuracy above 90% [4]. Goldstein et al. replaced keyboards with a glove embedded with pressure sensors [5]. Productivity on their Non-Keyboard, in terms of percentage of words or characters correctly entered, is higher than that on a Nokia 9000 phone and a PalmPilot. Matias et al. removed some keys to reduce the size of a keyboard to half of a standard keyboard, and achieved higher typing speed than using a compact keyboard [6]. Green et al. went further by removing more keys to achieve a “stick keyboard” that is only a 1/4 of the size of a standard keyboard [7]. They showed that typists could reach half of the typical typing speed with lexicon-based disambiguation. Another way of reducing the storage space of a portable keyboard is to use soft materials such as fabric or silicone to build roll-up keyboards. More recently, keyboards have been built into the protective covers of tablet devices, such as the Microsoft Surface Touch Cover and Type Cover. For on-screen input methods, typing speed has also been found to vary with keyboard layouts (e.g., [8], [9], [10]).

Haptic feedback has also been studied extensively in the context of typing performance on touchscreens. Most studies employed vibrotactile haptic feedback (e.g., Immersion Corp's TouchSense). Fukumoto & Sugimura introduced Active Click using a vibrotactile signal [11]. Their user evaluation showed that tactile feedback reduced the touch panel operation time by about 5% in a silent environment and 15% in a noisy environment. Brewster et al. used vibrotactile feedback to test users' performance in both acoustically quiet and noisy environments [12]. They found text typing speed on a touchscreen to benefit significantly from tactile feedback in a quiet laboratory environment but not in a mobile noisy environment, and corrected error rate to increase significantly in both environments. Hoggan et al. demonstrated an improvement to not only onscreen typing but also button interactions by using different vibrotactile feedback for confirmation of different events [13]. Poupyrev et al. introduced Ambient Touch for generating tactile feedback using multi-layer piezoelectric actuators (*piezo* for short), and demonstrated faster task completion time [14].

All of the above-mentioned studies used actuators that provided global haptic feedback on touchscreens. There have been several studies using equipment that provided haptic

feedback on individual keys. Weiss et al. designed SLAP Widgets, translucent silicone or acrylic add-ons such as sliders, knobs, keyboards and buttons, to add tactile feedback to multi-touch tables to improve input accuracy [15]. Savioz et al. designed a haptic keyboard with user-adjustable force feedback under each key by using coils and electromagnets, but provided no user performance data [16]. Kim & Tan used piezos to replace the dome structures of keys on a physical keyboard to simulate a flat, zero-travel keyboard with haptic feedback [17]. Their study showed that users typed faster with local haptic keyclick feedback (55.1 WPM) than with global feedback (51.8 WPM) or no haptic feedback (46.3 WPM). While the present study used a functionally similar flat keyboard, additional control circuitry has been developed for delivering haptic keyclick feedback to any combination of keys. This additional hardware capability allows us to make a direct comparison of typing performance with local, partial and global haptic keyclick feedback.

We would like to emphasize that our main research interest in the present study is the use of haptic keyclick feedback for keypress confirmation. The feedback signal is delivered upon a keypress. Different haptic technologies, such as [18], [19], [20], can be used to provide information for locating keys through surface texture modulation on a keyboard *before* a key is pressed. The technologies for keyclick feedback and key localization are therefore complementary, and our study focuses on the former. In the rest of this paper, we describe our methods, present experimental results and draw conclusions for practical use of our findings.

III. METHODS

A. Participants

Twenty-four participants (12 females; age: 25.4±4.1 years old) took part in the present study. They are all right handed by self-report. Except for one native English speaker, the rest of the participants learned English as a second language. They use keyboards in their daily work and living. They were screened with an online typing test to ascertain their touch typing skills. Thirteen of the participants had used a Microsoft Type Cover (a 5-mm thick keyboard with moving keys built into the cover for Microsoft Surface) or other similar keyboards prior to the study. Five reported having experience with a Microsoft Touch Cover (a 3-mm thick keyboard with no moving keys, also for Microsoft Surface). The participants signed an informed consent form approved by the IRB at Microsoft. They were compensated for their time.

B. Apparatus

The experimental setup is shown in Fig. 1a. The main apparatus is the flat keyboard enabled with haptic feedback as shown in Fig. 1b. It has the same embossed fabric cover as the Microsoft Touch Cover (Fig. 1c). There are no moving keys on this keyboard. Instead, piezos (3203HD, CTS Corp., Elkhart, Indiana, USA) are used under each key. There is one 11×11×0.3 mm piezo beneath each alphabetic key. A larger piezo, measuring 24×11×0.3 mm, is used under the Enter key and Backspace key. Two piezos of the size 46×18×0.3 mm are used under each half of the Space bar, one on the left and one on the right. The piezos are mechanically isolated so that when one piezo buckles, the displacement of the surrounding piezos due to mechanical coupling is sufficiently attenuated and

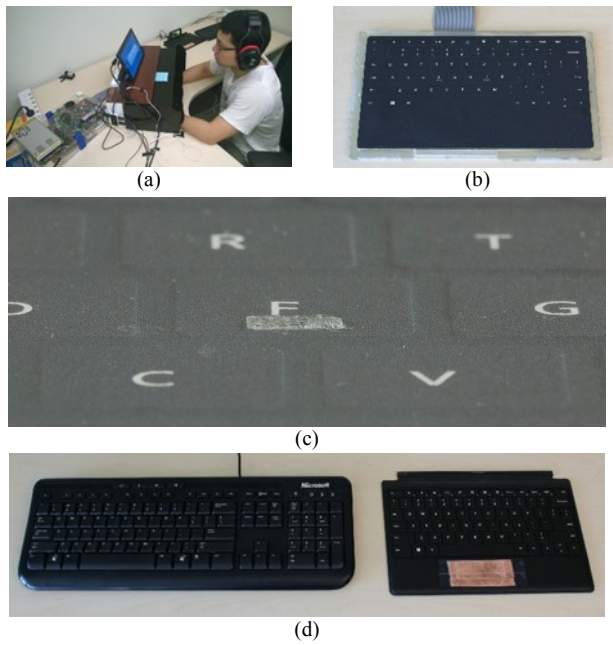


Figure 1. (a) Experimental setup. (b) Haptic keyboard apparatus. (c) A close-up of the embossed cover on the flat keyboard. (d) Microsoft Wired 600 keyboard (left) and Microsoft Type Cover (right).

perceptually non-detectable (cf. [21]). The piezos are used for both sensing and actuation (more details later). Each piezo is individually addressable and any combination of piezos can be activated simultaneously.

We built a custom circuit around an ARM processor running at a clock speed of 72 MHz (STM32F103RET6, STMicroelectronics, Geneva, Switzerland). To sense a keypress, the circuit actively scans all keys in a pre-determined sequence. The scan rate for the whole keyboard is 27 Hz. Each scanning sequence starts with a 3.7-ms initialization, followed by a sequential scanning of the 30 piezos (26 for alphabetic keys, 1 for Enter, 1 for Backspace, and 2 for Space bar), each lasting 280 μ s. Once the change in piezo voltage is detected to be above a threshold for three consecutive scanning cycles, a keypress event is detected. The identity of the pressed key is sent to a PC (a Microsoft Surface Pro) running the experiment. If a haptic feedback condition (*local-H*, *partial-H*, *global-H*) is configured, the circuit will send a high-voltage signal to the corresponding piezos to be activated. Three cycles of a 250-Hz sinusoidal signal is used to drive the piezo(s) as it was found to create a crisp keyclick-like sensation (cf. [22] for the selection of this waveform). This step is skipped if no haptic feedback is to be delivered. The scanning circuit is then re-initialized and piezos discharged to be ready for the next keypress event.

Two additional keyboards were used to collect baseline performance metrics against which performance with the haptic flat keyboard can be compared. As shown in Fig. 1d, they are the Microsoft Wired Keyboard 600 (455 \times 160 \times 24 mm in overall size, with alphanumeric keycaps that measure 13 \times 15 mm) and the Microsoft Type Cover (275 \times 186 \times 5.5 mm in overall size, with keycaps that measure 18 \times 17.5 mm). Both have mechanically-movable keys. The Touch Cover has keys that measure 16 \times 16 mm in size, based on which the haptic keyboard apparatus was constructed.

The keyboards were connected to the Surface Pro via its USB port as standard keyboard devices. A configuration tool was written in C# using the .Net Framework 4.0 and the DirectX SDK. It provided a GUI for setting haptic feedback options on the haptic keyboard, system sound volume (always 100%), pink noise (always on), and the audio-click feedback (on or off). We used the program TextTest created by Wobbrock & Myers to present the text to be typed and the StreamAnalyzer for calculation of performance metrics [23].

Our goal is to bring performance on touchscreen and flat external keyboards closer to touch typing performance on physical keyboards. Therefore, to assess the impact of the feedback conditions on touch typing performance (no visual attention), a black box made of opaque black acrylic plates was constructed to visually shield the haptic flat keyboard, the Microsoft Wired Keyboard 600, and the Microsoft Surface Type Cover as well as the typing hands from the participant's view (Fig. 1a). The box measures 505 \times 255 \times 155 mm in size. The front of the box was covered with a double-layer black velour curtain that drapes over the participant's wrists. Sound-absorbing foam was attached to the inside of the box to reduce the sound emitting from the experimental apparatus. The eyes-free testing environment was possible because the cover of our keyboard uses the same embossed fabric cover of the Touch Cover that provides tactile cues for key localization, and we added extra glue under "F" and "J" to help users better initialize finger positions (see Fig. 1c).

C. Stimuli

Visual, haptic and auditory stimuli were used to provide sensory feedback. The visual TextTest display consists of two text boxes. The top text box contains the phrase to be typed, and the bottom box shows what the participant has typed so far. All text phrases were randomly chosen from MacKenzie & Soukoreff's corpus [24]. From the 500 phrases, we removed 21 phrases that contained words that are offensive or rarely encountered by the participants who are non-native English speakers. We also replaced all uppercase letters with lower case. The TextTest program was modified to prevent the same phrase from appearing twice during one session.

Four types of haptic keyclick feedback were available: off (*no-H*), delivered only to the typing finger (*local-H*), delivered to the 5 digits of the typing hand (*partial-H*), or to all fingers (*global-H*). For example, consider the case where the participant presses down the "s" key with the left ring finger. Only the piezo under the "s" key is activated in the *local-H* condition. In the *partial-H* condition, the piezos under all the keys covered by the typing (left) hand are activated (i.e., "qwerty", "asdfg", "zxcvb", and the left half of the Space bar). In the *global-H* condition, all the piezos are activated. Our choice of the *partial-H* condition is of a practical nature. Kim & Tan concluded that *local-H* feedback leads to significantly better performance than *global-H* [17]. Since it requires many more parts (and possibly higher cost) to implement *local-* than *global-H* feedback, we were curious as to how "local" haptic feedback has to be in order to maintain the significant typing performance advantage. Furthermore, Kim et al. reports that people are less sensitive to haptic feedback from under fingers of another hand than the same hand, and suggest the use of two actuators, one under each hand [21]. We therefore tested typing performance under this *partial-H* condition.

The strength of *local-H* haptic keyclick feedback was calibrated as follows. An accelerometer (Type 8688A50 with temperature compensation, KISTLER, Winterthur, Switzerland) was placed on top of the “f” key. A 50-gram weight mimicking the force required to push down a key was affixed to the top of the accelerometer with double-sided tape. A waveform of a maximum amplitude of 165 V was used to activate the piezo under the “f” key. The peak acceleration was measured to be 1.2 g (1 g = 9.8 m/s²). We also measured the attenuation of feedback signal on the immediately adjacent keys (i.e., “gdrv” keys) using the accelerometer. The results showed attenuation levels (cf. [21]) of 24.1, 25.1, 22.8, 22.8, and 23.6 dB on the “gdrv” keys, respectively. According to Kim et al., haptic keyclick feedback signals “leaked” from a single piezo are not perceivable if the signal attenuation is greater than 19.7 dB [21]. Our measurements showed higher attenuation levels than the threshold, meaning that our *local-H* feedback signal was well isolated, and this was also verified with a pilot perception test prior to the experiment.

For the *partial-H* and *global-H* conditions, we found, as expected, that the perceived intensity of the keyclick feedback signal was greater than that for the *local-H* condition when the same maximum waveform amplitude was used to trigger multiple piezos. To equalize the perceived intensity of keyclick feedback under these conditions, we used the method of adjustment [25] to estimate the waveform amplitude levels at which the feedback intensities for the *partial-H* and *global-H* conditions were perceived to be equal to the intensity of the *local-H* feedback signal at the maximum amplitude. As a result, the feedback signal amplitudes for the *partial-H* and *global-H* conditions were adjusted to be at 79% and 63% of the maximum amplitude of 165 V, respectively.

The piezo sizes for some keys, such as Enter, Backspace, and Space, are larger than the alphabetic keys. We decreased the signal amplitudes so the haptic feedback on the larger keys feel similar in intensity to that on the smaller alphabetic keys. The signal amplitude was reduced to 73% of that of the alphabetic key for the Enter and Backspace keys, and 37% for the Space bar, under the same haptic feedback condition.

Auditory stimulus was delivered through an in-ear headset (ATH-CKL202 WH, Audio-Technica, Tokyo, Japan). During the experiment, pink noise at 55 dBA was played continuously through the earphones at all times, except when the baseline measures were taken with the Microsoft Wired Keyboard 600 and the Surface Type Cover where no additional haptic or auditory feedback was provided beyond what was available naturally. Under some conditions, a keyclick sound (default system sound on Surface Pro) was also played through the earphone. The level of the pink noise was sufficiently loud to mask the sound emitted by the piezos, yet still safe for hearing protection. The participants also wore a circumaural headset (Peltor H10A Optime105, 3M Corp., Minnesota, USA) with 30 dB attenuation to further block any auditory distractions.

The overall system latency was measured with an oscilloscope to ensure that typing performance was not affected by excessive signal delays. Kaaresoja et al. suggested that feedback latency should not exceed 50 ms for haptic feedback and 70 ms for auditory feedback [26]. The latency of our system included the delay from within the haptic keyboard and the delay from the operating system. Our measurements

showed a total delay of 40.2 ms for haptic feedback and 106.9 ms for auditory keyclick feedback. While the delay for haptic feedback is still below the threshold defined by Kaaresoja et al., the delay for auditory feedback is not. Therefore, our auditory results should be taken with caution.

D. Experiment Design and Procedure

To investigate the effect of different haptic keyclick feedback and auditory keyclick feedback, we used a 4×2 within-participant design. The two independent variables were haptic and auditory keyclick feedback. There were four levels for haptic keyclick feedback: *no-H*, *local-H*, *partial-H* and *global-H*. The two levels of auditory feedback included the presence and absence of auditory keyclick feedback (audio-click and no audio-click) in addition to the pink noise played through the in-ear headset. The eight experimental conditions were blocked into two sessions, with audio-click on one day and no audio-click on the other day. Within each session, the haptic feedback types were ordered by using a Balanced Latin Square. The participants were randomly assigned to presentation orders.

Each participant took part in two sessions conducted on two consecutive days. Before each experimental condition, the participant was allowed to familiarize themselves with the keyboard by typing anything in the Notepad application. They were asked to rest all fingers on the home row at all times during typing. The participant was instructed to review the phrase to be typed and try to memorize it before typing as fast and accurately as possible. The first and second sessions took about 1.5 and 1.0 hour to complete, respectively. During the first session, the participant signed an informed consent form, gave demographic information and received instructions from the experimenter. Two baseline conditions were conducted at the beginning of the experiment, using the Microsoft Wired Keyboard 600 and followed by the Type Cover. The participant typed 60 text phrases with each keyboard. During both sessions, the participant completed the four haptic keyclick feedback conditions. To minimize possible learning effects, half of the participants completed the four haptic conditions with audio keyclick feedback during the first session and without audio keyclick feedback during the second session, and the other half in the reversed order. For each of the 2 baseline conditions and the 8 experimental conditions (4 haptic keyclick feedback × 2 audio-click feedback), the participant was required to type 60 text phrases. The first 10 were regarded as practice and they were not included in data analyses.

The participant was debriefed after each session. The debriefing consisted of the same set of interview questions for both sessions, plus one additional question comparing the presence and absence of audio-click feedback after the second session. During the debriefing, the participants were asked to describe the differences among the *local-H*, *partial-H* and *global-H* haptic feedback conditions, and to indicate which feedback they liked the best and why.

E. Data Analysis

We used StreamAnalyzer [23] to process time-stamped key stroke recordings and extract four independent performance metrics: typing speed, keystrokes per character, uncorrected error rate and corrected error rate. Typing speed

was measured in words per minute (WPM), calculated as $WPM = ((|T| - 1)/S) \times 60 \times 1/5$, where $|T|$ stands for the length of transcribed text in number of characters, and S stands for the elapsed time in seconds from keypress of the first character to that of the last one (cf. [27]). Keystrokes per character (KSPC) was calculated as $KSPC = |IS|/|T|$, where $|IS|$ stands for the length of input text stream (including keypresses for error correction) in number of characters [28]. This metric therefore assesses the efficiency of typing, with 1.0 as the minimum and optimal value. Corrected and uncorrected error rates in percentages were calculated as:

$$\text{corrected error rate} = (IF/(C+INF+IF)) \times 100\%$$

$$\text{uncorrected error rate} = (INF/(C+INF+IF)) \times 100\%$$

where C stands for the number of correct characters in the transcribed text, IF stands for the number of non-editing key strokes (i.e., excluding Backspace or Delete) that is in the input stream but not the transcribed text, and INF stands for the number of incorrect characters that appears in the transcribed text [28]. The sum of corrected and uncorrected error rates is the total error rate in percentage. While higher typing speed indicates better typing performance, lower KSPC and error rates are desired for better typing efficiency and accuracy.

Repeated measure analysis of variance (RM ANOVA) was performed on the data at a significance level of $\alpha = 0.05$.

IV. RESULTS

A. Typing Speed

Fig. 2 shows the average typing speed, typing efficiency and error rates for all participants. From Fig. 2a, it is clear that typing speed in the baseline conditions (58.7 WPM with Wired 600 and 55.9 WPM with Type Cover) were a lot higher than the conditions with the flat keyboard (29.0 to 38.5 WPM). Among the eight non-baseline conditions, the *no-H* conditions led to the lowest typing speed (29.0 and 33.0 WPM without and with audio-click, respectively) as compared with any of the three haptic keyclick feedback conditions (36.5 to 38.5 WPM). These data trends were confirmed with a repeated measure ANOVA with two factors: haptic feedback (*no-H*, *local-H*, *partial-H*, *global-H*) and audio-click (with and without). The results indicated haptic feedback to be a significant factor ($F_{3,69}=40.0$, $p<0.001$, $\eta^2=0.635$) while audio-click was not ($F_{1,23}=0.498$, $p=0.487$, $\eta^2=0.021$). There was also a significant interaction of audio-click and haptic conditions (see Fig. 3; $F_{3,21}=3.85$, $p=0.024$, $\eta^2=0.355$).

Given the significant interaction of audio-click and haptic feedback conditions, we analyzed the simple main effect of haptic feedback by a multivariate test. The results showed that the simple main effect of haptic feedback remained significant within each level of audio-click conditions (no audio-click: $F_{3,21}=13.9$, $p<0.001$, $\eta^2=0.666$; audio-click: $F_{3,21}=12.7$, $p<0.001$, $\eta^2=0.645$). For the no audio-click conditions, pairwise comparisons (Bonferroni corrected) indicated that the *no-H* condition resulted in a significantly lower typing speed than the three conditions with haptic keyclick feedback ($p<0.001$ for all three comparisons). There was no significant difference among the three conditions with haptic feedback. Similarly, with the audio-click conditions, we found that the typing speed of the *no-H* condition was significantly lower

than that of the *global-H* ($p=0.003$), *partial-H* ($p=0.025$) and *local-H* conditions ($p<0.001$). None of the other pairs were significantly different. Finally, we also found that audio-click feedback had a significant simple main effect only when there was no haptic feedback ($F_{1,23}=5.19$, $p=0.032$, $\eta^2=0.184$).

A paired sample t-test showed a difference between the baseline conditions (57.3 WPM, average typing speed on the Wired 600 and Type Cover keyboards) and haptic-feedback conditions (37.5 WPM, average of the 6 conditions with haptic feedback, with and without audio-click). Therefore, typing speeds on the flat keyboard with haptic feedback were significantly lower than those in baseline conditions ($t_{23}=8.92$, $p<0.001$).

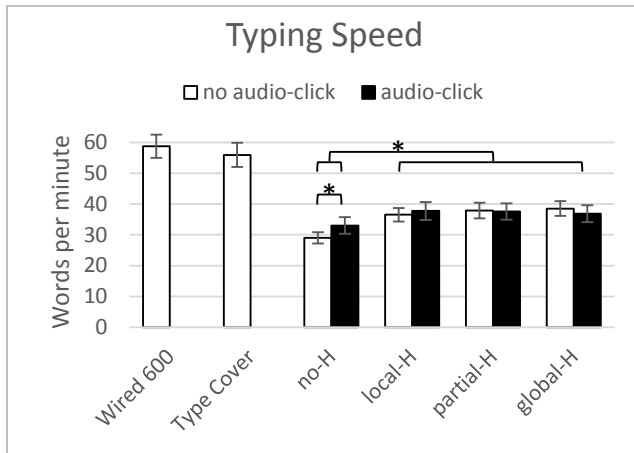
B. Keystrokes per Character

The keystrokes per character data shown in Fig. 2b shows fairly consistent values (1.15 to 1.26) across all conditions, including the baseline data. In general, the auditory and haptic keyclick feedback did not affect the typing efficiency significantly as indicated by keystroke-per-character results.

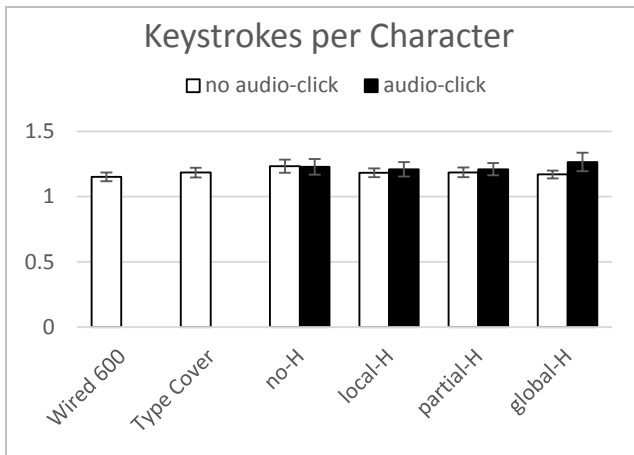
C. Error Rates

Error rates are shown in Fig. 2c. In the plot, corrected and uncorrected error rates are shown in a stacked column format so that the height of each column corresponds to the total error rate for the corresponding condition. A visual inspection shows the lowest total error rates for the baseline conditions (5.6% for Wired 600 and 6.9% for Type Cover) and the highest total error rates for the *no-H* conditions (8.9% without audio-click and 8.2% with audio-click). The total error rates for the haptic feedback conditions ranged from 7.3% to 7.9%. Looking at uncorrected error rates, they occupied a small percentage of the total error, especially in the two baseline conditions. A two-way repeated measure ANOVA was performed on the error rate data. It was found that three participants had data that were more than three standard deviations away from the group mean. Such data were replaced with the group mean values. (Removal of outliers was not necessary for the typing speed data.) The ANOVA results showed that haptic feedback had a significant effect ($F_{3,69}=4.75$, $p=0.005$, $\eta^2=0.171$) on total error rate, but audio-click feedback did not ($F_{1,23}=0.004$, $p=0.949$, $\eta^2=0.000$). There was no significant interaction between audio-click and haptic feedback ($F_{3,69}=1.69$, $p=0.178$, $\eta^2=0.068$). Pairwise comparisons showed that the *no-H* conditions resulted in a significantly higher total error rate than the *local-H* conditions ($p=0.003$). A comparison between the *no-H* and the *partial-H* conditions ($p=0.066$) was found to approach significance, and no significant difference between other pairs was found.

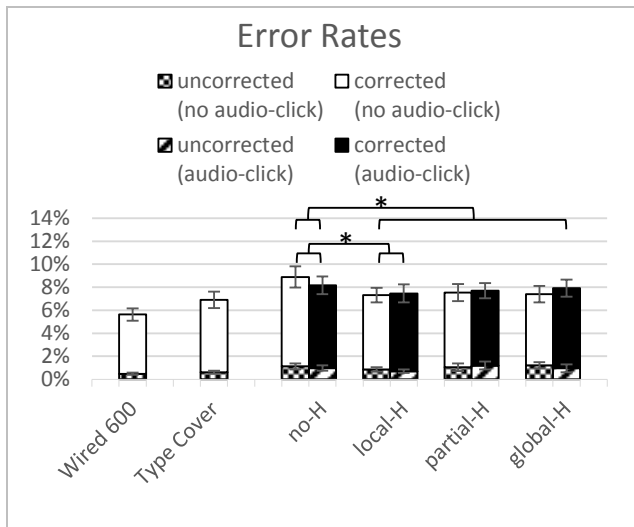
The same ANOVA was performed on corrected and uncorrected error rates. The results showed that haptic feedback had a significant main effect on corrected error rate ($F_{3,69}=4.67$, $p=0.005$, $\eta^2=0.169$) while audio-click did not ($F_{1,23}=1.57$, $p=0.695$, $\eta^2=0.007$). No significant interaction was found between the two factors of haptic and audio-click feedback ($F_{3,69}=2.31$, $p=0.084$, $\eta^2=0.091$). The results of pairwise comparisons between haptic feedback conditions found the difference between *no-H* and *local-H* conditions to remain significant ($p=0.039$). No significant main effect or interaction was found on uncorrected error rate.



(a)



(b)



(c)

Figure 2. Experimental results. (a) Typing speed. (b) Keystrokes per character. (c) Error rates. Error bars show standard errors. (The asterisk * indicates significant difference at $p < 0.05$.)

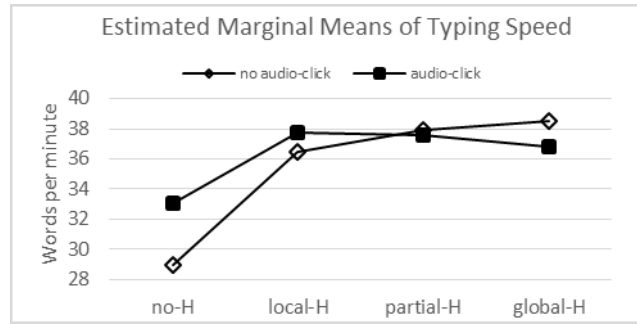


Figure 3. Estimated marginal means of typing speed, showing a significant interaction of audio-click and haptic feedback.

D. Interview Results

An analysis of the interview data showed that, as far as auditory feedback is concerned and regardless of haptic feedback conditions, 15 of the 24 participants regarded audio-click feedback to be helpful for typing, 7 preferred no audio-click, and the other 2 remained neutral. When comparing the four haptic conditions (*no-H*, *local-H*, *partial-H* and *global-H*) within an audio-click or a no audio-click block, the *local-H* conditions were the most favored haptic feedback option (13 votes with audio-click and 16 votes without audio-click). The *global-H* condition was the second most popular (7 votes) among the no audio-click conditions and the *partial-H* condition was the second most popular (9 votes) among the audio-click conditions.

We used a chi-square goodness of fit test to analyze the effect of haptic feedback on the preference counts. The results showed that the four haptic feedback conditions (*no-H*, *local-H*, *partial-H*, *global-H*) had different effects on the participants' preference with audio-click ($\chi^2_3=15.6$, $p < 0.05$, $\Phi=0.41$) or without audio-click ($\chi^2_3=10.0$, $p < 0.05$, $\Phi=0.33$). The results also suggest a big positive contribution of the *local-H* conditions on the participants' preference ($\chi^2=9.63$ with audio-click and $\chi^2=4.03$ without audio-click).

Interestingly, half of the participants reported a new use of haptic keyclick feedback: they located key positions by where the haptic feedback was felt. One participant said: "I can tell whether my finger is right on the center of a key, or the relative position, by feeling the haptic feedback." Another said: "I can feel the dimension of the keyboard when it gives out global feedback. For an example, when I'm typing with my right hand, I can feel where 'a' key is under my left little finger." Fifteen participants reported that the *partial-H* and *global-H* conditions felt similar. Furthermore, eight of the fifteen participants reported all 3 haptic feedback conditions (*local-H*, *partial-H*, *global-H*) to feel similar to them. However, two participants commented that *global-H* feedback felt weird because it made them think that they pressed the wrong key. Three participants reported that audio-click feedback distracted them from haptic feedback and made it harder for them to locate the keys. One of them said: "Adding auditory keyclick sound makes me ignore the haptic feedback, which makes me feel worse during global feedback condition. I can't concentrate on feeling where the center of keys are."

These observations indicate that users of a flat keyboard welcome haptic keyclick confirmation for enhanced user experience. The currently available auditory keyclick confirmation for typing on a touchscreen or the Touch Cover does not work as well as haptic keyclick feedback. Furthermore, providing auditory feedback in addition to haptic feedback may not be desirable as the audio clicks may be distracting. Therefore, it is worthwhile to pursue the development of touchscreen soft keyboards and lightweight detachable flat keyboards with haptic keyclick feedback.

V. DISCUSSIONS

The present study used a flat keyboard without moving keys and enabled with haptic keyclick feedback to examine the effect of haptic keyclick feedback on touch typing performance. We investigate, with well-controlled stimuli and a within-participant design, how haptic keyclick feedback might improve typing performance in terms of typing speed, typing efficiency and typing errors. Of the three kinds of haptic feedback we tested, all increased typing speed and decreased typing errors compared to the two conditions without haptic feedback. We did not find significant differences among the types of haptic feedback. We also found that auditory keyclick feedback alone is not as effective as haptic keyclick feedback, and the addition of auditory feedback to haptic feedback does not lead to any significant improvement in typing performance. Note that our auditory feedback had a perceptible delay that might have contributed to this finding. We also learned that global haptic keyclick feedback simulated through local keyclick feedback on each key (as opposed to haptic feedback all over the keyboard) might have the additional and unexpected benefit of helping a typist to locate keys on a keyboard. Furthermore, the participants preferred auditory or haptic keyclick feedback to no feedback, and haptic feedback restricted to the typing finger alone is preferred to that over a larger area of the keyboard.

Our work builds upon and extends that of Kim & Tan [17]. We were encouraged by the finding in [17] that *local-H* keyclick feedback leads to significantly improved typing performance. Our study investigated further if *partial-H* feedback is just as beneficial as *local-H* feedback, and if auditory feedback in addition to haptic feedback can bring additional performance gain. Comparing [17] and the present study, both study the effect of visual, haptic and auditory feedback on touch typing. The eight conditions in [17] are blocked by visual feedback (letter vs. asterisk; the latter provides keypress confirmation, but not key identity). We used visual letter feedback in all eight conditions in our study. Of the four conditions in [17] with visual letter feedback, either auditory or haptic feedback was used but never both. We used the four conditions in [17] and four more: A beep with *local-H*, beep with *global-H*, and *partial-H* with or without beep. Our study is therefore more comprehensive than and builds upon [17].

We took care to develop the haptic keyboard so that three feedback options were available. In the most stringent case, haptic feedback was only available through the key that was just pressed. We consider the local haptic feedback to be most analogous to typing on a physical keyboard with moving keys where the keypress confirmation comes directly from the key

being pressed due to its mechanical movements. We also tested the extreme case of activating all keys on the haptic keyboard for keyclick confirmation. The *global-H* conditions simulated the use of one large actuator to provide keyclick feedback on the entire keyboard. From a manufacturing and cost point of view, global haptic feedback may be desirable due to the simplicity of building and driving only one actuator per entire keyboard. Additionally, we measured typing performance with haptic feedback delivered to only the hand with the typing finger, but not the resting hand. The partial haptic feedback is the second simplest case where two actuators, one for each hand, can be used in a flat keyboard to deliver somewhat isolated keyclick confirmation to half a keyboard, or one hand, at a time. The finding that all three haptic feedback options, local, global and partial, led to higher typing speed and lower errors indicates that some form of haptic keyclick confirmation is better than none. The finding that the three options resulted in similar typing performance indicates that the construction of haptic feedback can be flexible, depending on the size of the actuators available, power consumption and other manufacturing constraints.

One important difference exists between truly global haptic feedback and our simulated global haptic feedback. When one actuator is used to provide haptic feedback, then the haptic sensation can be felt on any part of the keyboard, including the keys, the gaps between keys and any surrounding structure. In our haptic keyboard, however, the piezos are slightly smaller than each keycap and are placed beneath the center of the keys, but not under the gaps or surrounding borders of the keyboard. When the simulated global feedback is delivered, the fingers resting on the home row can discern a large attenuation of signal intensity from the center of a keycap to its border, due to the intended mechanical isolation of piezos in the haptic keyboard. At least half of our participants noticed the phenomenon and took advantage of it to improve the alignment of their fingers on the home row, although some thought it weird that haptic keyclick confirmation could be felt under all fingers. This advantageous side-effect might have inadvertently improved participants' typing performance in the global haptic feedback condition, and masked any performance differences that might have existed among the local, global and partial haptic feedback conditions. We hasten to point out that even though we used the embossed fabric cover of the Touch Cover for Microsoft Surface for our haptic keyboard, some participants still found it difficult to localize the different keys on the keyboard during touch typing. Therefore, we might also regard our way of constructing global haptic feedback through local feedback elements as a possible method to help a typist localize keys on a surface that similarly lacks distinctive physical features for keycap borders.

VI. CONCLUSION

We conclude with the results from the present study that haptic keyclick feedback on a flat keyboard can improve typing performance in terms of higher typing speed and lower typing errors. The exact configuration of the haptic feedback appears not to be critical, so the designers of haptic feedback technology have some freedom in choosing actuators and their attachment in a way that matches the unique requirements of a keyboard. For example, effective keyclick feedback for flat

keyboards such as the Touch Cover for Microsoft Surface can be achieved with a single large actuator with sufficient mechanical coupling for the haptic sensation to be available over the entire keyboard surface. If a large actuator is not available and/or if power consumption is of concern, then several smaller actuators can also be used for haptic keyclick confirmation. On a touchscreen, however, actuators can only be placed along the borders of the visual display due to the transparency requirement. Our results suggest that doing so is still effective for improving typing performance on a touchscreen. Finally, we conclude from our results that haptic keyclick feedback is preferred to auditory keyclick feedback for improving typing performance. This finding is of significant practical importance given that auditory feedback is not appropriate in many social and physical contexts.

One limitation of the present study is a possible learning effect associated with the use of novel haptic keyclick feedback. While most computer users are familiar with physical keyboards with moving keys and many use auditory feedback for typing on touchscreens, few have experience typing with haptic keyclick feedback using a special apparatus such as the haptic keyboard developed for the present study. It is therefore remarkable that the participants in the present study have already benefited significantly from haptic keyclick feedback within the 2.5 hours of our study over two days. It is possible that further typing improvement might be achieved over a longer period of exposure to haptic feedback, and that further insight might be revealed about the different types of haptic feedback as the participants gain more experience with the haptic keyboard. Future work will design and conduct a longitudinal study to investigate the long-term effect of haptic keyclick feedback on typing performance.

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