A Masking Study of Key-Click Feedback Signals on a Virtual Keyboard

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Abstract. We study masking of key-click feedback signals on a flat surface for ten-finger touch typing with localized tactile feedback. We hypothesize that people will attribute tactile feedback to the key being pressed, even with global tactile feedback, provided that the tactile signal on other parts of the surface is sufficiently attenuated. To this end, we measure the thresholds at which a tactile signal is barely perceptible to a finger that is resting passively on a surface while another finger actively presses on the surface and receives a key-click feedback signal. Combinations of the index and middle fingers of both hands are tested. The results indicate that the thresholds are independent of the signal amplitude on the active finger. Larger signal attenuation is needed when the index fingers of both hands are involved than when two fingers of the same hand are involved. Future research will extend the current experimental design to ten fingers and typing-based tasks.

Keywords: touch surface, virtual keyboard, zero-travel keyboard, key-click feedback, tactile masking, attenuation threshold.

1 Introduction

As touch screens become increasingly pervasive on computing devices, finger typing on soft (or virtual) keyboards has become a part of our daily activities. Despite its prevalence, typing on a non-reactive glass surface can be challenging due to the need to 1) visually place the fingers in the correct "home" locations above the keyboard and 2) confirm key entries without the familiar tactile feedback of a mechanical keyboard. The visual search can cause frequent gaze shifts between the keyboard and the text display areas on a touch screen, degrading the typing experience and performance [1-3]. However, we believe we can alleviate this problem in the case of a large surface that supports ten-finger typing by leveraging people's existing experience of eyes-free touch typing on traditional keyboards. Findlater et al. studied unconstrained text entry patterns of twenty touch-typists on a flat surface with or without a visual keyboard

P. Isokoski and J. Springare (Eds.): EuroHaptics 2012, Part I, LNCS 7282, pp. 247–257, 2012.
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[4]. They found that even without the reference of a visual keyboard, touch typists were still able to make key presses at relatively consistent locations within an individual typist, even though the "natural" distribution of key-press locations deviated from those of a rectangular *qwerty* keyboard (e.g., the "natural" rows tend to be curved, there is a larger gap between hands, etc.). Their finding is promising for developing personalized key-press classification systems that support eyes-free touch typing without tactile cues for key locations [5, 6], especially for larger form factor displays.

The other challenge of typing on a flat glass surface is the need for confirmation of key entries. Without the tactile feedback that usually accompanies the depression and release of keys with moving parts, other forms of feedback (e.g., visual enlargement of a key, an auditory ring, or a vibration) are helpful for faster and more accurate key entries [7-10]. Many mobile phones and devices have built-in vibrotactile feedback for confirming touch-screen virtual-key presses. There is typically one tactor that delivers the same tactile signal to the entire device, providing *global* feedback. However, such global feedback may not be appropriate for multi-touch interactions on a larger screen such as on a tablet or slate, because all contacted fingers might receive feedback simultaneously. At any time during ten-finger typing, several fingers rest on a touch screen while one finger does the typing. In order for the tactile feedback to emulate what happens on a mechanical keyboard, the key-click feedback signal should be clearly perceivable to the typing finger but not to any of the fingers that are simply resting on the virtual keys. The present study attempts to address this second challenge of providing *localized* key-click feedback to enhance the experience of typing on a zero-travel virtual keyboard on large form factor display surfaces.

There have been numerous inventions for providing localized tactile feedback on a touch screen. Instead of vibrating the entire device, actuators can be mounted on the display glass plate or to the touch-sensitive glass only [11, 12]. By mechanically isolating the vibrating glasses from the casing, vibrotactile feedback can be directed towards the touching finger instead of the hand holding the device. Other mechanisms such as ultrasound-based air squeeze film effect [13] and electrovibration [14] can also effectively confine haptic effects on a touch surface without vibrating the whole unit. These solutions work well as long as only one finger touches the surface at a time. However, for multi-touch interactions such as full-size ten-finger touch-typing keyboards, the aforementioned solutions cannot offer localized tactile feedback for each of the fingers in contact with the screen. One way to achieve localized feedback is to restrict tactile feedback to a small area [15] or to construct multiple actuators with each actuator affecting only a small part of a screen [16]. The latter approach could be applicable to a full-size virtual keyboard (i.e., by mounting one actuator on each key of the keyboard), albeit at the cost of increased hardware complexity and decreased reconfigurability of the keyboard layout. This motivates us to investigate the optimal (and most economical) placement of actuators for delivering localized tactile feedback that can support touch typing on a virtual keyboard.

The present study takes a perception-based approach. Instead of aiming to achieve a surface with *physically* localized tactile feedback, we ask the question of *when a global tactile feedback is perceived to be local*. We hypothesize that with sufficient attenuation, a tactile feedback signal "leaked" from the touched location on a surface can become imperceptible to the fingers holding or resting on the device. This way, the system can effectively provide localized tactile feedback without instrumenting one actuator for every single key of the keyboard. Our hypothesis is based on observations made during a previous study of key-click feedback using a piezoelectric actuator mounted on the bottom half of a cellphone mockup [17]. When the user pressed on a virtual key at the center of the piezo, the key-click feedback signal appeared to originate from the virtual key underneath the thumb. However, when the user held the phone and let another user press the surface, the user holding the phone could perceive key-click feedback on the hand. In both cases, the mechanism of tactile feedback was the same, but the perception of the location of tactile feedback was different. This is a classic example of sensory *masking* which means "the reduced ability to detect the target signal in the presence of a background, or masking, stimulus" [18]. In the present study, we assume that the presence of a stronger tactile feedback on the finger actively pressing on the surface can make it harder for the passively resting fingers to feel a weaker version of the same feedback signal. We believe that we can take advantage of this phenomenon in constructing a typing surface on which a global tactile feedback signal *feels* local.

The goal of the present study is to measure the thresholds at which key-click feedback signals on passive fingers (the fingers resting on the screen) are masked by the signal on an active finger (the finger interacting with the screen). This initial investigation starts with two fingers, one actively pressing on a surface and the other passively resting on the surface. As a first step, we limit our study to the index and middle fingers of both hands using simple clicks. The results will inform the design of follow-up studies in which we plan to extend the experimental design to realistic ten-finger typing tasks.

2 Methods

2.1 Participants

Twelve volunteers (P1-P12; 6 males and 6 females; average age 27 years old, std. dev. 3.4 years old) participated in the experiments. Eight of the participants were right-handed and four were left-handed by self-report. The participants were not remunerated for their participation.

2.2 Apparatus and Stimuli

We constructed two identical stimulators with sensing and actuation capabilities. The stimulators resemble keys on a zero-travel virtual keyboard that are common on most mobile phones and touch screens. Unlike keys on most virtual keyboards, however, these stimulators could emulate the tactile feedback that the user would experience with mechanical keys. Each key in our experimental setup consisted of a two-layered piezoelectric actuator (a 22-mm ceramic disk mounted concentrically on a 35-mm metal disk; Figure 1a) sandwiched between two clear plastic layers with two force-sensing resistors (Standard 400 FSR with 4 mm diameter active area, Interlink Electronics, Inc., USA) attached to the bottom of the structure. Figures 1(b) and 1(c) show the top and bottom views of one key, respectively. In order to help participants place and maintain the positions of their fingers on the two keys, a red dot was glued on top of each flat surface (Figure 1b). Each key was then placed on a thick foam pad that served to isolate the vibrations of the key from the tabletop underneath it. The foam pads supporting the two stimulators were mechanically isolated with a 3 mm gap between them. The distance between the two red dots measured 32 mm. The keys and the foam pads were housed inside a clear box measuring 360 mm (length) × 270 mm (height) × 270 mm (depth) with an open front for the participant's hand and forearm. During the experiment, the top and the front of the box were covered to prevent the participant from viewing the fingers. In addition, the participant listened to pink noise and wore noise-reduction circumaural headphones (Peltor H10A Optime105 with 29 dB attenuation, 3M Corporation, USA) to block any auditory cues from the experimental apparatus. The clear side panels of the box allowed the experimenter to observe and reinforce the placement of the participant's fingers on the two red dots. Figure 1(d) shows the experimental setup without the visual covers.

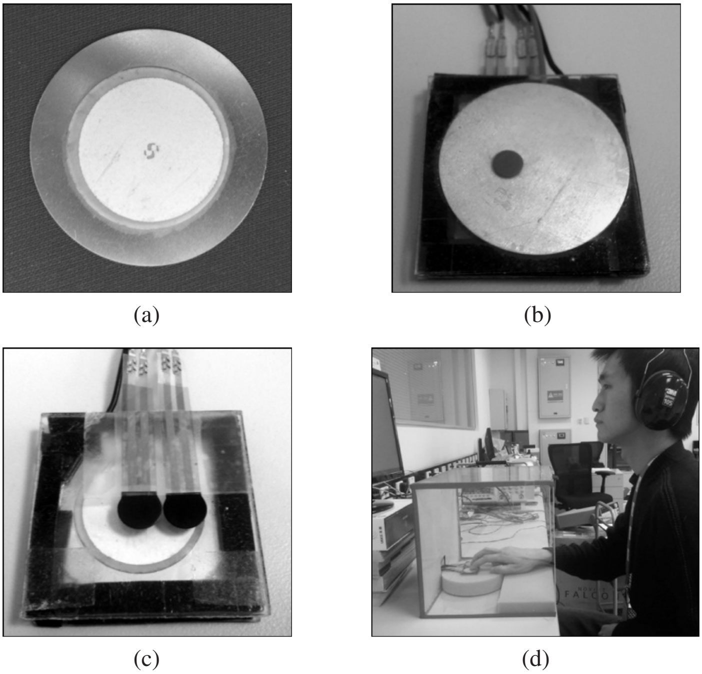


Fig. 1. (a) One side of the piezoelectric actuator showing both the ceramic and metal disks. (b) Top view of one stimulator key. (c) Bottom view of one stimulator key. (d) Experimental setup without the visual covers.

When a finger pressed a key, the FSRs were triggered and a waveform was sent to the piezoelectric actuator to deliver a key-click feedback signal to the finger. We used the two output channels of a sound card (SoundBlaster SB0100, Creative Technology, Ltd., Singapore) to independently control the waveforms sent to the two keys. The outputs of the sound card went through a voltage amplifier with a gain of 100 (Dual

Channel High Voltage Precision Power Amplifier, Model 2350, TEGAM Inc., USA) before driving the piezoelectric actuators on the two keys. The experimental application was coded in Visual C++ and OpenGL.

The waveform sent to each piezo consisted of one cycle of a raised sinusoidal pulse at 500 Hz. In a previous study, it was found that the piezo response to a single-cycle 500-Hz input signal felt like a "crisp" key click [17]. Acceleration at the red dot (Figure 1b) was calibrated using a triaxial accelerometer (8688A50, Kistler Group, Switzerland) under unloaded condition (i.e., without the finger pressing or resting on the instrumented key). Note that finger loading was expected to have a negligible effect on the piezo response at the relatively high frequency of 500 Hz (e.g., see [19]). The peak acceleration ($m \cdot s^{-2}$) changed linearly with the peak-to-peak (ptp) input voltage (V) with a gain of 0.0683 ($m \cdot s^{-2} \cdot V^{-1}$). At an input voltage of 100 V ptp, this corresponded to a peak acceleration of 6.83 $m \cdot s^{-2}$. The waveform for the finger that passively rested on the key was similar except that the amplitude changed according to an adaptive procedure (see the next section). In the rest of this article, we specify signals in terms of the input voltage (ptp) to the piezoelectric actuator.

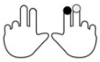
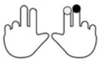
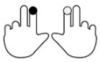
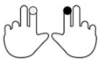
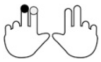
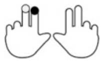
2.3 Procedure

We used a well-established psychophysical method called the "three-interval, one-up and one-down method" that adapts to the participant's performance level [20, 21]. On each trial, the participant was asked to "press down on the pad as if typing on a keyboard" three times (the three "intervals"). Each time, a tactile feedback signal with amplitude A_{active} was sent to the active finger as soon as the FSRs detected a key strike. During one randomly-selected interval, the passive finger received a tactile feedback signal with amplitude $A_{passive}$. The passive finger received no feedback signal during the other two intervals. The participant was asked to indicate during which interval (first, second, or third) the passive finger felt a signal by saying "one," "two" or "three". The experimenter then entered this response on a computer keyboard. It was necessary for the experimenter to enter the responses for the participant because some of the experimental conditions required the participant to place both hands inside the box containing the two keys. This was a forced choice paradigm and the participants had to make a guess if they were not sure.

According to the "one-up, one-down" adaptive rule, $A_{passive}$ was increased after each incorrect response (to make the task easier) and decreased after each correct response (to make the task harder). A_{active} was kept the same at 228 V ptp after each key press. For each series of trials, the initial value of $A_{passive}$ was always 200 V ptp. It changed by 2 dB during the first 4 reversals (a reversal is defined as $A_{passive}$ changing from increasing to decreasing, or vice versa) and by 1 dB during the remaining 12 reversals. The larger step size (2 dB) allowed the $A_{passive}$ level to converge to the expected threshold quickly, and the smaller step size (1 dB) ensured the resolution of the estimated threshold.

There were six experimental conditions that differed in the fingers used and the assignment of active and passive fingers (see Table 1). Conditions C1 and C2 involved the index and middle fingers of the right hand, C3 and C4 involved the index fingers of both hands, and C5 and C6 involved the index and middle fingers of the left hand. At the beginning of each condition, the participant was told which finger was the active finger and which was the passive finger. Training was provided so the participant could become familiar with the task. During the training, the amplitude of $A_{passive}$ was kept constant at 200 V ptp. Correct-answer feedback was provided after each trial. The order of conditions was randomized for each participant. The total number of trials for each condition was between 25 to 48 trials. It took each participant up to 50 minutes to complete all six conditions.

Table 1. Experimental conditions

Condition	**C1** 	**C2** 	**C3** 	**C4** 	**C5** 	**C6** 
Hand	Right		Both		Left	
Active finger	Index	Middle	Index (L)	Index (R)	Middle	Index
Passive finger	Middle	Index	Index (R)	Index (L)	Index	Middle

Note: Filled and open circles on the fingertips indicate the active and passive fingers, respectively.

Prior to the main experiment, we ran a pilot test to investigate the possible effect of feedback signal strength on masking thresholds. Three of the twelve participants took part in the pilot study. In addition to the six conditions listed in Table 1 where A_{active} was kept at 228 V ptp, the three participants were also tested with another set of the same six conditions with an A_{active} of 100 V ptp. The order of the twelve conditions was randomized for each participant. The results indicated that the amplitude A_{active} did not have a significant effect on the thresholds. Therefore, the remaining nine participants were tested using one amplitude value of 228 V ptp.

2.4 Data Analysis

Figure 2 shows a series of trials for one participant under condition C2 that is reasonably representative of all participants across all conditions. The local maximum values (peaks) and minimum values (valleys) of the last 12 reversals at the 1-dB step size were extracted from the recorded values of $A_{passive}$ in dB re 1V. The 12 peaks and valleys were then averaged to obtain an estimate of the threshold at which the passive finger could barely detect the feedback signal. The threshold was then converted to the corresponding attenuation from A_{active} to $A_{passive}$. For example, in the plot shown in Figure 2, the threshold for $A_{passive}$ was 36.3 dB re 1V. Since A_{active} was 228 V ptp (i.e., 47.2 dB re 1V), this corresponded to a minimum attenuation of 10.9 dB in order for the feedback signal on the passive finger to be unnoticeable. We report experimental results in terms of this ***attenuation threshold***, calculated as $20 \times \log_{10}(A_{active}/A_{passive})$. We ran an analysis of variance (ANOVA) and *post hoc* Tukey tests, all with $\alpha = .05$.

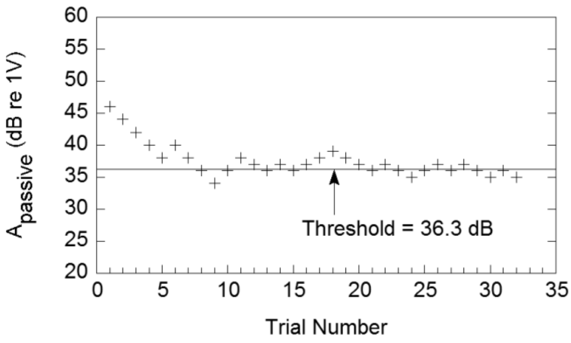


Fig. 2. A typical series of trials for condition C2 for one participant. Shown are the levels of $A_{passive}$ (dB re 1V) that changed adaptively to the participant's responses, while A_{active} was kept at 228 V ptp (47.2 dB re 1V).

3 Results

Figure 3 shows the attenuation thresholds obtained from all twelve participants under the six experimental conditions at a feedback signal strength of A_{active} = 228 V ptp on the active finger. We observe a trend that thresholds for conditions C3 and C4 were higher than those from the other four conditions. A one-way ANOVA confirmed that condition was indeed a significant factor ($F_{5,426} = 79.34$; $p < .0001$). A post hoc Tukey test showed three groups of thresholds: C4 (μ = 19.7) and C3 (μ = 19.2); C1 (μ = 12.5), C6 (μ = 12.1) and C2 (μ = 11.0); C6, C2 and C5 (μ = 10.2). The fact that C2 and C6 belong to both of the latter two groups indicates that the main difference among the six experimental conditions has to do with whether one hand or both hands were tested. This was further confirmed with a one-way ANOVA with the factor hand combination (right hand alone, both hands, left hand alone). It was found that hand combination was a significant factor ($F_{2,429} = 187.61$; $p < .0001$), and a post hoc Tukey test showed two groups of thresholds: both hands (μ = 19.4), right hand alone (μ = 11.7) and left hand alone (μ = 11.1). Therefore, when both hands are involved, the passive finger is more sensitive and larger signal attenuation is needed from the active to the passive finger.

Among the four conditions C1, C2, C5 and C6, there is an apparent trend for attenuation thresholds to be higher when the middle finger is passive (C1 and C6) than when the index finger is passive (C2 and C5). This suggests a higher sensitivity of the middle finger than the index finger when the active finger is on the same hand. Could this trend reflect a bias in the way the participants allocated their attention to the two fingers? Note that we did not explicitly instruct the participants to focus more on an active vs. a passive finger or an index vs. a middle finger. To gain insight into attention allocation, the participants were debriefed after the experiment. They were asked to describe the strategies they used to perform the experimental task. The participants reported that they tried to maximize the focus on the passive finger while ignoring the sensations on the active finger. They also commented that the task appeared more difficult when one hand instead of both hands were involved. These anecdotal notes support the general trend of the data, but do not explain the apparent higher sensitivity of the middle finger as suggested by the data in Figure 3.

There were significant inter-participant differences, as confirmed by a one-way ANOVA ($F_{11,420} = 11.59$; $p < .0001$). A post hoc Tukey test showed mainly two groups of thresholds: P2 and P3 ($\mu = 8.3$ and 9.8, respectively); P1 and P4-12 ($\mu = 12.8$–17.8). Note that ten of the twelve participants required a higher attenuation threshold in order for the key-click feedback signal not to be noticed by the passive finger. If we can develop a virtual keyboard that can satisfy the more demanding requirements of this majority, then it will be guaranteed that the key-click feedback signals will feel localized to the remaining two participants (P2 and P3).

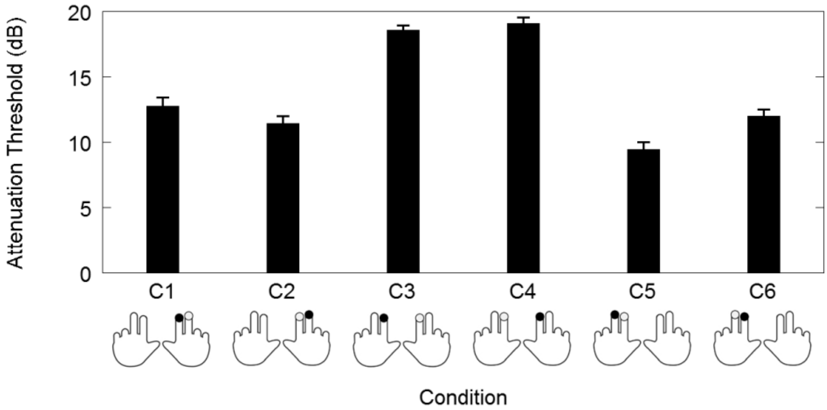


Fig. 3. Attenuation thresholds for all twelve participants from the main experiment. Shown are the average attenuation thresholds and the standard errors.

4 Discussion and Conclusions

In this initial study on global vs. local tactile feedback on a large form factor soft keyboard, we asked the question of whether it is necessary to instrument the individual areas occupied by each key in order to achieve localized tactile feedback. We hypothesize that people will attribute tactile feedback to the key being pressed, even with global tactile feedback, provided that the tactile signal on other parts of the surface is sufficiently attenuated. To this end, we measure the thresholds at which a tactile signal is barely perceptible to a finger that is resting passively on a surface while another finger actively presses on the surface and receives a key-click feedback signal. We report this threshold in terms of $20\times\log_{10}(A_{active}/A_{passive})$, called the attenuation threshold, that specifies the difference in signal strength between the active and passive fingers, for two reasons. We chose to use a log scale instead of a linear scale to report signal amplitude because it is well established that perceived magnitude of vibrations grows linearly with the log of vibration amplitude [18]. We also chose to report attenuation threshold, instead of $20\times\log_{10}(A_{passive})$, because the former appears to be independent of the overall signal strength, based on the results of a pilot study (see below).

Before the main experiment, we conducted the pilot study with three participants to investigate the effect of feedback signal strength using two A_{active} levels: 100 V ptp and 228 V ptp. For a 7.2 dB [i.e., $20\times\log_{10}(228/100)$] change of reference signal strength, the average difference in attenuation threshold across all six experimental conditions changed by only 0.1 dB. The same average difference specified in $20\times\log_{10}(A_{passive})$ would have been 7.1 dB. In other words, when A_{active} increased by 7.2 dB, the measured threshold $20\times\log_{10}(A_{passive})$ increased by almost the same amount (7.1 dB), whereas the corresponding attenuation threshold $20\times\log_{10}(A_{active}/A_{passive})$ remained almost constant. This finding supports the use of the relative measure, *attenuation threshold*, as a more parsimonious way to specify the conditions under which a tactile feedback signal on the passive finger can be effectively masked by the signal on the active finger. Based on the results of the pilot study, we were also able to decide that subsequent data collection could proceed at one feedback signal level on the active finger.

From the results of the main experiment, the attenuation threshold averaged over all experimental conditions was about 14.1 dB, corresponding to an A_{active} over $A_{passive}$ ratio of roughly 5. That such a threshold exists, as opposed to an $A_{passive}$ value of 0 before the key-click feedback on the passive finger could no longer be detected, confirms that people can indeed attribute a global tactile feedback to the key being pressed by the active finger, provided that the intensity of the signal "leaked" to the passive fingers are below the measured thresholds.

Another major finding of the present study is that larger signal attenuation is needed when the index fingers of both hands are involved (average of C3 and C4 = 19.5 dB) than when the index and middle fingers of the same hand are involved (average of C1, C2, C5 and C6 = 11.5 dB). This finding is consistent with the optical imaging data reported in [22]. Li *et al.* studied the neuromechanism for the tactile funneling illusion, where stimulation to two locations on the skin (e.g., index and middle fingertips) can be felt at a point between the two locations (e.g., a point in space between the two fingers) where no physical stimulus exists. They showed that stimulation to two adjacent fingers on squirrel monkeys resulted in one fused activation area between the known topographic locations for the two fingers on the primary somatosensory cortex, but stimulation to two non-adjacent fingers resulted in two distinct activation areas at the expected topographic locations. The stimulation method used in our present study was not conducive to eliciting the tactile funneling illusion because of the key-pressing action required of the active finger. However, it is conceivable that, for conditions C1, C2, C5 and C6 where two adjacent fingers received tactile feedback, the neural representation might have been less distinct in their locations on the somatosensory cortex than those for conditions C3 and C4 where two non-adjacent fingers were stimulated. This would help to explain why masking of tactile feedback signal is less effective for fingers of different hands.

In light of Li *et al.*'s (2003) findings, it may be predicted that the attenuation thresholds for two non-adjacent fingers on the same hand (e.g., index and ring fingers) should be similar to those of conditions C3 and C4 (index fingers of both hands) rather than those of the remaining four conditions (adjacent fingers of the same hand). This however turned out not to be the case. A follow-up experiment was conducted with three of the twelve participants under four conditions that were almost the same as C1, C2, C5 and C6 in the main experiment except that the middle finger was replaced with the ring finger. The attenuation thresholds involving the index and ring fingers were very similar among the four conditions tested and averaged 13.1 dB, which was similar to the average of 11.5 dB obtained with the index and middle fingers under four similar conditions in the main experiment. Therefore, whereas Li *et al.*'s study predicts a marked difference in perception based on whether the stimulated fingers are adjacent, our results show a difference in masking thresholds based on whether the stimulated fingers are on the same hand. Without further investigation, it is not exactly clear why the results of our follow-up experiment do not follow the prediction of Li *et al.*'s study. The discrepancy may be attributed to the fact that Li *et al.* used a passive perception task whereas our present study required the participants to actively press on a key.

The present study examined only one passive finger, but touch typing on a full-size soft keyboard may involve up to nine passive fingers. In the future, we will investigate how attenuation thresholds may change when, for example, the index finger is active and any combination of the rest of the fingers of the two hands are passive. An increase in the number of passive fingers to be monitored may enhance the masking effect (i.e., lower attenuation thresholds). Furthermore, the simple click task used in the present study may not reflect the differential attention allocation to different fingers during a real typing task. It is conceivable that when people are asked to type a pre-specified passage of text, they will focus their attention mostly on the active finger for the typing task, making the passive fingers less sensitive to "leaked" tactile feedback signals, further lowering attenuation thresholds. Any decrease in attenuation thresholds is welcomed news because it will decrease the amount of signal attenuation needed for tactile feedback on a virtual keyboard.

Ultimately, the results of the present and future studies will provide quantitative engineering specifications for the development of a tactile feedback system that supports faster and more enjoyable touch typing experience on flat surfaces with strategically placed actuators. For example, based on the result that people are more sensitive to leaked tactile feedback when the active and passive fingers are on different hands, we can propose the use of two actuators with maximum mechanical isolation, one for each hand, to be placed under the left and right halves of a soft keyboard. The attenuation thresholds obtained from the present and future studies can provide the quantitative specifications for how much signals can "leak" on each half of the proposed virtual keyboard before they become noticeable. Additional actuators and mechanical isolation among them can be deployed if sufficient signal attention cannot be realized with one actuator per hand. We believe that in the near future, we can take advantage of sensory masking and use human perception threshold data to construct a typing surface on which a global tactile feedback signal *feels* local, thereby supporting a more natural and pleasant typing experience on slate surfaces.

Acknowledgment. The authors thank Jaeyoung Park of Purdue University for his assistance with statistical data analysis. We thank Koji Yatani, Darren Edge, and Gunhyuk Park for comments and discussions on an earlier version of this article.

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