Effect of Information Content in Sensory Feedback on Typing Performance using a Flat Keyboard

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Abstract— **We investigate the effect of information content in sensory feedback on typing performance using a flat keyboard. We build a flat keyboard apparatus with haptic and auditory keyclick feedback. We evaluate and compare typing performance with key-press confirmation and key-correctness information through sensory feedback. Twelve participants are asked to touch-type a number of randomly selected phrases under various combinations of visual, auditory and haptic sensory feedback conditions. The results show that typing speed is not significantly affected by the information content in sensory feedback, but the uncorrected error rate is significantly lower when key-correctness information is available. The results also show that key-correctness information leads to more corrected errors and lowers typing efficiency. Our findings are useful for developing flat keyboards with assistive information through sensory feedback. Our study is the first step towards improving typing performance on flat keyboards by delivering more advanced and comprehensive assistive information beyond the visual channel.**

I. INTRODUCTION

This paper presents a study on the effect of information content in sensory feedback on typing performance using a flat keyboard. We use the term flat keyboard to refer to keyboards with keys that do not move when they are pressed. A soft keyboard is one example of a flat keyboard and it is widely available on mobile devices with touchscreens. Another example of a flat keyboard is an external pressure-sensitive keyboard like Microsoft's Touch Cover keyboard [1]. The difference between an on-device soft keyboard and an external pressure-sensitive keyboard is that the latter can have a top surface that provides tactile cues for the keyboard layout, such as the embossed fabric top of the Touch Cover. This makes it possible for the user to rest fingers on the home row and perform touch typing (i.e., typing without looking at the keyboard). Both types of flat keyboards are convenient to use, but the resulting typing performance is typically inferior to that with full-size physical keyboards.

Many researchers, ourselves included, have investigated the role of sensory feedback on typing performance. A number of studies found that tactile information significantly affects typing performance [2] [3] [4]. Gordon et al. [3] studied the use of tactile afferent information in sequential finger movements using typists with anesthetized fingertips and found that tactile information from the keyboard keys affects typing error rates. Rabin et al. [4] found that tactile feedback contributes to the consistency of finger movements during

touch typing. Hoggan et al. [5] studied the effectiveness of haptic feedback on touchscreen keyboard using smartphones. In their study, they compared typing on three keyboards: i) physical keyboard; ii) standard touchscreen (no haptic feedback); and iii) touchscreen with vibrotactile feedback. They showed that the additional haptic feedback can significantly improve fingertip typing performance on the touchscreen keyboard. Lee et al. [6] compared the performance of soft buttons with haptic and auditory feedback. In their study, several experiments were conducted with different feedback conditions (auditory only, haptic only, both auditory and haptic, and no feedback) to explore the performance difference among the conditions. The results showed that both auditory and haptic feedback improve the soft button click performance, but no further improvement is achieved when they are combined. Bender [7] studied touchscreen keypad performance as a function of the duration of auditory feedback to determine if touchscreen keypad entry speed and/or accuracy can be improved by the introduction of an auditory feedback signal. The study evaluated the effect of the duration of auditory feedback (between 12.5 and 800 *ms*) for ten-key keypad entries on a touchscreen and found the appropriate duration to be between 50 and 400 *ms*.

In sensory feedback design, it is important to optimize the consistency among modalities and the intended meaning of feedback signals. Several studies indicated that certain properties of auditory and haptic feedback such as rhythm, texture and tempo are critical for information mapping. Hoggan et al. [8] focused on the meanings that can be delivered by auditory and haptic feedback and how the information can be congruently mapped to sensory feedback. They discovered that some signal properties play an important role in certain scenarios. For example, rhythm and location were ranked higher in a confirmation scenario and texture and tempo were ranked higher in an error notification scenario. Brown et al. [9] studied multidimensional haptic messages for non-visual information presentation. In their study, a single haptic message can represent several dimensions of information by encoding each dimension with a different signal property such as rhythm, roughness, and spatial location. Their work showed the possibility to communicate multi-dimensional information through haptic messages when non-visual information is required in mobile devices.

Sensory feedback from the keyboard also conveys information and multiple meanings can be represented based on how information is encoded into sensory feedback. Given

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that typing is a motor activity, each transcribed letter displayed on the screen provides keypress confirmation that allows the users to type faster with less errors. At the same time, the typist also perceives haptic feedback of key depression and release, and the auditory sound from the keyboard. Visual feedback of each transcribed letter together with haptic and auditory feedback from the keyboard carry the information that the key entry has been made. Visual feedback also carries the key-identity information of which letter has been entered. This makes it easier for typists to correct typing errors, reducing uncorrected error rates significantly [10]. Given the fact that about a half of typing errors are detected by visual feedback [11], the key-identity information of transcribed letters reduces a large amount of uncorrected errors.

Further sensory information can be delivered through visual feedback during typing. In word processing applications such as Microsoft's Word, the spell checker detects the incorrect input letters based on dictionary words and puts a red squiggly underline under the word that contains the errors. This visual feedback of a red squiggly underline carries the information that there exists one or more errors in a word. Similar visual feedback for typing assistance include auto correction, key enlargement, and word prediction that are available in most soft keyboards. The auto correction feature automatically corrects typing errors based on similar words from the dictionary [12]. Key enlargement is typically useful on small devices like smartphones by enlarging the pressed keys for key entry confirmation. The word prediction feature is also widely used in soft keyboards where several candidate words are displayed based on the first few input letters in order to reduce the number of key inputs required. The above-mentioned visual feedback shows the power of information delivery through visual cues. It would be worthwhile to explore the possibility of extending visual information delivery into non-visual sensory feedback like haptic and auditory feedback by creating new keyclick sensation and sound.

We define the following three types of information that can be encoded into visual, haptic and auditory feedback during typing on a flat keyboard, in order of increasing information content.

- **Key-entry information** provides confirmation for each key entry. Every time a key is pressed, key entry information can be delivered through visual, haptic, and/or auditory modalities. For visual feedback, the transcribed letter is displayed on the screen. Each transcribed letter itself represents key entry confirmation although it also reveals key-identity information of which letter has been entered. For haptic feedback, a keyclick-like signal is delivered to the typing finger. For auditory feedback, a beep sound is played to confirm a key entry.

- **Key-correctness information** provides information on whether the correct key has been pressed. Different signals can be sent depending on whether the input letter is correct or incorrect. This binary information can be helpful for faster error detection and possibly leading to earlier error correction (i.e., correcting typing errors as soon as they occur as opposed to waiting until after an entire word or phrase has been typed). Visual feedback can encode the key-correctness information using different colors. For example, the incorrectly transcribed letters are displayed in red while the correctly entered letters are displayed in black. Auditory keyclick feedback can encode the key-correctness information by using two different auditory beep sounds, one for correctly-typed letters (e.g., a lower pitch sound) and the other for incorrect keystrokes (e.g., a higher pitch sound). Haptic keyclick feedback can encode the key-correctness information by using two different haptic signals (e.g., two keyclick feedback signals at different durations). Note that key-correctness information always contains key-entry confirmation.

- **Key-identity information** provides information on which letter has been entered for each key press. Key-identity information can be conveyed using either visual or auditory modalities, and it is difficult to do so through haptic feedback. For visual feedback, the displayed letter provides the identity of the letter just entered. For auditory feedback, a speech sound of the alphabet can be played to identify the letter. However, it is not clear that such auditory feedback is suitable during high-speed typing. Similar to key-correctness information, key-identity information always implies key-entry confirmation.

Key-entry confirmation is the most basic information among the three as it provides only information that a key has been pressed. Key-entry confirmation has been examined in a number of studies on the effect of sensory feedback on typing on a flat keyboard [5] [6] [10]. Since a number of studies have already investigated key-entry confirmation, it is not the focus of our present study. Key-correctness information goes beyond key-entry confirmation by indicating whether the key just pressed is correct or incorrect, either compared to text to be transcribed or based on a dictionary corpus. Visual, haptic and auditory feedback can all provide sensory feedback that encode key-correctness information. Such feedback can be combined with word prediction algorithms to develop real-world applications. Key-identity information is usually presented visually. Auditory feedback can encode the key-identity information using speech, but it is uncertain that it is suitable for high speed typing. It would be extremely difficult, if not impossible, to encode key identity via haptic feedback. It is therefore beyond the scope of the present study to compare key-identity feedback through different sensory modalities.

In the present study, we examine how the addition of key-correctness information in sensory feedback can benefit typing performance on flat keyboards. We note that many typing studies mix sensory feedback with different levels of information content (visual letter feedback vs. auditory/haptic keyclick feedback) [5, 13]. There is therefore a need to "equalize" the information content in sensory feedback when making comparison of typing performance under different sensory feedback conditions. The present study aims to fill this gap.

A. Participants

We recruited 12 participants (6 females; mean age: 23.0 ± 4.3 years old; all right handed by self-report) for this experiment. They were all touch typists who can type 50 or more words per minute, and were compensated for their participation.

B. Apparatus

We built a flat keyboard apparatus with haptic and auditory keyclick feedback (see [10] for a full description of the keyboard apparatus). The flat keyboard had an embossed rubber cover that provides tactile cues on the locations of individual keys, but the flat keys did not move downward when they are pressed. This was achieved by separating the USB-based keyboard matrix circuit from all the mechanical keys and dome structures for key depression and release on a regular keyboard (compatible with Apple's A1242 model). We replaced the moving parts with 15×15 mm foam pads for each key while keeping the keyboard matrix circuit inside the keyboard intact (see Figure 1). The stiff foam pads prevent the downward movement of the keys when pressed and any false trigger due to fingers resting on the home row. The circuit consists of three layers. The top and bottom layers had circular conductive buttons and they were insulated by the middle layer. When a key was depressed, the foam pad triggered the two conductive buttons through the trigger attached under the foam pad to make an electrical connection through the hole in the middle layer. This way, the key press sensing mechanism remains the same as the original keyboard.
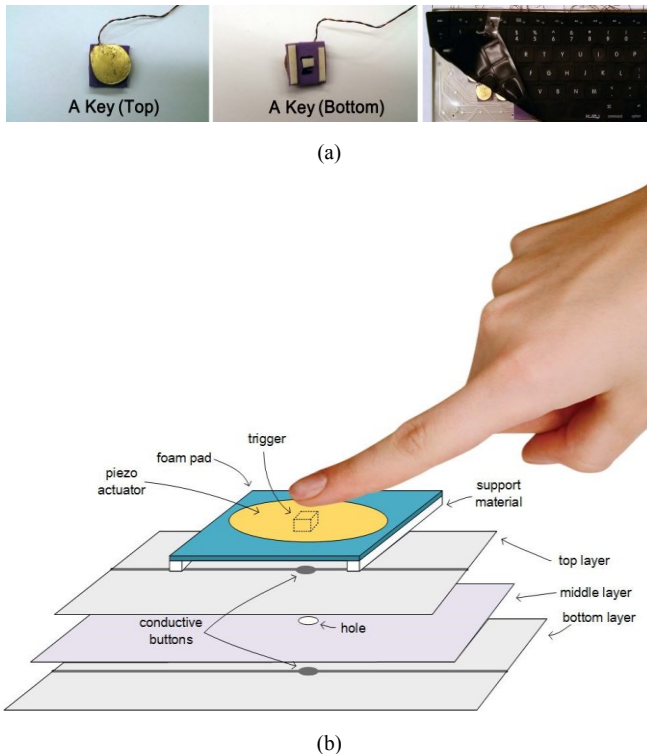

(a)

(b)

Figure 1. (a) Views of one key with the piezoelectric actuator (left and middle) and under the rubber keyboard cover (right) and (b) a schematic drawing of a key press

Haptic keyclick feedback was delivered through piezoelectric (*piezo* for short) actuators. They were made of 14-mm diameter ceramic disks mounted concentrically on 20-mm diameter metal disks (Murata Inc, Japan) that were cut to 14-mm diameter to fit between keys and the square foam pads (see Figure 1). In order to create a keyclick-like sensation using the piezo actuators, a 500-Hz sinusoidal signal was generated through the audio channels (stereo: left and right) of a PC whenever a key press was sensed. The waveform was then sent to input channels of a high voltage amplifier (Dual Channel High Voltage Precision Power Amplifier, Model 2350, modified to have a gain of 100, TEGAM Inc., USA). The amplified signal was sent to the corresponding piezo actuator through high voltage analog switches (HV20822, Supertex, Inc., USA) to deliver the haptic keyclick feedback. The high voltage analog switches were controlled by an Arduino Microcontroller unit (ATmega168, Clock Speed: 16MHz, Arduino Diecimila, Italy), which is in turn controlled by a keyboard agent to independently drive the piezo actuators to route the amplified signals to each key.

The construction of the keys as described above provided localized keyclick feedback in the sense that the haptic feedback is felt by the typing finger only. For example, if the 'a' key was pressed, a keyclick feedback signal was generated through the left channel of the sound card, amplified through the first channel of the high voltage amplifier, and then routed to the group of keys being assigned to the left little finger (i.e. 'a', 'q', and 'z' keys) to deliver localized keyclick feedback. For more details of our apparatus and its settings, please refer to [10].

C. Procedures

We conducted a multi-finger touch-typing experiment to measure the typing performance on the flat keyboard apparatus as shown in Figure 2. During the experiment, we covered the keyboard apparatus with a black cloth to block any visual cues from the participants' fingers and the keyboard apparatus, allowing the participants to focus their visual attention only on the computer monitor. Therefore, the participants had to perform eyes-free typing without looking at the keyboard. We asked the participants to keep their non-typing fingers on the home row and monitored their compliance using a webcam placed inside the cover. All participants listened to pink noise from an earphone and in addition wore a circumaural noise-reduction headphone (Peltor H10A Optime105 with 29 dB attenuation, 3M Corporation, USA) to block any auditory cues. For the conditions involving auditory feedback, a beep sound was played through the earphone instead of the pink noise.

During the experiment, combinations of visual, auditory and haptic feedback were used to study sensory feedback with two levels of information content: key press confirmation only without key identity, and key correctness feedback without key identity. We hid key-identity information in visual feedback by using an asterisk character for each key entry in order to evaluate the effect of key-entry and key-correctness information. For key press confirmation, visual feedback was delivered as an asterisk (in black), auditory as a beep (lower pitch) and haptic as a keyclick. For key correctness feedback, visual feedback was shown as an asterisk character in black if the correct key was entered or in red if the incorrect key was pressed. Auditory key correctness feedback was delivered as

the lower-pitch beep if the correct key was pressed and a higher-pitch beep if the incorrect key was pressed. For haptic key correctness feedback, one cycle of a 500-Hz raised sinusoidal waveform with a duration of 2 *ms* was delivered to the piezos if the correct key was pressed, and ten cycles of a 500-Hz sinusoidal waveform with a duration of 20 *ms* was used if the incorrect key was entered. The former signal felt like a buckling of the key while the latter signal felt more like a vibration.
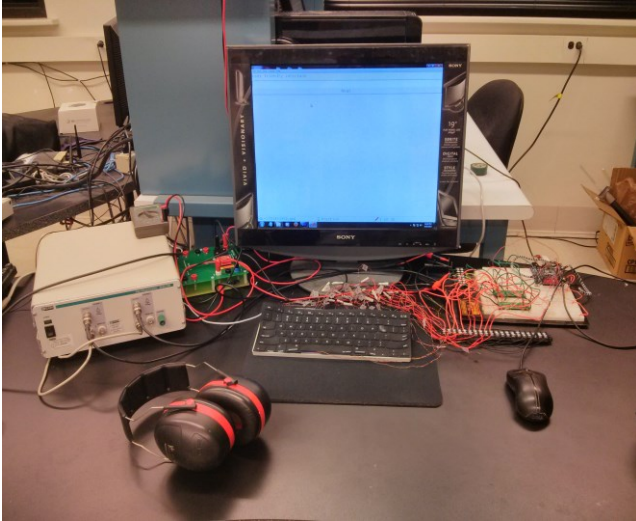
(a)

(b)

Figure 2.   (a) Experimental setup and (b) actual typing experiment.

There were six experimental conditions. We use a lower case letter ("*v*" for visual, "*a*" for auditory, "*h*" for haptic) to denote conditions with key entry confirmation only and an upper case letter ("*V*", "*A*", "*H*") to denote conditions with key correctness information. The conditions were *v*, *va*, *vh*, *V*, *vA*, and *vH*. We believe that testing the selected six conditions out of all possible combinations is a first step towards understanding the benefits of information content in sensory feedback since we compare each modality with two levels of information content. Across all the conditions, we always

provided visual feedback (asterisk character) since it is almost impossible to type without visual feedback. The entire experiment took about an hour per participant.

There existed a potential discrepancy in the duration of key-correctness feedback signals among the different sensory modalities. In the *vA* and *vH* conditions, the participants were informed of the incorrect key inputs for a short duration (20 *ms*) when the auditory or haptic feedback signal was delivered. In the *V* condition, however, the participants could see the red color of the incorrect characters until the end of each phrase. We observed that the typists' visual attention was usually focused on the phrase that they need to type and checks the actual transcribed letters occasionally. Considering that typists' visual cue was not always focused on the transcribed letters, 20 *ms* might be too short a duration for the visual feedback to be noticed. In order to roughly equalize the amount of time that key-correctness feedback signals were noticed across the conditions, we conducted a pilot test and selected 200 *ms* as an appropriate duration for each incorrect character to be displayed in red before the color changes back to black.
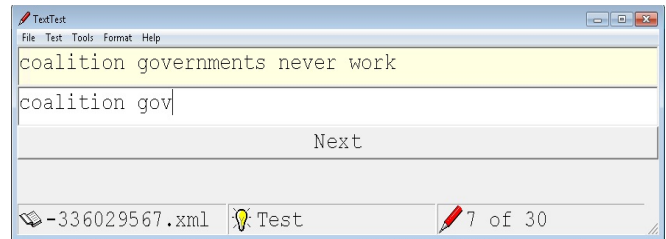

Figure 3.   TextTest typing tool.

We used a common typing test tool called TextTest (see Figure 3) and a common typing analysis tool called StreamAnalyzer [14], with the commonly-used MacKenzie phrase set [15]. Twenty five phrases were randomly selected from the MacKenzie phrase set for each condition and the first five out of the twenty five phrases were used for practice. We asked the participants to type as fast and as accurately as possible. We held the *"recommending"* error correction policy in that the participants were asked to correct any typing errors that they detected or felt that they made during the typing task [16], but the correction of all errors was not mandatory. The participants were asked to take a break between experimental runs in order to avoid fatigue. Baseline typing performance was also measured for each participant with a regular desktop keyboard at the beginning of the experiment (*baseline* for short).

D. Data analysis

For typing performance metrics, we considered typing speed, typing efficiency and typing error rates. Typing speed was measured in words per minute (WPM) as

$$WPM = \frac{|T| - 1}{S} \times 60 \times \frac{1}{5}$$

where $|T|$ is the length of the transcribed string in number of characters and S is the time in seconds from the first keystroke to the last [17]. We subtract 1 from $|T|$ to remove the time for

typing the first character from the calculation of inter-character speed. The average length of a *"word"* is reported to be 5 characters [18] and we multiply the speed by 60 to convert the unit from words per second to words per minute.

Typing efficiency was measured in keystroke per character (KSPC) [19]. KSPC is widely used in typing studies and it is the ratio of the length of input string to the length of transcribed text string. KSPC is calculated as

$$KSPC = \frac{|IS|}{|T|}$$

where *IS* (Input Stream) is the length of the input string. KSPC considers the cost of committing errors and fixing them so it provides a general idea of how efficient the typing process is [16]. KSPC is 1.0 for the ideal case of no error corrections. It is greater than 1.0 when errors are found and corrected.

Typing error rate was measured using two metrics [20]: uncorrected and corrected error rates. The uncorrected and corrected error rates are calculated as

$$Uncorrected\ Error\ Rate = \frac{INF}{C + INF + IF} \times 100\%$$

$$Corrected\ Error\ Rate = \frac{IF}{C + INF + IF} \times 100\%$$

where *INF* (Incorrect Not Fixed) is the number of wrongly-typed characters that are not fixed, *IF* (Incorrect Fixed) is the number of wrong characters fixed, and *C* (Correct) is the number of correctly-typed characters. As shown in the equation, the uncorrected error rate measures the ratio of the number of incorrect characters to the total number of correct, incorrect, and corrected characters. In the same manner, the corrected error rate measures the ratio of the number of corrected characters to the total number of correct, incorrect, and corrected characters. The total error rate is the summation of uncorrected and corrected error rates. Since the total error rate computes the ratio of the total number of incorrect and corrected characters to the total effort to enter the text, it can provide a general idea of how participants handled the typing errors [16]. The total error rate is calculated as follows:

$$Total\ Error\ Rate = \frac{INF + IF}{C + INF + IF} \times 100\%$$

The performance metrics were analyzed with an one-way analysis of variance (ANOVA) and *post hoc* Tukey tests, all at a significance level of $\alpha = .05$. For multivariate effect, a multivariate analysis of variance (MANOVA) was also performed.

III. RESULTS

A. *Typing speed in words per minute*
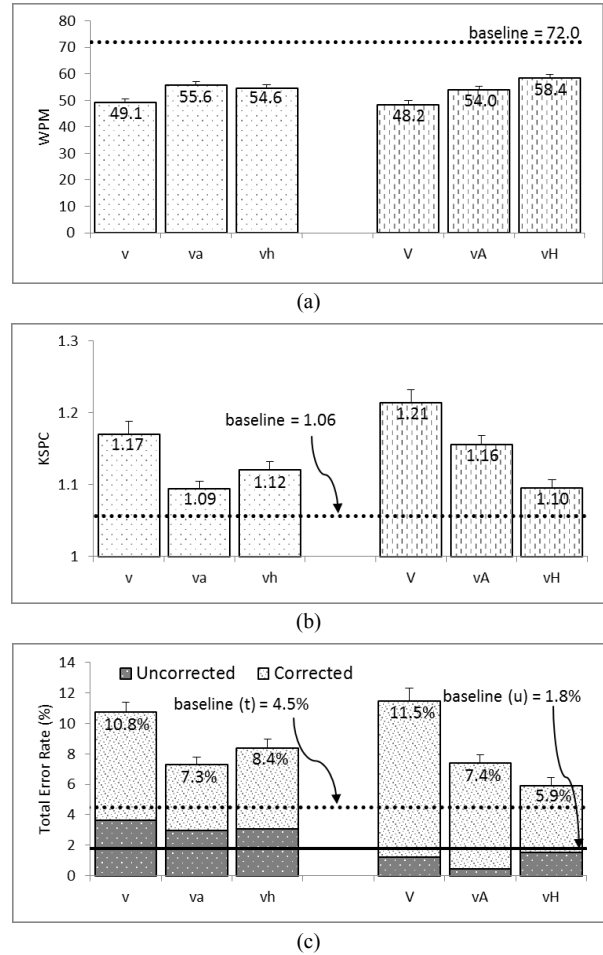

(a)

(b)

(c)

Figure 4. Experiment results in (a) typing speed, (b) typing efficiency, and (c) error rates. Error bars indicate standard errors.

Figure 4 shows the results of the experiment. Figure 4(a) shows the typing speed in words per minute averaged over all participants for each feedback condition. The average typing speed was 49.1, 55.6, and 54.6 words per minute for *v*, *va*, and *vh*, respectively, and 48.2, 54.0, and 58.4 words per minute for *V*, *vA*, and *vH*, respectively. The baseline average typing speed was 72.0 words per minute (dotted line in Figure 4(a)). We observed a trend that the average typing speed was relatively lower in the visual only conditions (i.e. *v* and *V*). However, we could not find any increasing or decreasing trend between *vh* and *va*. Neither could we find any increasing or decreasing trend between *va* and *vA* or between *vh* and *vH*. We observed that the *baseline* was significantly higher than any other conditions. A one-way ANOVA confirmed that feedback condition was not a significant factor for typing speed ($F_{5,66}=1.59$, $p<.1761$).

B. *Typing efficiency in KSPC*

Figure 4(b) shows the average typing efficiency in keystrokes per character (KSPC). Typing efficiency was 1.17, 1.09, and 1.12 for *v*, *va*, and *vh*, respectively, and 1.21, 1.16, and 1.10 for *V*, *vA*, and *vH*, respectively. The average typing

efficiency for *baseline* was 1.06 (dotted line in Figure 4(b)). In general, typing efficiencies were lower in *v* and *V*. Interestingly, KSPCs for *V* and *vA* increased (typing efficiency becomes lower) with the key-correctness information as compared to *v* and *va*, respectively, but not for *vH* as compared to *vh*. Furthermore, *vH* had the lowest KSPC (i.e., highest typing efficiency) among the key-correctness conditions (i.e. *V*, *vA*, and *vH*). *Baseline* had the lowest KSPC over all conditions, indicating the highest typing efficiency. A one-way ANOVA confirmed that feedback condition was a significant factor for typing efficiency ($F_{5,66}$=2.56, *p*<.0351). A *post hoc* Tukey test showed one group.

C. Typing error rates

Figure 4(c) shows the average error rates in a stacked bar graph, with the lower bar representing uncorrected error rate, upper bar representing corrected error rate, and the total height representing total error rate in percentages. On average, the uncorrected error rate was 3.7, 2.9, and 3.1% for *v*, *va*, and *vh*, respectively, and 1.2, .4, and 1.5% for *V*, *vA*, and *vH*, respectively. The average uncorrected error rate for the *baseline* (baseline (u)) was 1.8% (solid line in Figure 4(c)). In general, conditions with the key-correctness information (i.e. *V*, *vA*, and *vH*) showed lower uncorrected error rates, indicating that key-correctness information benefits typing performance. The uncorrected error rate was the lowest for *va* and the second lowest for *vh* among the conditions without the key-correctness information (i.e. *v*, *va*, and *vh*). The uncorrected error rate was the lowest for *vA* and the second lowest for *V* among the conditions with the key-correctness information. The uncorrected error rates in the conditions with the key-correctness information were all lower than the *baseline* although the result was not significant. A one-way ANOVA confirmed that feedback condition was a significant factor for uncorrected error rate ($F_{5,66}$=5.60, *p*<.0002). A *post hoc* Tukey test showed three groups: *v, vh, va, vH* (μ=2.8%); *vh, va, vH, V* (μ=2.2%); and *vH, V, vA* (μ=1.1%).

The average corrected error rate was 7.1, 4.3, and 5.3% for *v*, *va*, and *vh*, respectively, and 10.2, 6.9, and 4.4% for *V*, *vA*, and *vH*, respectively. The average corrected error rate for the *baseline* was 2.7% (not shown). A visual inspection showed *va* to led to the lowest corrected error rate while *vh* led to the second lowest corrected error rate among the conditions without the key-correctness information. Among the conditions with key-correctness information, *vH* showed the lowest and *vA* showed the second lowest corrected error rates. The corrected error rates for *V* and *vA* increased relative to those for *v* and *va*, respectively, but the corrected error rate for *vH* decreased instead. A one-way ANOVA confirmed that feedback condition was a significant factor for corrected error rate ($F_{5,66}$=3.35, *p*<.0093). A *post hoc* Tukey test showed two groups: *V, v, vA, vh* (μ=7.4%) and *v, vA, vh, vH, va* (μ=5.6%).

The average total error rate was 10.8, 7.3, and 8.4% for *v*, *va*, and *vh*, respectively, and 11.5, 7.4, and 5.9% for *V*, *vA*, and *vH*, respectively. The total error rate for the *baseline* (baseline (t)) was 4.5% (dotted line in Figure 4c). The *vH* condition showed the lowest total error rate. The total error rate was decreased from *vh* to *vH*, but the total error rates for both *V* and *vA* were slightly increased from *v* and *va*, respectively, indicating that *vH* was the only one that decreased the total error rate. A one-way ANOVA confirmed that feedback was a

significant factor for total error rate ($F_{5,66}$=2.71, *p*<.0274). A *post hoc* Tukey test showed two groups: *V, v, vh, vA, va* (μ=9.1%); and *v, vh, vA, va, vH* (μ=7.9%).

The results from a MANOVA demonstrated a significant multivariate effect (*Roy's Greatest Root*=0.7084, $F_{5,66}$=9.35, *p*<.0001). We found the following pair-wise correlations to be significant: WPM and KSPC (*r*=−.6389, *p*<.0001), WPM and uncorrected error rate (*r*=−.2556, *p*<.0303), WPM and corrected error rate (*r*=−.6405, *p*<.0001), and WPM and total error rate (*r*=−.7195, *p*<.0001). This means that WPM was closely related to all other metrics. We also found the following correlations to be significant: KSPC and corrected error rate (*r*=.9856, *p*<.0001), and KSPC and total error rate (*r*=.8957, *p*<.0001), indicating that KSPC was closely related to corrected and total error rates.

IV. DISCUSSION AND CONCLUSIONS

The present study investigated the effects of information content in sensory feedback on typing performance using a flat keyboard. We accomplished this by balancing the information content among visual, auditory and haptic sensory modalities and by differentiating between providing key press confirmation only and key correctness information through sensory feedback. We hypothesized that encoding key-correctness information into visual and non-visual feedback can benefit typing performance. Throughout the study, we discovered several findings to support our hypothesis.

First, the key-correctness information contributed to a lower uncorrected error rate. The uncorrected error rate was significantly higher in *v*, *va*, and *vh* than in *V*, *vA*, and *vH*. Note that the key-correctness information significantly reduced the uncorrected error rate even without key-identity information. The users' uncorrected error rates were significantly reduced while their total error rates stayed almost the same, implying that with additional key-correctness information the users corrected more errors. Another interesting finding was that uncorrected error rates appeared to be lower (although not significantly) than those for the *baseline* in the key-correctness conditions (i.e. *V*, *vA*, and *vH*). The uncorrected error rate was as low as .4% in *vA* and lower than 2% for *V* (=1.2%) and *vH* (=1.5%), all of which are lower than the *baseline* (=1.8%). This clearly showed the benefit of key-correctness information alone, as compared to key-entry information. It is noted that the uncorrected error rate was the lowest for *vA* and the highest for *vH* among the key-correctness conditions (i.e. *V*, *vA*, *vH*). One possible reason for the apparent advantage of auditory key-correctness information over haptic key-correctness information might be that the key-correctness information of *vA* was delivered through auditory cues via the headset without any background noise whereas the key-correctness information of *vH* was delivered to a single typing finger. In this case, the auditory feedback could be considered *global* whereas the haptic feedback to a single typing finger could be *local*; therefore the global auditory feedback was more effective than the local haptic feedback.

Second, the increment in corrected error rate in *V* and *vA* might indicate that there is a tradeoff between uncorrected and corrected error rates since the total error rates remained almost the same between *v* and *V*, and between *va* and *vA*. We also notice that *vH* led to a decrease in both uncorrected and

corrected error rates (and thus a decreased total error rate), indicating that *vH* outperformed *vh* in terms of typing errors. It is noted that there exists a tradeoff between corrected and uncorrected error rates that the decrement in uncorrected error rate brings an increment in corrected error rate while keeping the total error rate constant in some conditions. Therefore, it is important to notice the decrement in uncorrected error rate while keeping or decreasing the corrected and total error rates.

Third, typing speed did not improve with key-correctness information. Key-correctness information led to more corrected errors and increased KSPC (lowers typing efficiency), which could potentially slow down typing speed. It is therefore not surprising that we did not find any benefit of key-correctness information for typing speed.

It is encouraging to observe that information for assisting typing can be effectively delivered through non-visual modalities. Even though most feedback information for typing is based on visual cues, our results show that it is possible to deliver information beyond key-entry confirmation (in our case, key-correctness information) to typists through auditory and haptic feedback to improve some aspects of typing performance. Key-correctness information can be implemented using well known word prediction algorithms and be extended into real-world applications like word processors with visual, auditory and haptic feedback. A number of our findings support our hypothesis that the addition of meaningful information through sensory feedback improves typing performance on a flat keyboard. Our findings are well-suited for not only flat keyboards but also mechanical keyboards by delivering useful information for typing assistance through haptic and auditory feedback. Our findings can shed light on the development of flat and mechanical keyboards, the latter of which can be further improved with additional, artificial sensory feedback. Future work will extend the present study by considering the use of letter visual feedback that contains key-identity information and compare its effect on typing performance with that of key-correctness information.

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