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Effects of force feedback on VR Keyboards with different key travel distances

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***Abstract*—Virtual keyboards are important for virtual reality (VR) as they could enable intuitive text input. Although our touch sensation plays an important role in efficient typing, force feedback that could simulate touch sensation for virtual objects has not been used to augment VR keyboards. This was mainly due to the lack of appropriate haptic devices. Additionally, key travel distance is a critical factor in the design of physical keyboards, which greatly affects user typing performance. However, its effects on VR typing, especially in the presence and absence of force feedback, remains unexplored. Therefore, we developed multiple haptic keyboards with different key travel distances and conducted a text entry experiment by employing current state-of-the-art haptic gloves. The results showed that adding force feedback improved typing accuracy and reduced subjective workload. The interaction effects suggested that force feedback was associated with the perception of key travel distances, which modulated user typing performance differently depending on the presence of force feedback. Overall, this study is one of the first to enhance VR keyboards with force feedback and examine its effects with different key travel distances.**

***Index Terms*—haptic glove, force feedback, virtual keyboard, key travel distance, text entry, VR.**

I. Introduction

Virtual keyboards are essential for virtual reality (VR), as they offer intuitive text entry methods. They enable users to efficiently input text for communication, data entry, and information search, benefiting VR applications, such as entertainment [1], medical services [2] and industrial collaboration [3]. However, although touch sensation plays an important role in our daily typing [4], haptics remains an underutilized interaction modality for VR keyboards, and research on the effects of haptic feedback on virtual typing is still limited.

Previous haptic studies with VR keyboards mainly employed actuators to generate tactile click feedback (vibration) for typing (e.g. [5]–[7]). However, tactile feedback often serves as a feedback signal for interactions but cannot provide the reaction force needed to realistically simulate touch sensation of virtual objects [8]. Using force feedback to augment VR keyboards has the potential to significantly improve user typing performance and experience. However, due to the novelty of force-feedback devices suitable for VR typing (i.e., devices that can track finger motions and provide force feedback on fingers, such as HaptX[1], Weart[2] and Sense[3] gloves), there have been no studies to augment VR keyboards with force feedback. Thus, it remains unexplored how force feedback affects virtual typing, in terms of typing efficiency and user experience.

Furthermore, key travel distance is one of the key parameters for designing physical keyboards, which greatly affects user typing performance [9], [10]. Current physical keyboards commonly adopted an appropriate range of key travel distances (typically 2-4 mm[4,5]) for achieving the best typing performance. However, it remains unknown that, when typing in a VR environment, how key travel distance affects user typing performance, and more importantly, whether the effects of key travel distance on user typing performance change depending on the presence or absence of force feedback.

To answer these questions, this study employed current state-of-the-art HaptX gloves as the interaction tool and conducted a VR text entry experiment with two groups of virtual keyboards (haptic and non-haptic). The keyboards of each group had different key travel distances. Participants were asked to type predefined texts with each keyboard to collect objective data including typing speed and errors. For user experience, this study focused on assessing subjective mental workload, and the NASA-TLX questionnaire [11] was used. The aim of the study was to answer the following research questions in the context of text entry with VR keyboards:

- How does force feedback affect typing efficiency and subjective mental workload in virtual typing?
- Whether the presence of force feedback influences the effects of key travel distance on user performance?

The rest of the paper is organized as follows: We first introduce the relevant previous work and provide the experimental method and procedure, followed by the results and discussion.

II. Background

A. Virtual Keyboards in VR

Touch sensation is vital for our typing on a physical keyboard, enabling efficient touch typing [4], [12]. When pressing

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[1]https://www.haptx.com/
[2]https://www.weart.it/
[3]https://www.senseglove.com/
[4]https://www.cherry.de/en-gb/products/keyboards/office-keyboards
[5]https://www.logitechg.com/en-us/products/gaming-keyboards.html

Fig. 1. The prototype system: (A) The participant wore the equipment, and her hands were resting on a cushion and could type in midair. (B) The exoskeleton structure of gloves could generate force on the fingertip and transfer it to the entire finger. (C) The VR workspace included a virtual screen with the task and typed texts, the green button used to transfer to the next trial, and the experimental keyboard. (D) When pressing a key with a specific key travel distance, the entire finger could feel a reaction force when reaching the key bottom and could not press further, similar to typing on a physical keyboard.

physical keys, touch sensation of the keys not only contributes to the consistency of finger movements [13] but also serves as a feedback signal to confirm the input, thus improving both typing speed and accuracy [14]. However, current VR research focuses on designing novel text entry interfaces using other modalities such as gaze [15], speech [16] and gesture [17] or studying the elements of graphical user interface (GUI) for virtual keyboards, such as the position, type and size of keys [18]–[20]. Haptic modality is often underused.

Existing haptic studies mainly utilized vibration (e.g. [5]–[7]) or other types of tactile feedback (e.g., pneumatic [32]) to enhance VR keyboards, which could improve typing efficiency [6], [7] and reduce workloads [6], [32] as well as make the keyboard comfortable and convenient to use [5]. However, tactile feedback focuses on cutaneous sensation, which could be used as a simple feedback signal but could not simulate reaction force [8], while force feedback focuses on movement sensation originating in the muscles, tendons and joints [8], and thus can be used to provide more realistic touch sensation for virtual objects. Haptic gloves, such as HaptX and SenseGloves, use an exoskeleton structure to tracker finger movement (especially for HaptX that has sub-millimeter tracking precision) and provide force feedback on the user's fingers. Using such feedback may greatly improve user typing performance and experience. One of our goals was to examine its effects on typing efficiency and user workload.

B. Key Travel Distances of Keyboards

Key travel distance refers to the depth a key moves when pressed on a keyboard, which directly impacts typing speed, accuracy, and overall user satisfaction [21]. Current mechanical keyboards commonly use an optimal travel distance, often between 2 and 4 mm (short to long travel distances)[4][5]. Earlier research has shown that variations of key travel distance within this range have comparable typing efficiency [9], but they also found higher distances could lead to higher typing forces [9], [22]. Besides the long and medium travel distances, short and ultra-short travel distances are popular for compact designs such as laptops and tablets, offering quicker key activation. However, several studies have found that shorter distances may lead to lower typing efficiency [10], [23], [24].

Key travel distance has been extensively studied for physical keyboards. However, its role for VR keyboards remains unclear. Investigating this could provide valuable insights for designing effective and user-friendly virtual text input systems.

III. Method

To answer the research questions, a VR text entry experiment was conducted. We developed a prototype system and then designed a text entry task.

A. The Prototype System and Apparatus

A pair of HaptX gloves (DK2) and an HTC VIVE headset[6] made up the prototype hardware. The software was developed by Unity (2021.3.4f1)[7], with SteamVR[8] to connect the headset and HaptX SDK (2.1) to control the gloves. The host computer was an MSI GS63VR 7RF Stealth Pro laptop with an Intel i7-7700HQ processor and a GeForce GTX 1060 graphics card.

When users wore the equipment (Figure 1A), they could use virtual hands to type in midair (Figure 1C). HaptX generates force on each fingertip perpendicular to its surface and transfers the force to the entire finger relying on the exoskeleton structure (Figure 1B). When reaching the key bottom, the force resistance blocked the finger movement and prevented further pressing (Figure 1D). This interaction closely resembled the experience of touching a physical key, different than applying tactile feedback on the skin. We adopted the default force amplitude of HaptX SDK. Based on the glove specification, they could provide an operating force of 4.5 lbf with a peak resistance 8 lbf.

Furthermore, when interacting with physical keys, we could feel a weak spring force during pressing a key and a strong force when reaching the key bottom. Since the force from the key bottom was much stronger and directly relevant to the key travel distances, and also dynamic spring force was a challenge for current HaptX gloves, the spring force was not involved (set to 0). Force feedback was only enabled when reaching the key bottom. Additionally, the gloves used could provide tactile feedback on the hands (mainly palm and finger pads)

[6]https://www.vive.com/
[7]https://www.unity.com/
[8]https://store.steampowered.com/app/250820/SteamVR/

but could not provide it properly on the tips of fingers for typing (based on finger gestures), so we did not involve it as a variable. HaptX SDK could enable/disable force feedback to have two groups of virtual keyboards (haptic vs. non-haptic).

For the two groups of keyboards, we selected four key travel distances. Thus, eight virtual keyboards were implemented: 2 (haptic vs. non-haptic) × 4 (four distances) = 8 (keyboards). The selection of key travel distances was based on literature and touch sensitivity. When using physical keyboards, no significant differences in typing performance were found from the short to long key travel distances (i.e., 2-4 mm) [9]. Considering touch sensitivity for the simulated touch sensation by the gloves, we expanded the selection range and chose four distances ranging from a short distance (2 mm) to an ultra-long distance (8 mm) with an interval of 2 mm, that is, 2, 4, 6 and 8 mm. This selection could help comprehensively evaluate how the variation in key travel distance influences user performance in VR typing. In addition, character input event was triggered when the key reached to its bottom, similar as force feedback. This event could be triggered only once for each contact.

All keyboards were located in the same spatial position and adopted the QWERTY layout with 27 keys (26 letters and a space key). The deletion key was not included, preventing participants from revising the input text. A QWERTY keyboard typically has single-unit keys with keycap width 13 mm, gaps between keys 6 mm, and the space key is 6.25 units wide[9]. However, small virtual keys (keycap 13 x 13 mm) could lead to lower typing efficiency and higher fatigue than using larger keys (16×16 and 19×19 mm) [25]. This study thus adopted square keys with 16 mm width, a gap of 6 mm, with the space key size of 137.5 mm. The spring and damper coefficients were set at 750 and 50 in Unity for the key rebound behavior, to ensure a quick and realistic reset after the key press.

B. The Experiment Task

The experiment used a within-subjects design and asked participants to perform two text entry trials using each keyboard. For each trial, the task text involved nine different English words with the same total number of letters (61 characters) and spaces (8 spaces). The words for each trial were selected from a predefined database, and the used words would not be selected again for the participant. After one trial, participants touched a green button behind the keyboard (Figure 1C) to move to the next one. In total, participants typed 138 characters with each keyboard and 1104 characters for the experiment.

Participants could see the task text (yellow) and the typed text (white) on a virtual screen perpendicular to the keyboard (Figure 1C). After each trial, typing speed and errors were recorded. Typing speed was measured by collecting the time data from the start of each trial to its end (when touching the green button). Typing errors were counted by comparing the typed and task texts (including spaces), and any extra, missing or incorrect character was counted as an error. After completing four keyboards of one group, they filled in the 7-point Likert scale NASA-TLX questionnaire with the workload items including mental and physical demand, temporal demand, performance, effort and frustration [11].

[9]https://deskthority.net/wiki/Unit

C. Pilot Study

Four participants with experience of the hardware were recruited first to conduct a pilot study. The purpose was to ensure the validity and reliability of the experiment system.

The experiment was decided to use only index fingers for typing. The haptic gloves had a fixed size which could not perfectly match each finger of all users, especially for ring and little fingers. Also, typing skills can vary significantly. Some people may be proficient in typing using five fingers, while others may not. To control these variables, only index fingers were allowed for typing. This would not affect the study as our objective was to examine the effects of force feedback on virtual typing instead of examining the usability of the gloves.

The layout and parameters of virtual keyboards, such as key size, force magnitude, spring and damper coefficients were verified. This ensured that the participants could have smooth and realistic typing experience using haptic gloves. The positions of the keyboards, the green button and the screen were adjusted to ensure they could be easily accessed.

D. Participants

Twenty-four participants were recruited from the local university community (15 women and 9 men), and the ages varied between 20 and 45 years (M = 30.08, SD = 7.73). Participants whose hands were too big or small for haptic gloves were not involved. Among them, 16 participants had used a similar VR headset for one to four times, but no participants had experience of using HaptX gloves or similar wearable haptic devices and all participants had normal touch sensitivity.

E. Experiment Procedure

According to the national and university-specific guidelines on research ethics, this study did not require ethics board approval due to no significant risks involved. The participants were first introduced to the experiment and the apparatus used, and then they signed an informed consent form and filled in their background information in a questionnaire. After signing, their hand sizes were measured to calibrate the gloves using HaptX SDK and the same appearance of the virtual hand was used for them.

Before the experiment, the participants wore the equipment and sat on a chair. They could rest their forearms on a cushion that allowed them to type in midair, reducing fatigue caused by the weight of gloves. Rubber bands were used to physically restrict the movement of the remaining four fingers (Figure 1A), preventing them from touching the keyboard and maintaining the typing posture with the index finger.

In the experiment, the order of two groups of virtual keyboards was counterbalanced and also the order of four key travel distances was counterbalanced using the balanced Latin square [26] to ensure that the order effect was evenly distributed among the participants. White noise was streamed through the headset to block ambient sounds. When the experiment started, participants were able to familiarize themselves with the system for 2-3 minutes. After that, they were required to complete the task with one group of keyboards (haptic or non-haptic). For each keyboard, they had one minute to try the keyboard with the specific key travel distance and then completed the two trials without pausing. They were informed to perform the task as quickly and accurately as possible, and accuracy was the top priority since there was no deletion key. Also, they had to continue typing even noticing an typing error and could not retype the word. After finishing the task with the four keyboards of one group, the participants could have up to five minutes to take a break and filled in the questionnaire to collect the subjective workload data. Then, they performed the text entry task with another group. The experiment lasted about one hour for each participant in total.

IV. Results

Both objective and subjective data were collected. Typing speed was evaluated by calculating characters per minute (CPM) and typing accuracy was evaluated by calculating error rates for the input texts. Subjective workload was evaluated by collecting the scaling data from the NASA-TLX questionnaire.

The Shapiro-Wilk test was conducted to check the normality of data. The results showed that the speed data were normally distributed ($p > .05$) but the accuracy data were not ($p < .05$). Therefore, we analyzed the time data using a 2 x 4 (haptic conditions x distances) repeated-measures parametric ANOVA and analyzed the accuracy data using Aligned Rank Transform (ART) repeated-measures non-parametric ANOVA [27]. The t-test was used for post-hoc analysis of the speed data and the Wilcoxon signed-rank test was used for post-hoc analysis of the accuracy data. We performed the Holm-modified Bonferroni correction [28] to control the family-wise type-1 error. All p values in the post-hoc analysis were after the correction.

TABLE I
Results of ANOVA tests for typing efficiency.

Sources		Haptics	Distances	Interaction Effect
Speed	df	1, 23	3, 69	3, 69
	F	0.043	16.206	1.886
	Sig.	0.838	**<0.001**	0.14
Accuracy	df	1, 23	3, 69	3, 69
	F	13.647	4.046	3.382
	Sig.	**0.001**	**0.01**	**0.023**

A. Typing Efficiency

For typing speed, ANOVA showed a significant main effect for key travel distances but not for haptics. Their interaction effect was not significant. For accuracy, ART ANOVA showed significant main and interaction effects for haptics and key travel distances (Table I). Because of our research questions, we focused on the main effect of haptics and the interaction effect in the post-hoc analysis. The lowest key travel distance was the baseline for analysis, which could demonstrate the trend in typing efficiency with the increase of distance.

For typing speed, although no main effect and interaction effect for haptic conditions were found, we presented their boxplots (Figure 2) and conducted analysis for the interaction effect to better understand the situation of typing speed based on the key travel distances. Based on t-test, without force feedback (Figure 2B), there were no significant differences between 2 mm (M = 53.95, SD = 12.82) and 4 mm (M = 53.72, SD = 13.45, t (23) = 0.156, p = 0.878) and also between 2 mm and 6 mm (M = 52.28, SD = 12.35, t (23) = 1.252, p = 0.446), but using 8 mm (M = 45.78, SD = 12.71) led to lower speed than 2 mm (t (23) = 5.485, p <0.001). With force feedback (Figure 2C), using 6 mm (M = 50.12, SD = 12.8) and 8 mm (M = 47.01, SD = 10.63) led to lower speed than 2 mm (M

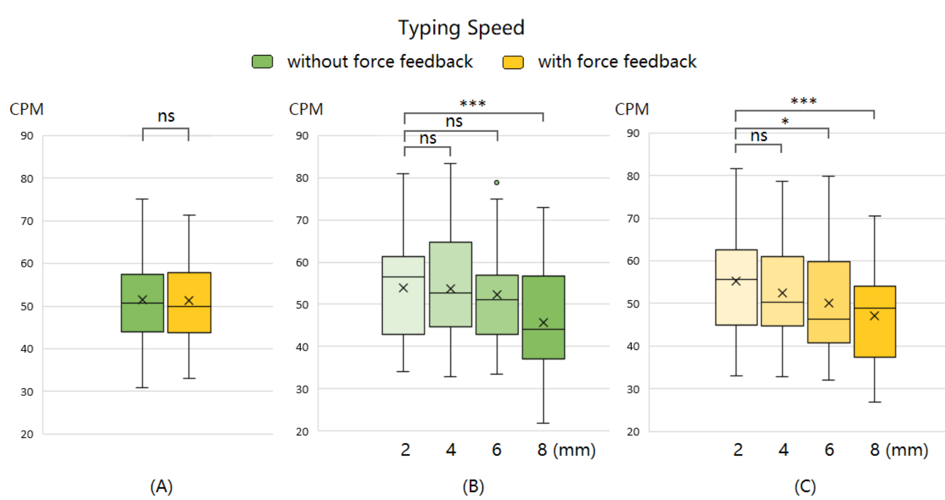

Fig. 2. Boxplots for typing speed: (A) typing speed based on haptic conditions (haptic vs. non-haptic); (B) typing speed based on different key travel distances without force feedback; (C) typing speed based on different key travel distances with force feedback. The line in the boxplot is the median value and the cross mark is the mean value (the following figures use the same marks). Note: *p <0.05, **p <0.01, ***p <0.001.

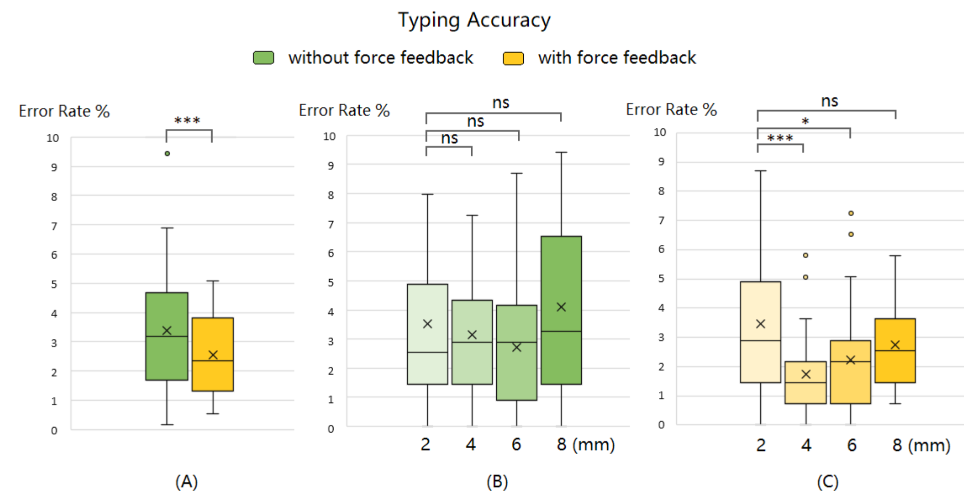

Fig. 3. Boxplots for typing accuracy: (A) error rates based on haptic conditions; (B) error rates based on different key travel distances without force feedback; (C) error rates based on different key travel distances with force feedback. Note: *p <0.05, **p <0.01, ***p <0.001.

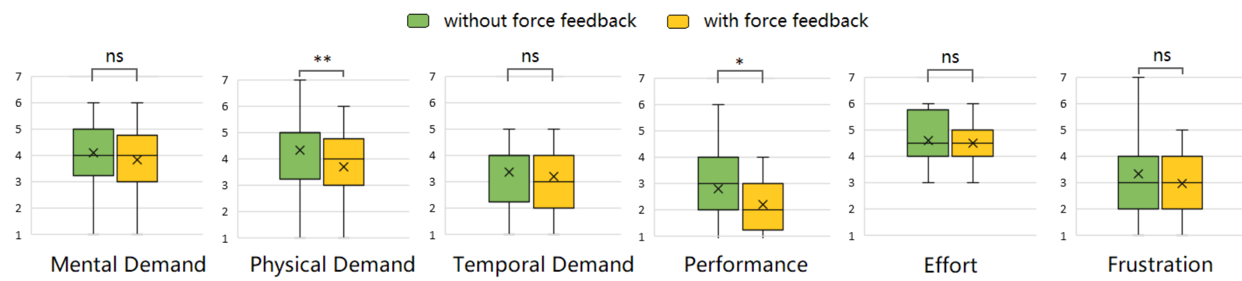

Fig. 4. Boxplots for subjective mental workloads (lower value means lower workload). Note: *p <0.05, **p <0.01, ***p <0.001.

= 55.28, SD = 11.1, t (23) = 2.962, p = 0.014 and t (23) = 4.176, p <0.001), but there was no difference between 2 mm and 4 mm (M = 52.54, SD = 11.88, t (23) = 2.009, p = 0.056).

For typing accuracy, the results (Figure 3A) showed that with force feedback (M = 0.026, SD = 0.015) led to significantly lower error rates than without force feedback (M = 0.034, SD = 0.023). For the interaction effect, Wilcoxon signed-rank test showed that there were no significant differences in typing accuracy among the four distances when without force feedback (Figure 3B), that is, 2 mm (M = 0.035, SD = 0.031) vs. 4 mm (M = 0.031, SD = 0.022): Z = - 0.797, p = 0.852; 2 mm vs. 6 mm (M = 0.027, SD = 0.021): Z = - 1.205, p = 0.684; 2 mm vs. 8 mm (M = 0.041, SD = 0.037): Z = - 0.687, p = 0.492. However, when with force feedback (Figure 3C), using 4 mm (M = 0.018, SD = 0.017) and 6 mm (M = 0.022, SD = 0.019) caused lower error rates than 2 mm (M = 0.035, SD = 0.025, Z = - 3.661, p <0.001 and Z = - 2.773, p = 0.012), but there was no difference between 2 mm and 8 mm (M = 0.027, SD = 0.015, Z = - 0.961, p = 0.337).

B. User Experience

Because the subjective data were not normally distributed (p <.05 shown in the Shapiro-Wilk Normality test), Wilcoxon Signed-Rank test was used to analyze the data. The results (Figure 4) showed that the participants using the keyboards with force feedback perceive less workload than when using the ones without force feedback, in terms of physical demand (Z = - 2.968 , p = 0.003) and performance (Z = - 2.357, p = 0.018). For other workload items, there were no significant differences (Mental Demand: Z = - 1.182, p = 0.237; Temporal Demand: Z = - 0.977, p = 0.329; Effort: Z = - 0.42, p = 0.675; Frustration: Z = - 1.502, p = 0.133).

V. Discussion

This study explored the effects of force feedback on typing efficiency when using virtual keyboards with different key travel distances as well as examined its effects on subjective mental workloads. Overall, force feedback was found to be beneficial for both user typing performance and experience.

A. Typing Efficiency

Adding force feedback to VR keyboards was found to benefit typing accuracy (Figure 3A) but not typing speed (Figure 2A). Although touch sensation is critical for efficient typing [4], [13] and force feedback could simulate touch sensation for virtual objects [8], force feedback alone, without additional cutaneous sensations, is insufficient to provide touch sensation for virtual objects as if they are real [29]. Because accuracy was the top priority in the experiment, the users were likely unable to increase their speed relying on force feedback while maintaining a high typing accuracy. On the other hand, as they focused on typing accuracy, force feedback as an additional interaction cue was expected to improve it, similar to visual feedback [30] used for VR keyboards.

We studied the interaction effects between force feedback and key travel distances. Based on data observations, force feedback could modulate both typing speed (Figures 2B and 2C) and accuracy (Figures 3B and 3C) with different key travel distances. One possible reason is that the changes of key travel distance might be more noticeable to users when with force feedback, as they could rely on force feedback to detect the moment the key reached the bottom besides the visual feedback. This could explain that there was a decreasing trend in text entry speed following the distance increase (especially after 4 mm) when with force feedback, whereas there was no such trend when without force feedback. Our results confirmed the finding of early research with physical keyboards [9] but further extended it to the context of VR keyboards, that is, when using keyboards with force feedback, key travel distance between 2 mm to 4 mm would not significantly affect typing speed but further increasing key travel distance could lead to a negative impact. Our results also demonstrated that users were not sensitive to the key travel distances (2 mm to 6 mm) when without force feedback, unless a ultra-long distance (8 mm) was used, causing excessive finger movement per keystroke.

For typing accuracy, the benefit of force feedback for key travel distances was more noticeable. As shown in the significant interaction effect, when without force feedback, typing accuracy was not affected by different key travel distances, whereas, when with force feedback, using different distances could lead to different typing accuracy. This result was consistent with early research using physical keyboards (e.g., [9], [10]) that using appropriate key travel distances could achieve better typing accuracy. However, the distances suitable for VR keyboards were different than for physical keyboards. Early research has demonstrated that adopting short to long key travel distances (2-4 mm) for physical keyboards could lead to comparable typing accuracy [9], while short key travel distance (2 mm) was found unsuitable for VR keyboards in our results. That may be because of the simulated virtual hands. Although haptic gloves could precisely track finger motions, the virtual hands likely could not be used as flexibly as our real hands, therefore increasing the risk of accidental keystrokes. Longer travel distances effectively prevented such accidental keystrokes and thus improved accuracy. This issue could be alleviated through future technological advancements

Overall, our results demonstrated that user typing performance could be improved by using suitable key travel distances when with force feedback. Although it has not been directly measured, these interaction effects suggested that force feedback contributes to enhancing the perception of key travel distances. This may need further verification.

B. User Experience

The subjective data demonstrated that force feedback could reduce subjective mental workload, consistent with the effect of vibrotactile feedback for VR typing [6], [30], but its effects on the sub-aspects of mental workload were different (i.e., vibration was shown to decrease mental demand, frustration, and effort [6]). Subjective workload could be affected by many factors, such as task complexity, interface design, environmental factors, and interaction tools [31]. Thus, it was difficult to directly compare the results from two different studies. However, there is a key difference between force feedback and vibrotactile feedback for VR typing, that is, force feedback applied on fingers could support finger gestures when typing in midair, whereas vibrotactile feedback could not. This could be the main reason for force feedback to reduce physical demand and improve user confidence, shown in our results.

C. Limitations and Future Studies

This study has several limitations. First, this study did not involve vibrotactile feedback as an experimental variable. Such feedback could benefit typing efficiency and user experience [6], [7], [30]. The differences between vibrotactile and force feedback with different key travel distances could be explored in future research. Second, there was no spring force implemented when pressing the keys. This was mainly due to hardware limitation, and additionally because it is a weaker force compared with the force from the key bottom. However, whether and how such dynamic spring force affects typing performance would be an interesting research topic which could be conducted in the future. Third, the participants were novice users and the experiment only allowed for a short practice time. A long-term experiment could be conducted to examine the potential performance differences for experienced users. Lastly, this study only allowed index fingers for typing which limited natural hand behaviors and negatively affect user typing performance (e.g., typing speed). This would not affect examining the effects of force feedback, but the practical usability of the gloves remained unknown. As usability could be affected by many factors such as hardware weight, finger tracking accuracy and ergonomic comfort, a focused usability study is needed. It could be conducted with other available haptic gloves (e.g., Weart and Sense gloves) using natural hand typing behaviors to examine their strengths and weaknesses.

VI. Conclusion

This study explored the effects of force feedback on VR keyboards with different key travel distances. The results suggested that force feedback was associated with the perception of key travel distance and, thus, modulated user typing performance. Overall, adding force feedback was found to be beneficial for typing accuracy and subjective mental workload. This study was one of the first to employ force feedback to enhance VR keyboards and also examined its effects with various key travel distances. It offered empirical insights for developing efficient and user-friendly haptic VR keyboards.

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