Ultrasonic Keyboard: A Mid-Air Virtual Qwerty with Ultrasonic Feedback for Virtual Reality

Tafadzwa Joseph Dube
Inclusive Interaction Lab
University of California, Merced
Merced, California, United States
tdube@ucmerced.edu

Ahmed Sabbir Arif
Inclusive Interaction Lab
University of California, Merced
Merced, California, United States
asarif@ucmerced.edu

ABSTRACT

Free-hand mid-air Qwerty enables entering text in virtual reality without the use of controllers. However, it is much slower and more error prone than its physical counterpart, primarily due to the absence of haptic feedback and reduced spatial awareness. In this paper, we design three different ultrasonic haptic feedback for mid-air Qwerty: feedback only on keypress, on both touch and keypress, and gradual feedback that increases intensity as users push down a key. In a pilot study, the touch & press feedback performed significantly better both quantitatively and qualitatively. We then compare a mid-air Qwerty with and without touch & press feedback in a user study. Results revealed that haptic feedback improves entry speed by 16% and reduces error rate by 26%. Besides, most participants feel that it improves presence and spatial awareness in the virtual-world by maintaining a higher consistency with the real-world, and significantly reduces mental demand, effort, and frustration.

CCS CONCEPTS

• **Human-centered computing** → **Text input**; **Virtual reality**; **Haptic devices**; **Gestural input**.

KEYWORDS

Qwerty, 3D interface, mid-air, gesture, VR, XR, text entry, haptics

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1 INTRODUCTION

Text entry in virtual reality (VR) continues to be a challenge regardless of the widespread use of head-mounted displays (HMD) in diverse scenarios. Currently, the most popular text entry solutions are physical and on-surface or mid-air virtual Qwerty [8], neither of which are ideal for entering text in VR. Physical Qwerty tend to break immersion by forcing users to switch between the virtual and the actual worlds [8], although this can be remedied by blending the appearance of the keyboard in the virtual world [40] and making the animation of the hand as realistic as possible [35]. On-surface and mid-air virtual Qwerty facilitate presence but lack tactile feedback. With physical Qwerty, users feel an opposite force when pressing down a key and can use the keys as spatial reference. The absence of these feedback affects text entry performance with virtual keyboards. Many have attempted to mitigate these issues by providing synthetic haptic feedback on each keypress (Section 2). Most of these approaches, however, use either impractical extramural hardware or wearable devices like digital rings or gloves.

In this work, we augment a mid-air virtual Qwerty with ultrasonic haptic feedback that does not require custom hardware or wearable devices. First, we compare three different types of ultrasonic feedback in a pilot study. We identify the best performed feedback, then use it with a mid-air Qwerty. We compare the keyboard with haptic feedback (ultrasonic keyboard) with another keyboard without haptic feedback in a user study. Finally, we conclude the paper with reflection on future extensions of this work. All studies reported here were approved by the Institutional Review Board (IRB) and conducted abiding by the institute's COVID-19 preventive measures.

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2 RELATED WORK

Many enabled text entry with physical Qwerty keyboards by using external sensors to track the keyboard and the hands, then displaying their virtual representations in the virtual world [4, 18, 27, 32, 34, 40, 43, 47, 51]. These techniques are relatively fast (~39 wpm [18]) but break immersion by forcing users to switch between the virtual and the actual worlds [10, 47]. Some attempted to address this by developing on-surface and mid-air virtual Qwerty [9, 12, 41, 50, 53]. However, these approaches are not as effective as physical Qwerty (~12 wpm [9]) due to the absence of haptic feedback [6, 12, 14]. Alternative input methods have also been explored, such as head pointing [37, 38, 53, 62] and eye pointing [48]. These methods are not only much slower than physical Qwerty (10–16 wpm [48, 53]) but also cause high physical strain in prolonged use [8]. A different approach overlays a new layout on the palm, enabling using the index finger of the other hand to type [57]. A similar approach splits Qwerty into two parts to assign each half to one of the hands and a group of keys to each fingers, enabling users to enter text by pinching the thumb and fingers [13]. These methods are highly error prone with error rates over 10%. Some have also used alternative input devices, such as handheld controllers [30, 46, 53], interactive

Table 1: Performance of free-hand text entry techniques with haptic feedback reported in the literature. "Method", "target", and "haptic" represent the medium used to provide haptic feedback, the body-part targeted for feedback, and the type of feedback provided, respectively. "Surface" signify hard flat surfaces, such as a desk. The symbol "γ" signifies two fingers, "σ" ten fingers, "α" one part of the wrists, and "τ" different parts of the wrists.

Method	Target	Haptic	WPM	ER (%)
Surface [9]	Fingertip	Passive	12.08	2.02
Surface [42]	Fingertip	Passive	-	-
Surface [12]	Fingertip$^{\gamma}$	Passive	55.5	4
Surface [12]	Fingertip$^{\sigma}$	Passive	51.6	7
Wearable [59]	Fingertip	Vibrotactile	-	-
Wearable [21]	Wrist$^{\alpha}$	Vibrotactile	22.5	13.5
Wearable [21]	Wrist$^{\tau}$	Vibrotactile	22.8	14.8
Wearable [21]	Fingerbase	Vibrotactile	23.0	11.2

gloves, rings, and straps [31, 58–61], digital pens [7, 29], and smartphones [3, 20, 25, 33]. Entry speed with these techniques range between 6 and 14 wpm [31, 33, 53]), but are highly error prone (15–35% [7, 29, 58]). Dube and Arif [8] provide a comprehensive review of existing text entry techniques for virtual reality.

The lack of tactile feedback in mid-air interaction has prompted research into unorthodox haptic feedback approaches. Gupta et al. [21] used wearable actuators to provide remote vibrotactile feedback on the wrist and the base of the finger. In an evaluation, both feedback methods performed comparably, however participants preferred the feedback on the finger since it felt more natural. Some used digital gloves to provide vibrotactile feedback on the hand and the fingertips [19, 54, 59]. Muthukumarana et al. [45] used shape memory alloys to provide touch sensation on the forearm. Lopes et al. [36] used a full-body suit and objects attached to the elbows and the shoulders to induce electrical muscle simulation. Gupta et al. [22] provided mid-air haptic feedback through air vortex. Some have also explored haptic feedback through ultrasound [5, 16, 49]. Table 1 presents performance of popular free-hand text entry techniques that provide haptic feedback.

The closest to this work is the one by Dube et al. [11] that compared four mid-air target selection methods: push, tap, dwell, and pinch, with two types of ultrasonic haptic feedback: select and hover & select (which are comparable to the press and touch & press feedback methods explored in this work), in a Fitts' law experiment. They found out that both haptic feedback methods improve selection performance by increasing users' spatial awareness. These methods, however, have not been explored or evaluated in the context of text entry.

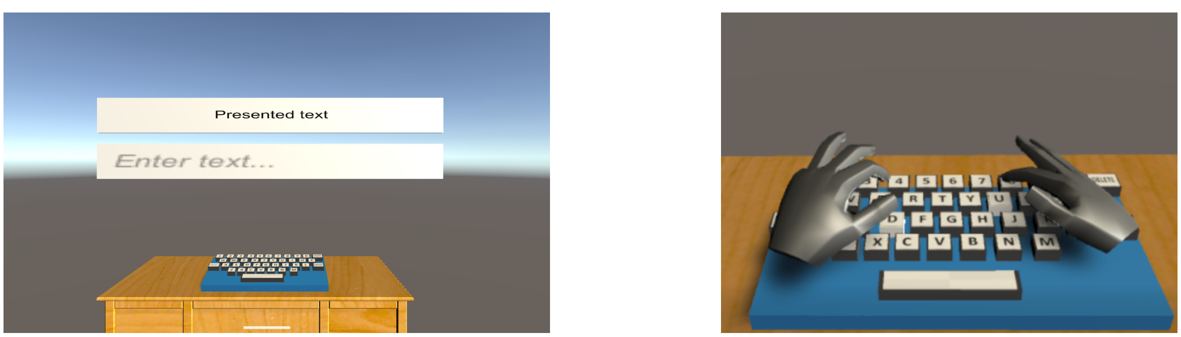
3 THE ULTRASONIC KEYBOARD

We developed the experimental system using Unity3D 2019.4.8f1, Leap Motion Orion 4.0.0 SDK, Leap Motion Unity Core Assets 4.4.0, and Ultraleap Unity Core Assets 1.0.0 Beta 9. The virtual environment consists of a desk, a keyboard, and a text input area above the desk (Fig. 1a). We kept the environment simple to avoid any distractions and used neutral colors to reduce visual fatigue [44] during text entry. Besides, we designed the environment to be immersive so that users feel that they are sitting in front of a desk.

3.1 Keyboard Design

We developed a 1335.5 × 478.5 px (307 × 110 mm) virtual Qwerty (Fig. 1b), which has a dark-blue base and 91.4 × 91.4 × 30.5 px (21 × 21 × 7 mm) keys with light-grey top and black sides and labels. This color combination was picked to aid contrast. The size of the keyboard was influenced by the effective interaction area of the ultrasonic haptic board (Section 3.2). We used square-shaped 3D keys based on a prior research that showed that square-shaped keys improve text entry speed, while 3D keys improve accuracy [9]. The keyboard provides visual feedback on both hover and press. When the finger is 108.8 px (25 mm) above a key, the sides of the key change color from black to light-grey. Likewise, when the user presses down the key, it plays a key-down animation to mimic an actual key. The keyboard does not provide any auditory feedback.

A Leap Motion Controller [55], attached upward to the haptic board, tracks both hands at 200 fps, then presents their virtual



(a) The virtual environment

(b) The keyboard and the abstract hands

Figure 1: (a) The virtual environment developed for this research and (b) the mid-air Qwerty keyboard with abstract virtual representations of the hands.

(a) Ultraleap Stratos Explore

(b) The complete experimental setup

Figure 2: (a) The haptics device with the transducers exposed. In the study, they were covered with a metal cover that came with the device, (b) The Ultraleap device was placed on a small table (height: 52 cm) closer to the users for comfortable mid-air actions.

representations to the user. It uses a dark-grey abstract hand representation (Fig. 1b) for gender neutrality and to avoid the effect of uncanny valley [1, 17]. Although the keyboard can track all fingers, we focused only on two-finger typing using the index fingers since prior work found two-finger typing to be substantially faster than ten-finger typing with mid-air virtual Qwerty in VR [12].

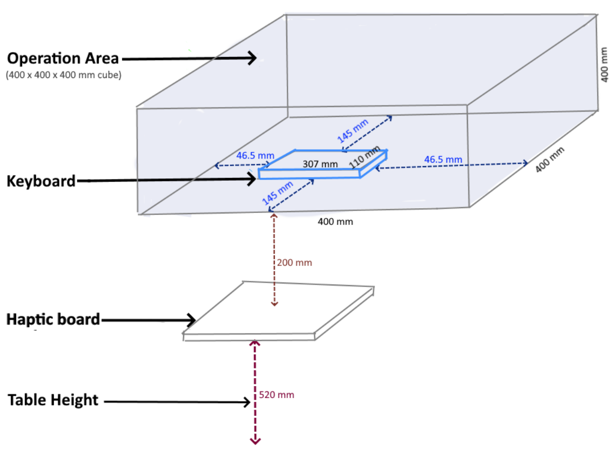


Figure 3: The operation area in the experiment setup (the shaded area).

3.2 Haptic Sensation

The system uses an Ultraleap Stratos Explore [56] haptics board (242 × 207 × 34 mm, 0.7 kg) to provide mid-air haptic feedback (Fig. 2a). The device is a phased array composed of 16 × 16 transducers that operate at a frequency of 40 kHz. The ultrasound waves produced by the transducers can be focused on a point in a 400 × 400 mm plane about 600 mm above the device. When focused on the hand or a finger, the mechanoreceptors in human skin sense the waves as pressure or vibration [5]. The experimental system tracks the hand and the fingers using the Leap Motion Controller (Section 3.1), then aims ultrasound waves at the tip of the index finger. The device limits interactions between 200 to 600 mm above the haptics device. We designed three different types of ultrasonic haptic feedback using the Ultraleap Unity Core Assets 1.0.0 Beta 9, described below. These feedback methods simulated touch sensations using spatiotemporal modulation [15, 28] with a drawing frequency of 70 Hz.

- **Touch & press feedback** provides haptic feedback on both touch and keypress. When the finger touches a key, the haptic board provides feedback in reference to the shape of the key at 60% intensity. When the finger presses down the key beyond the 30.5 px (7 mm) threshold, it provides the same feedback at 100% intensity. We designed the feedback to match the shape of the key to resemble the haptic feedback of an actual keyboard. Besides, we compared the square-shaped feedback with a Lissajous curve feedback in a pilot study (N = 3, M = 29.3 years), where the former was the most preferred by the participants, because it felt more natural and covered a larger area. The feedback remained active until users moved the finger away from the key.
- **Press feedback** provides haptic feedback only on keypress. It uses the same convention used for press by the touch & press feedback.
- **Gradual feedback** also provides feedback on both touch and press. However, instead of providing two distinct levels of feedback, it gradually increases the intensity of the feedback relative to the distance the key is depressed. More specifically, when the finger touches a key, the keyboard provides haptic feedback at 60% intensity, then gradually increases to 100% as the user presses down the key.

Fig. 3 illustrates the operation area in the experiments.

4 PILOT: THREE FEEDBACK METHODS

We conducted a pilot study to compare the three feedback methods in text entry tasks.

4.1 Participants

Six volunteers participated in the pilot study. Their age ranged from 21 to 37 years (M = 27.5, SD = 5.1). Three of them identified themselves as women and three as men. They all were native or bilingual English speakers. None of them wore corrective eyeglasses. Two of them had used a virtual reality system in the past, but none of them owned an HMD. None of them had prior experience with ultrasonic feedback. They all received U.S. $10 for participating in the study.

4.2 Apparatus

We used an ASUS ROG GU501GM Gaming Laptop with an Intel core i7 processor, 16 GB ram, NVDIA GeForce GTX 1060 graphics card, running on a Windows 10 OS. We used an Oculus Rift HMD with 110° field of view and 90 Hz refresh rate. Participants were seated on a chair resting their arms on the armrest to reduce the gorilla arm effect [26]. However, this posture was not enforced in the study. The Ultraleap Stratos Explore haptic board was placed on top of a small table (height: 52 cm) in front of the user. Fig. 2b illustrates the complete setup.

4.3 Design & Procedure

The study used a within-subjects design with one independent variable (feedback) with three levels (touch & press, press, and gradual). In each condition, participants transcribed 12 random English phrases from a set [39]. The conditions were counterbalanced in a Latin square to eliminate the effect of learning. The dependent variables were the commonly used words per minute (wpm) and total error rate (TER) performance metrics in text entry research [2]. TER, unlike the conventional error rate, accounts for both corrected and uncorrected errors in the calculation of error rate [52].

The study was conducted in a quiet room. First, we described the research to all participants, and collected their informed consent and demographics. We then demonstrated the system and the three feedback methods, and enabled them to practice with the system by entering 5 phrases with each feedback method. These phrases were not repeated in the study. Then, we started the main study, where the system displayed one random phrases at a time above the input area. Participants were instructed to transcribe the phrase as fast and as accurate as possible. Error correction was recommended but not forced. Once done with a phrase, they pressed the "Enter" key to see the next phrase. This process continued until they were done with all phrases in a condition. We enforced a 5-minute break between the conditions to reduce the effect of fatigue. However, participants could extend the break when needed. The system automatically calculated and recorded the performance metrics. Upon completion of all conditions, participants were asked to pick their most preferred feedback method and justify the choice.

4.4 Results & Discussion

A complete study session took about 45 minutes to complete, including demonstration and practice. A Shapiro-Wilk test revealed that the response variable residuals were normally distributed. A Mauchly's test indicated that the variances of populations were equal. Hence, we used a repeated-measures ANOVA for within-subjects factors.

We identified a significant effect of haptic feedback on text entry speed ($F_{2,5} = 7.28, p < .05$). On average entry speed with the touch & press, press, and gradual feedback were 10.25 wpm (SD = 1.85), 10.67 wpm (SD = 1.93), and 9.66 wpm (SD = 1.62), respectively (Fig. 4a). A post-hoc Tukey-Kramer test identified entry speed with gradual feedback to be significantly slower compared to the other methods (~6–9% slower). An ANOVA failed to identify a significant effect of feedback method on total error rate ($F_{2,5} = 2.52, p = .13$). Average TER with the touch & press, press, and gradual feedback were 6.45% (SD = 5.62), 5.17% (SD = 5.26), and 7.77% (SD = 6.48), respectively (Fig. 4b). In the post-study discussion, four participants preferred the touch & press feedback as they found it to be the most natural and effective. With this feedback they could sense the keys before pressing them, thus could use it as spatial reference, which they believed improved their performance with the method. Two participants preferred the press feedback, because they felt with touch & press, sometimes it was difficult to tell whether they had pressed the key or not. A participant (female, 28 years) commented, *"It [press] is better [..] because I know I pressed something for sure."* In summary, touch & press yielded the best performance both qualitatively and quantitatively. Hence, we used it in the final study.

5 USER STUDY: HAPTIC VS. NO-HAPTIC

We conducted a user study to compare a virtual keyboard *with* touch & press feedback and *without* feedback to investigate the effects of haptic feedback on mid-air text entry performance in VR.

5.1 Participants & Apparatus

Twelve participants took part in the study. None of them participated in the pilot studies. Their age ranged from 21 to 37 years (M = 27.9, SD = 6.0). Four of them identified themselves as women and eight as men. They all were native or bilingual English speakers. Two of them wore corrective eyeglasses. Five of them had used a virtual reality system in the past, but none of them owned an HMD. None of them had prior experience with ultrasonic feedback. They all received U.S. $10 for participating in the study. The study used the same apparatus as the pilot study (Section 4.2).

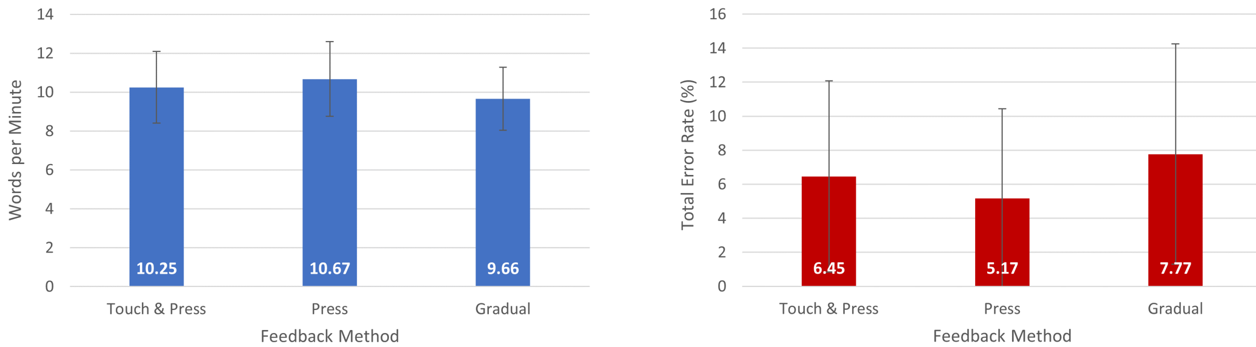
5.2 Design & Procedure

The study used a within-subjects design with one independent variable (feedback) with two levels (with, without feedback). In each condition, participants transcribed 12 random English phrases from a set [39]. The conditions were counterbalanced in a Latin square to eliminate the effect of learning. The study used the same dependent variables and procedure as the pilot study (Section 4.3). However, in this study, we asked participants to complete a custom usability and the NASA-TLX [24] questionnaires upon completion. They then took part in a brief informal interview session.

5.3 Results

A complete study session took between 45 and 60 minutes to complete, including demonstration, practice, and questionnaires.

5.3.1 Entry Speed. A paired samples T-test identified a significant effect of haptic feedback ($t_{143} = 6.94, p < .0001$) on text entry speed.



(a) Entry speed (wpm) **(b) Total error rate (%)**

Figure 4: Average text entry speed (wpm) and total error rate (%) with the three examined feedback methods. Error bars represent ±1 standard deviation (SD).

The average speed with and without haptic feedback were 12.33 wpm (SD = 2.75) and 10.59 wpm (SD = 2.23), respectively (Fig. 5a).

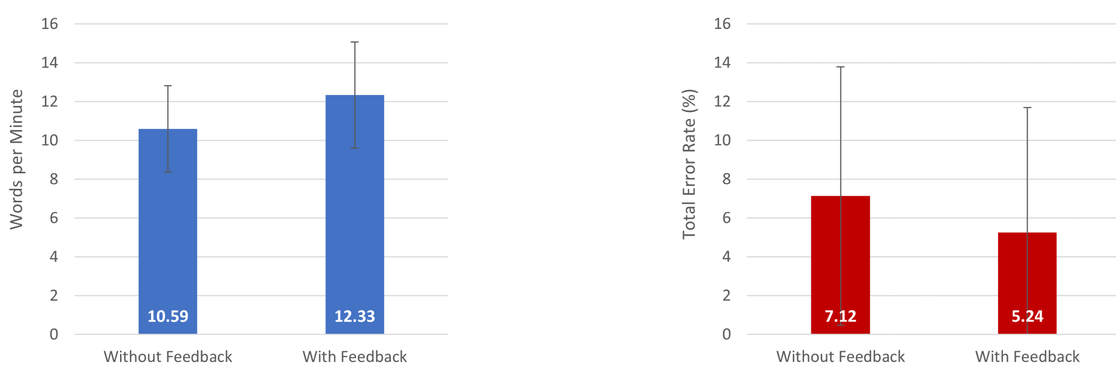
5.3.2 *Error Rate.* A paired samples T-test identified a significant effect of haptic feedback ($t_{143} = 2.52, p < .05$) on total error rate. The average error rate with and without haptic feedback were 5.24% TER (SD = 6.12) and 7.12% TER (SD = 6.65), respectively (Fig. 5b).

5.3.3 *Usability.* In the usability questionnaire, we asked participants to rate the perceived speed, accuracy, presence (felt physically present and accepted the reality of it), and consistency with real-world (the system seemed consistent with real-world experience) on a 5-point Likert-scale (1: disagree – 5: agree). A Wilcoxon Signed-Rank test identified a significant effect of feedback on perceived speed ($z = 2.322, p < .05$), presence ($z = 2.236, p < .05$) and consistency with real-world ($z = 2.332, p < .05$). However, no significant effect was identified on perceived accuracy ($z = 1.715, p = .08$). Fig. 6a illustrates median user ratings of the two methods.

5.3.4 *Perceived Workload.* In the NASA-TLX questionnaire, participants rated the perceived workload of the examined method on a 20-point scale (1: very low – 20: very high, except for "performance", where 1: perfect – 20: failure). Here, we present raw scores by analyzing the sub-scales individually, which is a common modification of the scale [23]. A Wilcoxon Signed-Rank test identified significant effects of haptic method on mental demand ($z = -1.999, p < .05$), performance ($z = -2.07, p < .05$), effort ($z = -2.598, p < .01$) and frustration ($z = -2.057, p < .05$). However, no significant effects were identified on physical demand ($z = -1.378, p = .16$) and temporal demand ($z = 1.06, p = .92$). Fig. 6b illustrates median NASA-TLX ratings of the two methods.

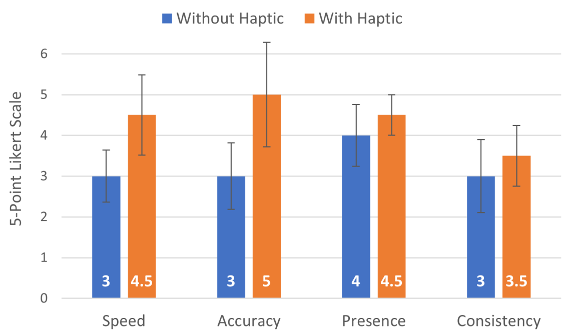
5.4 Discussion

The keyboard with haptic feedback outperformed the keyboard without haptic feedback both in terms of speed (16% faster) and accuracy (26% more accurate). Participants perceived the keyboard with haptic feedback to be significantly faster (Fig. 6) and felt that it improved their overall text entry performance (Fig. 6b). These results are most probably facilitated by the increased spatial awareness of the participants, reducing their reliability on sight and

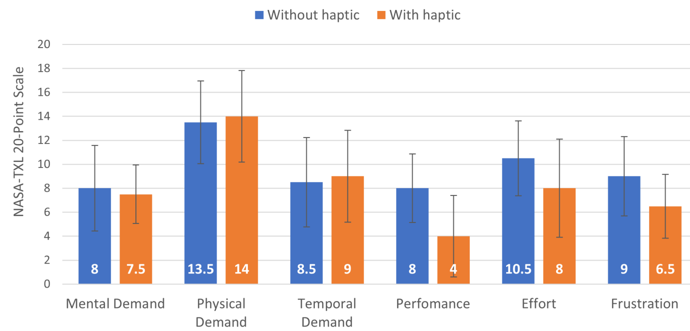


(a) Entry speed (wpm) **(b) Total error rate (%)**

Figure 5: Average text entry speed (wpm) and total error rate (%) with and without haptic feedback. Error bars represent ±1 standard deviation (SD).



(a) Median usability ratings



(b) Median raw NASA-TLX ratings

Figure 6: Median usability and raw NASA-TLX ratings of the keyboard with and without haptic feedback. Error bars represent ±1 standard deviation (SD).

proprioception to press the keys. In the post-study interview, one participant (male, 22 years) commented, *"I can type and know I pressed the key, I do not need to look that much."* Most participants were also more confident with haptic feedback. One participant (female, 36 years) felt that she performed much better with haptic feedback because *"I was more confident with my button presses when there is haptic feedback."* Naturally, participants found the keyboard with haptic feedback significantly less demanding in terms of mental demand and effort, thus caused significantly less frustration during text entry (Fig. 6b). Subjective feedback revealed that participants felt physically present and perceived their text entry experience comparable to real-world experience significantly more when interacting with the virtual keyboard with haptic feedback (Fig. 6a). In post-study interview, participants contributed these to the fact that they could sense the keys and receive feedback on keypress like actual keyboards. They articulated that they could use haptic feedback on touch as a "physical" point of reference, which helped them better orient in mid-air interaction by increasing spatial awareness. Yet, participants found both methods comparable in terms of physical and temporal demands (Fig. 6b). We speculate, this is due to the physical challenges associated with mid-air interaction in general.

One interesting observation is that participants in the final study yielded a higher text entry speed with touch & press haptic feedback than participants of the pilot study (12.33 vs. 10.25 wpm). This is most probably because the final study included more participants with virtual reality experience (∼42% of all participants). An analysis revealed that participants with prior experience were indeed on average 6% faster than participants without experience. However, this effect was not statistically significant ($p = 0.72$), possibly due to the small sample size.

Overall, the haptic sensation was well-received by the participants. Many compared the sensation with wind or vibration. One participant (female, 27 years) commented, *"I felt like wind is hitting my finger"*, while another (male, 23 years) said, *"I could feel the vibration on my finger."* They found the sensation *"cool"* and *"pretty good"*. However, two participants were not comfortable with it. One of them (female, 26 years) said that it *"annoyed"* her, the other (male, 22 years) compared the sensation with *"static electricity"*, thus *"too artificial for my liking."* Although text entry performance of these two participants were either better with haptic feedback or comparable to without haptic feedback. This suggests, further investigation is needed to make ultrasonic sensations more comparable to actual touch.

6 CONCLUSION

We designed three different types of ultrasonic haptic feedback to provide a better text entry experience with a mid-air Qwerty in virtual reality: feedback on keypress, feedback on both touch and keypress, and a gradual feedback that increases intensity as users push down a key. We compared the three feedback methods in a user study. Results revealed that text entry speed was significantly faster with both touch & press feedback and press feedback than gradual feedback, but participants found touch & press more natural than the others. We then compared a mid-air Qwerty with and without touch & press feedback in a user study. Results revealed that haptic feedback improved speed by 16% and reduced error rate by 26%. Most importantly, majority of the participants felt that the feedback improved their presence and spatial awareness in the virtual-world by maintaining a higher consistency with the real-world. They also felt that the feedback reduced mental demand, effort, and frustration in text entry tasks, thus wanted to continue using it.

7 LIMITATIONS & FUTURE WORK

There are several limitations of the work. First, the studies used a small sample size and collected insufficient datapoints for deeper analyses investigating the effects of practice (learning curve) and experience with virtual reality systems. This is particularly important because the results of this work indicated a potential effect of VR experience on text entry speed. Second, we did not include a physical Qwerty in the evaluations. It would have been interesting to record performance differences between physical and mid-air Qwerty keyboards, and particularly, to what extent haptic feedback bridges this gap. We will address these in a future work. In addition, we will investigate the effects of physical and mid-air Qwerty keyboards on immersion and presence in the virtual world. We will also explore different positions of the haptic board and the virtual keyboard, as well as different interaction postures, to improve text entry experience with mid-air Qwerty augmented with haptic feedback. Finally, we will investigate different ultrasound patterns and duration to make the feedback more realistic, distinguishable, and pleasant.

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