Pseudo-haptic and Self-haptic Feedback During VR Text Entry

Maria Kounalaki
mkoun22@gmail.com
University of Patras
Rio, Greece

Ioulia Simou
simo@ceid.upatras.gr
University of Patras
Rio, Greece

Andreas Komninos
akomninos@ceid.upatras.gr
University of Patras
Rio, Greece

ABSTRACT

The use of virtual reality (VR) equipment is becoming increasingly common in people's daily lives concerning a variety of applications and utilities. Text entry in the VR environment has always been a challenge and a main subject of research in HCI, especially when it comes to human-centered and user-friendly interfaces and implementations. To assist occasional text entry on small VR keyboards without specialised sensing equipment or external devices, we compare a single-finger method relying on pseudo-haptic feedback, and a novel bimanual approach that exploits the self-haptic feedback method. In a user study (n=24), we find that both methods have comparable performance but also distinct advantages and disadvantages, demonstrating good learnability and promising prospects for further refinement.

CCS CONCEPTS

• **Computer systems organization → Embedded systems**; *Redundancy*; Robotics; • **Networks** → Network reliability.

KEYWORDS

datasets, neural networks, gaze detection, text tagging

ACM Reference Format:
Maria Kounalaki, Ioulia Simou, and Andreas Komninos. 2023. Pseudo-haptic and Self-haptic Feedback During VR Text Entry. In *2nd International Conference of the ACM Greek SIGCHI Chapter (CHIGREECE 2023), September 27–28, 2023, Athens, Greece.* ACM, New York, NY, USA, 8 pages. https://doi.org/10.1145/3609987.3610002

1 INTRODUCTION

Text entry in virtual reality (VR) environments plays a crucial role in enabling users to interact and communicate within immersive virtual worlds. Efficient and accurate text input methods are essential for various applications, including gaming, simulations, training, and productivity tasks. However, designing effective text entry mechanisms in VR presents unique challenges due to the absence of physical keyboards and the need to provide users with appropriate feedback. Related work on text entry in VR environments, focuses on input techniques categorized as physical and virtual. Physical input techniques involve the use of external physical devices for text entry, while virtual techniques rely on in-scene virtual keyboards that can be manipulated through various means, such as head pointing, hand gestures, or the use of game controllers. Tactile feedback during text entry has been identified as a critical factor in task performance, and methods offering tactile feedback alongside visual or audio feedback are considered superior.

Various complex technical solutions have been proposed to provide tactile feedback in VR text entry, including advanced controllers with deformable or moving surface interfaces, non-contact haptics using ultrasound or air vortex, and wearable devices such as rings, gloves, or wrist wearables. While these solutions offer high-fidelity tactile feedback and enhance immersiveness and realism, they often require additional complex hardware and are more suitable for applications where realism is paramount, such as gaming or simulations. However, for basic text entry contexts, a realistic mapping of tactile feedback may not be essential. To this end, pseudo-haptic methods (e.g. simulating haptics through visual means) has been previously proposed and found to be a viable alternative.

This paper presents a novel bimanual input paradigm for VR text entry in the context of enabling target selection in a small area, comparable to the size of a smartphone, without relying on precise physical-virtual hand mappings. This bimanual method allows the user to highlight keys with one hand and uses a pinch-to-select gesture using the second hand, offering a level of abstract tactility (self-haptics) that helps users provide unambiguous input commands. We compare this method against a more "traditional" approach that leverages pseudo-haptic feedback (namely, colour highlighting on selection confirmation), and highlight the performance and experience aspects of each method.

2 RELATED WORK

Text entry in VR environments is reviewed comprehensively in [12], which distinguishes input techniques in two main categories: Physical (i.e. with the use of an external physical device for input), and Virtual (i.e. using an in-scene virtual keyboard instance which can be manipulated with various techniques. These may include physical movement (e.g. head pointing, mid-air hand gestures or movement), or use of an external device which is not dedicated to text entry (e.g. a game controller). As such, we can probably re-think the classification of input techniques into those which offer the user some form of tactile feedback during entry (e.g. the click of a game controller button, or the touch of a controller on a physical surface), and those which rely exclusively on visual or audio feedback (e.g. head-tracking, mid-air hand gestures). It has been documented since the early days of touchscreen mobile text entry, that lack of tactile feedback is a severe impediment in task performance [18]. Therefore, methods which offer some form of tactile feedback alongside visual indicators of action and effect during VR text entry, are highly important.

CHIGREECE 2023, September 27–28, 2023, Athens, Greece

ACM ISBN 979-8-4007-0888-6/23/09.
https://doi.org/10.1145/3609987.3610002

Tactile feedback can be offered through a variety of complex technical solutions, which may include advanced controllers using deformable or moving surface interfaces (e.g. [6], for a comprehensive review see [7]). Other technologically advanced solutions include non-contact haptics (e.g. through ultrasound or air vortex [4]) and the use of ring, glove or wrist wearables (e.g. see [28]). Although technically impressive, these approaches rely on use of further complex hardware to provide a direct mapping between the virtual world and the physical sensation for the user, which aims to approximate as closely as possible the experience of the real world. Therefore, these approaches are necessary in application contexts where immersiveness and realism are highly important (e.g. gaming, simulations, training). On the other hand, performance of basic tasks such as text entry is necessary in a range of other contexts, where the direct mapping between physical and virtual does not need to be highly accurate, as, for example, taking occasional notes in a VR application (e.g. [10]), or responding to real world messages while immersed in a VR environment for another purpose (e.g. [19]). In effect, such use contexts require simply that text entry is fast and accurate, i.e. benefits from the existence of multimodal feedback, including haptic feedback, and is not overly concerned with a realistic mapping of this feedback. Put differently, a more abstract mapping of haptic sensation and the VR environment is sufficient to improve text entry performance. Demonstrating this, work in [17, 34] showed that the actual design and mapping of haptic feedback may not play a significant role in VR text entry performance - it is enough that *some* form of feedback exists. Corroborating evidence is found in studies such as [14, 31], where VR keyboard placement so as to align with a physical surface (table) improved performance, simply because of the physical tactility inherent in the setup.

Additionally, in some use cases, the presence of external hardware for high-fidelity tactile feedback may not be available for reasons of cost, complexity, encumbrance, or mobility. Therefore, the challenge remains, how to afford some level of tactile physicality in the text entry task, without specialised equipment. Towards this, proposals for self-haptics (using the user's own body as a surface to provide tactile feedback) have been proposed [15, 22]. The concept has been successfully applied in various implementations for text entry, for example with an ambiguous keyboard mapped on user's nails [23] or hand knuckles [11], or using pinch gestures to indicate selection of a desired key in an ambiguous keyboard mapping [16, 20, 22]. The pinch gesture as a method to select and affirm input was found superior to pseudo-haptics (i.e. the visual illusion of haptic effects, for example 3D buttons being recessed as they are "pressed" [8, 13], or otherwise enhanced with some special visual effect [21]). One problem with current pinch-based approaches, is that the user needs to learn and remember the appropriate mappings in order to efficiently use the keyboard.

In this paper we present a novel bimanual input paradigm, in which the user uses one hand to precisely select the desired character in a virtual QWERTY keyboard, while using a pinch gesture in the other hand to confirm selection. This approach aims to overcome two problems with mid-air VR text entry. First, the need to precisely track fingers without hand-worn sensors or markers. Due to this problem, VR keyboard targets need to be very large, occupying extensive amounts of screen space [1, 9, 30, 33]. In contrast, our prototype enables target selection in a very small area, the size of a normal smartphone, which does not need precise mappings between the physical and virtual hands of the user. Secondly, the pinch-to-select gesture using the second hand, affords a level of abstract tactility which helps users provide unambiguous input commands, thereby aiming to improve the text entry process, without having to learn or remember complex self-haptic mappings. This novel method is compared against a more traditional approach, that leverages the pseudo-haptic paradigm introduced in [21].

3 SYSTEM DESIGN AND IMPLEMENTATION

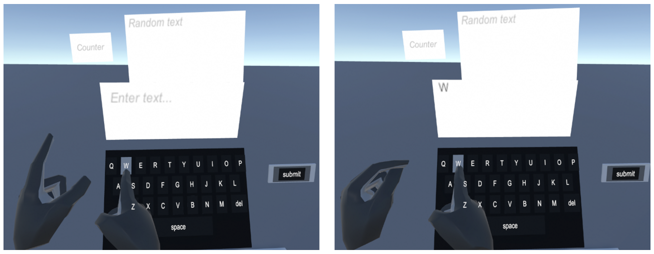
For the design and implementation, we used the HTC Vive VR headset on which we mounted the Ultraleap's Leap Motion Controller for hand tracking. For the development we used Unity game development platform and we installed the Ultraleap Unity API. This Ultraleap Unity Plugin empowers developers to build Unity applications using Unltraleap's hand tracking technology. After installing the Unity API, we created two new scenes and added a Leap Provider prefab to each scene. The Leap Provider defines the basic interface our plugin expects to use to retrieve frame data. We then added a set of hands to the scene as a child of the Leap Provider.

3.1 Implementation

We created two different implementations in order to represent and examine text entry in a VR environment. Our goal was to create user friendly interactions that would remind the user of the natural movements and gestures they make to type text with their mobile, but also suggest alternative ways in order to achieve the same goal.

3.1.1 Keyboard. For the design of the keyboard, we used the QWERTY layout which is the most common in mobile devices. The keyboard, which is used in both implementations, is basically a GameObject with two children, the keyboard screen which is a Canvas *GameObject* with an *InputField* and the UI panel which includes all the keys: the alphabet letters, the "space" button and the "backspace" button. Each key is a different *InteractionBehaviour*. InteractionBehaviours are components that enable GameObjects to interact with interaction controllers in a physically intuitive way. By default, they represent objects that can be poked, prodded, smacked, grasped, and thrown around by Interaction controllers, including Leap hands which we used in our implementations. They also provide a thorough public API with settings and hovering, contact, and grasping callbacks for creating physical interfaces or overriding the default physical behavior of the object. These GameObjects with an InteractionBehaviour component may be referred to as interaction objects. Thus, each GameObject button includes an InteractionButton script component which refers to a physics-enabled button. These are activated by physically pressing the button, with events for "press" and "unpress" actions.

3.1.2 "Two Handed Interaction" scene - Self-haptics (K1). In this implementation, the keyboard UI is stationary in the scene. We designed this implementation so that the user can experience self-haptic feedback when the keys are pressed. We created this feeling by adding gesture detection events in the typing process. Specifically, the users use their right index finger to indicate the key they



(a) Self-haptic keyboard (K1). Users glide (hover) their index finger over the keyboard to select a key, and pinch with the left hand to enter the selected key.

(b) Pseudo-haptic keyboard (K2). Users hover over the keyboard and push their index finger forward to enter the selected key. keys proximal to the fingertip are highlighted grey.

Figure 1: The two keyboards designed for our study.

want to press, simply by hovering over it. Keys proximal to the fingertip are highlighted grey. Then, in order to perform the "click" action they must use their left hand and make a pinch gesture by connecting their left index and thumb. Once these two fingers are successfully pressed together, the hovered key is clicked and the corresponding character instantly appears on the keyboard text entry area Fig. 1a.

3.1.3 "One Handed Interaction" scene - Pseudo-haptics (K2). In this implementation, the keyboard is stationary in front of the user and requires only one hand interaction for the text entry process. We designed this implementation so that the users can simply hover over the keyboard, with keys proximal to the fingertip highlighted grey. To enter a character, users press slightly the highlighted key using their index finger. When the virtual finger intersects the key plane, the users are provided with pseudo-haptic feedback, as the button recedes from its slightly protruding position, and turns green in order to indicate that it was pressed successfully (see Fig. 1b).

4 EXPERIMENTAL PROTOCOL

4.1 Experiment Design

We designed an experiment that consisted of three conditions: typing in a real mobile keyboard to establish a participant skill baseline for mobile QWERTY, typing using the first keyboard type with the gesture detector and typing using the second keyboard type with the press events. We followed the within-group design approach in which all the participants were involved in all the conditions. All participants began with the baseline condition of typing on an actual mobile device and then moved on to the VR keyboard implementations. We used the baseline condition post-experiment for the sole purpose of examining if any participants were extreme outliers (i.e. complete novices or with severe motor/cognitive issues). The order of presenting the two VR keyboards was counterbalanced to avoid unwanted effects. Each participant was asked to type 3 blocks of 7 random phrases from the Vertanen & McKenzie's Memorable Phrase Set [32] with each keyboard, resulting in a total of 21 phrases for each keyboard type. To record data, we used WebTEM [5] for the baseline condition, and custom code to capture participants' input streams integrated into our VR keyboards. For the VR keyboards, we recorded the entire timestamped input stream and analysed the data off-line to extract the following metrics: Words-per-minute (WPM), Keystrokes per Second (KSPS), Corrected Error Rate (CER), Total Error Rate (TER) and Keystrokes per Character (KSPC).

4.1.1 Demographics and questionnaires. Demographic data were collected at the initial stage of the study. Demographic data included personal data such as age, gender, current employment status, English knowledge level, previous experience in VR equipment, personal VR equipment ownership, frequency of use and finally subjective ratings on the typing skills in mobile keyboards in a Likert scale from 1 ("very low") to 5 ("very high").

User experience was measured using the structure of the first part of the Game Experience Questionnaire (GEQ), which has been used in several domains (such as gaming, augmented reality and location-based services) because of its ability to cover a wide range of experiential factors with good reliability [25–27]. The use of GEQ is also established in the VR domain in several studies around such topics as locomotion in virtual environments [24], haptic interaction in VR [2], VR learning [3], and VR gaming [29], among others. This questionnaire assesses game experience as scores on seven components: Immersion, Flow, Competence, Positive and Negative Affect, Tension, and Challenge.

4.1.2 Experimental procedure. We distributed an online invitation for the VR experiment, accompanied by a pre-experiment demographics questionnaire. Those interested then arranged a convenient date and time to participate in the experimental process. In the beginning of the experiment, the participants were welcomed in the lab, they were offered something to drink or eat, then they were asked to sign a consent form and they were assigned an ID number. They were also informed of the potential risk of motion-sickness and that they can opt out of the study at any time.

For each one of the three keyboard types, participants were asked to type the three blocks of seven random phrases each with small break times between every block. We instructed participants to type "as quickly and as accurately as possible" during the trials. At the start of the baseline condition, participants completed a familiarisation block of 7 phrases, without using input support (word suggestions and autocorrect). When the baseline session was completed, participants were asked to sit comfortably in front of the desktop. We explained to them that they would not use any VR controllers and that the head mounted camera would track their hands during the experiment. We performed a headset try-on so that they would feel comfortable in the VR environment and introduced them to the corresponding scene. For each VR keyboard, the participants were given the proper instructions concerning the hands and fingers they should use and the gestures they should perform for the typing process. Before the main keyboard sessions, participants practiced on the corresponding keyboard and typing technique by writing their names until they declared themselves ready to begin the experiment. After each VR keyboard session was completed, the participants were asked to complete the experience questionnaire for the corresponding keyboard type.

4.1.3 Materials. The equipment used for the study, besides the HTC Vive VR headset and the attached Leap Motion Controller camera for the VR sessions, was a Nokia 8.3 5G smartphone for the text entry in the baseline condition.

4.1.4 Participants. We recruited 24 participants (8 identified as female, 16 as male) through convenience sampling at our university department, aged between 19-32 years old (mean age $\bar{x} = 23.26, \sigma = 3.646$). Seven participants had occasionally used VR equipment and applications prior to the experiment but only one owned such equipment and used it regularly. Their English skills were reported as Intermediate (B2: 5 participants), Advanced (C1: 3 participants) and Proficient (C2: 16 participants). Participants self-rated their mobile typing skills on a Likert scale (1=very bad, 5=very good) with a mean rating $\bar{x} = 3.52$ ($\sigma = 0.73, min = 2, max = 5$). Based on the results of the baseline condition analysis (typing on an actual mobile device), we did not exclude any participants from the results (WPM $\bar{x} = 33.739, \sigma = 6.519, min = 22.198, max = 55.115$, TER $\bar{x} = 3.170, \sigma = 2.516, min = 0.0, max = 10.392$, all in-line with expected performances as per the literature).

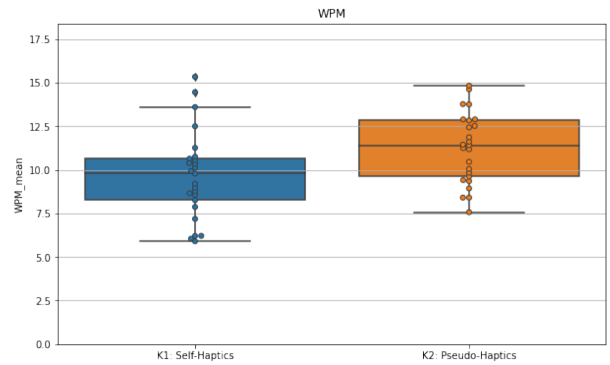
5 EXPERIMENTAL RESULTS

In this section, statistical tests are reported according to the relevant choice of test based on the examination of assumptions for the appropriateness of use.

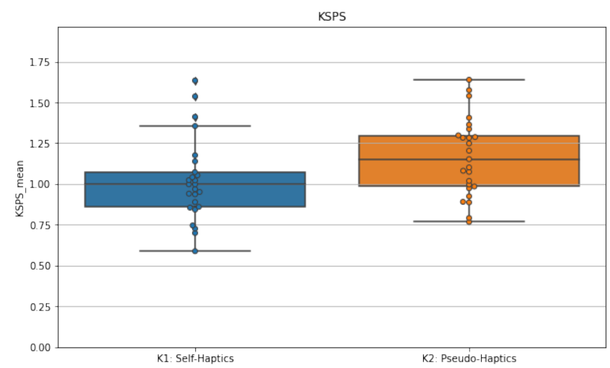
5.1 Text entry speed

We examined first the WPM rates for both keyboards. Text entry was faster with the pseudo-haptic keyboard (K2 WPM $\bar{x} = 11.249, \sigma = 2.010$) than the self-haptic keyboard (K1 WPM $\bar{x} = 9.657, \sigma = 2.511$), as per Fig.2a. A T-test showed this difference as statistically significant ($t = -3.803, p = 0.001$). This is partly explained by the KSPS, which was higher with the pseudo-haptic keyboard (K2 WPM $\bar{x} = 1.164, \sigma = 0.239$) than the self-haptic keyboard (K1 WPM $\bar{x} = 1.019, \sigma = 0.252$), as per Fig.2b, with statistical significance (T-test $t = -3.893, p = 0.001$). Overall text entry speed is not very high, but can be explained due to the novelty of the experience for most participants, the tracking accuracy of Leap Motion and also the size of the targets, which were quite small.

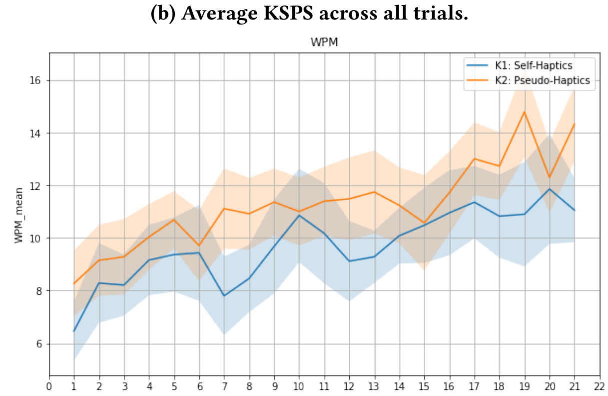
We examined the participants' performance over time as the experiment progressed. As seen in Figs.2c and 2d, it is evident that participants can become more proficient with more training, steadily improving both WPM and KSPS metrics. Participants started with very low entry rates that were almost doubled by the end of the experiment. Therefore, the low entry speed observed with both methods can be significantly improved over time.



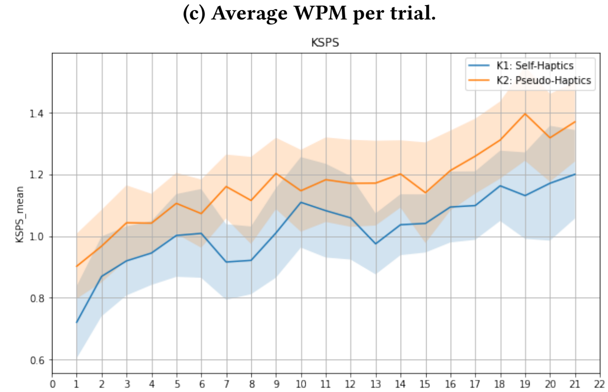
(a) Average WPM across all trials.



(b) Average KSPS across all trials.



(c) Average WPM per trial.



(d) Average KSPS per trial.

Figure 2: Text entry speed metrics (error margins at 95%c.i.).

5.2 Error Metrics

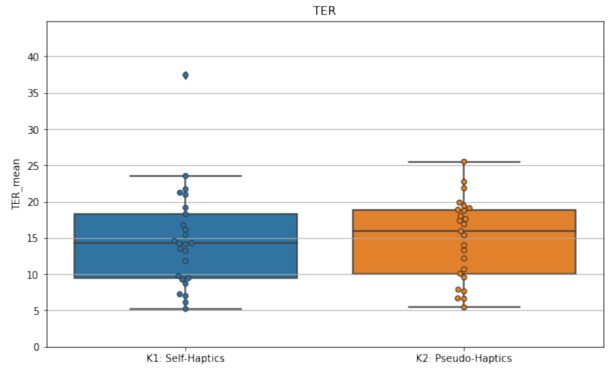
To examine errors, we first report the TER metric which encompasses both fixed, and unfixed errors during text entry. In both keyboards, the performance is near-identical (K1 $\bar{x} = 14.756, \sigma = 6.993$; K2$\bar{x} = 14.843, \sigma = 5.596$), as shown in Figs. 3b and 3a. The difference is not statistically significant (Wilcoxon $Z = 149.0, p = 0.731$). CER was also not statistically significantly different (K1 $\bar{x} = 0.134, \sigma = 0.065$; K2 $\bar{x} = 0.136, \sigma = 0.055$; Wilcoxon $Z = 152.0, p = 0.791$). Similarly, we did not find any statistically significant differences in KSPC (K1 $\bar{x} = 1.344, \sigma = 0.199$; K2$\bar{x} = 1.283, \sigma = 0.121$, Wilcoxon $Z = 109.0, p = 0.156$). Similar to the findings for text entry speed, we observe a clear trend towards performance improvement with more training. As can be seen in Figs. 3d and 3c, participants were able to improve both TER and KSPC towards the end of the experiment.

5.3 Subjective Feedback

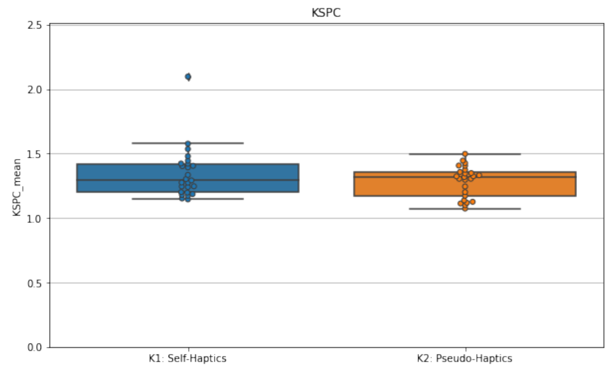
We used the GEQ, an instrument assessing scores on seven components with 30 questions: Immersion, Flow, Competence, Positive and Negative Affect, Tension, and Challenge. The questions in the components are measured with Likert scales (1 = not at all, 2=slightly, 3=moderately, 4=fairly, 5 = extremely). Question scores are averaged to report each component composite score, therefore in Table 1 the reported scores are between 1-5. We note that participants rated both keyboards equally with the exception of "Flow", where the observed difference in favour of K2: Self-Haptics was statistically significant. Interestingly, we note that participants self-reported to be *moderately competent* despite their low WPMs, having a *moderate flow* within the experience, and found the text entry process to be *slightly challenging*. Affect was *fairly positive* and only rated *slightly negative*, with tension reported between *not at all* and *slight* (Fig.4).

At the end of the GEQ, we left space for participants to note three things they liked and three they didn't like about each VR keyboard. From these comments, we present indicative responses with the number of participants in parentheses. Self-haptics were reported to be fun (6) and to afford good control over the input process (6). Several participants felt this method might be more appropriate for faster typing once mastered (7). On the other hand, some participants experienced problems with hand tracking and the pinch recognition (6) which detracted from the experience. Some participants felt tired because of the need to use both hands (8) and had some difficulty adjusting to the need of synchronising the select and confirm actions with different hands (3). Finally, four participants commented that they would have preferred a combination of colour highlighting with the pinch gesture.

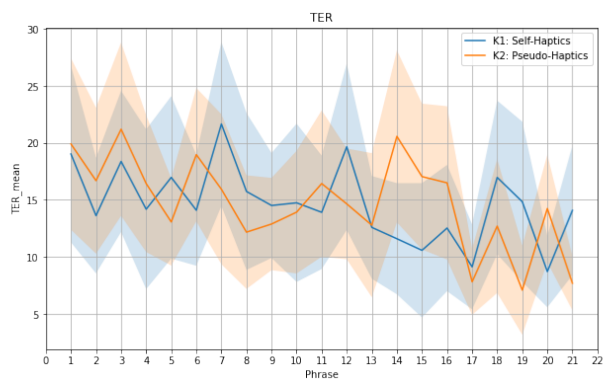
Pseudo-haptics were assessed as a faster and more effortless way to enter text (6) and afforded a more natural interaction (2). Several participants also commented they were impressed by the experience (8) and one participant even mentioned feeling "tricked" into having actual touch sensations on their finger. On the negative side, participants reported the method being tiring due to the constant back-and-forth of the entire arm (7). They also reported issues with hand-tracking that resulted in actions not being registered, being registered twice, or otherwise producing erroneous events (10), therefore believing the method afforded them less control over the self-haptic method.



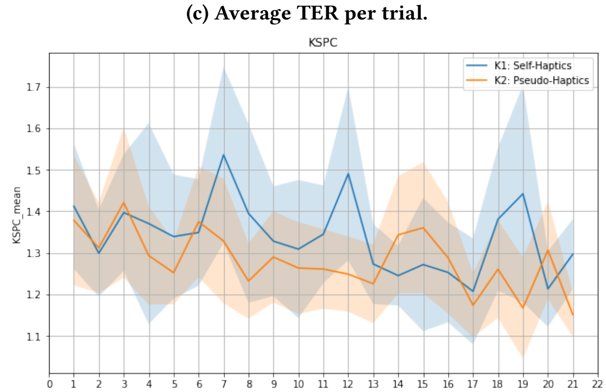
(a) Average TER across all trials.



(b) Average KSPC across all trials.



(c) Average TER per trial.



(d) Average KSPC per trial.

Figure 3: Error metrics (error margins at 95%c.i.).

GEQ component	K1: Self-Haptics	K2: Pseudo-Haptics	Statistical test
Competence	3.76 (0.698)	3.792 (0.471)	t=-0.278, p=0.784
Sensory and Imaginative Immersion	3.787 (0.700)	3.687 (0.568)	t=0.888, p=0.383
Flow	**3.136** (0.840)	**2.920** (0.619)	**Z=61.0, p=0.019**
Tension/Annoyance	1.613 (0.756)	1.667 (0.674)	Z=80.5, p=0.827
Challenge	2.104 (0.545)	2.056 (0.508)	t=0.456, p=0.653
Negative affect	1.810 (0.469)	1.78 (0.588)	Z=112.5, p=0.916
Positive affect	4.056 (0.803)	4.016 (0.565)	t=0.282, p=0.780

Table 1: GEQ component mean scores (standard deviations in parentheses), and pairwise statistical tests (t-test and Wilcoxon as appropriate, significant differences in bold).

6 DISCUSSION

In this paper, our goal was to create, examine and present input paradigms for mid-air text entry in small VR keyboards, using bare hands interaction. The self-haptic keyboard is a bimanual method which offered the users a level of abstract tactility (self-haptics) using the right hand to select keys and the left hand to confirm the selection with a pinch gesture. This method was compared to the pseudo-haptic depression and color feedback approach. Concerning the text entry speed, the pseudo-haptic keyboard (K2) demonstrated faster text entry speed compared to the self-haptic keyboard (K1). Overall, the findings suggest that the pseudo-haptic keyboard (K2) outperformed the self-haptic keyboard (K1) in terms of text entry speed, specifically in WPM and KSPS. However, there were no significant differences in error rates between the two keyboards. Subjectively, participants rated both keyboards similarly, except for higher ratings of "Flow" with the pseudo-haptic keyboard. The feedback highlighted both positive and negative aspects for each keyboard design, indicating areas of improvement such as hand tracking accuracy and providing visual feedback. The study also emphasized the potential for participants to improve their performance over time with more training.

The closest related work to ours are those in Kim and Xiong [22] and PinchText [20]. The former study [22] compared self-haptic vs pseudo-haptic feedback on a large QWERTY keyboard with dimensions similar to a physical full-size desktop keyboard. Typing with both hands, participants reached a WPM average of approximately 19WPM in both conditions, with a statistically significant difference in CER (self-haptics: $\bar{x} = 9.3\%$; pseudo-haptics $\bar{x} = 11.4\%$). In comparison, we found self-haptics mean entry speed to be slower than pseudo-haptics (K1: $\bar{x} = 9.657WPM$, K2: $\bar{x} = 11.249WPM$) and mean CER was the same across both keyboards (CER K1: $\bar{x} = 13.4\%$, K2: $\bar{x} = 13.6\%$). The difference in speed between our study and [22] is reasonable since our participants typed with one hand and on a small area keyboard (similar to performance differences in real desktop and mobile keyboards). We note that the difference in CER is quite small and is potentially attributable to the small size of our keyboard and hand-tracking issues encountered by the participants, as we used different hardware for our implementation.

Pinchtext [20] examined one-handed input on an ambiguous (12-key) keyboard using the whole lower arm to select a keyboard row and pinching between the thumb and index, middle or ring finger to select columns. Table 2 shows the performance statistics for participants, after exposure to the same number of phrases, demonstrating that our bimanual method has a potential for higher text entry rates with comparable error rates (note that [20] used CKER, a similar, but not the same metric as CER).

Based on the aforementioned findings, further research still needs to be carried out in order to investigate the promising concept of self-haptics more deeply. We provide some possible future improvements for the system. First, concerning hand tracking and pinch recognition, we could address the reported issues to ensure more accurate and reliable gesture detection. Improving these aspects would enhance the overall user experience and reduce frustrations. Second, we could consider single-handed input since some participants experienced fatigue and difficulties with synchronizing “select” and “confirm” actions using different hands. We should consider refining the interaction design to enable more intuitive and comfortable single-handed input, reducing the need for coordination between both hands. Third, additional visual feedback. By incorporating visual feedback to the self-haptic keyboard, such as color highlighting of the selected key, we could provide users with additional cues and enhance their understanding of the input process. Visual feedback can improve the user experience and reduce uncertainty during text entry. Fourth, training and mastery. Participants mentioned that self-haptics might enable faster typing once mastered. We could explore ways to provide training resources or tutorials that help users improve their proficiency and speed with the system. This could include interactive exercises and feedback mechanisms to facilitate skill development. Fifth, addressing fatigue. Participants reported fatigue with both the self-haptics and pseudo-haptics methods, albeit for different reasons. We could investigate ergonomic considerations and design adjustments to minimize physical strain and fatigue associated with long-duration text entry tasks. This could involve optimizing the hand and arm movements required or exploring alternative input methods. Sixth, error reduction. We should address issues related to actions not being registered or producing erroneous events, which were reported in both self-haptics and pseudo-haptics methods. The idea of adding a cursor as an indicator which could also be placed in different positions in the input field area, or adding more gestures for error correction, can afford the users greater control over their input actions and fewer frustrating errors. Seventh, user training and familiarity. Participants rated themselves as moderately competent despite their low typing speeds. We could consider conducting studies with participants who are more experienced or familiar with using virtual reality (VR) keyboards, as their feedback may

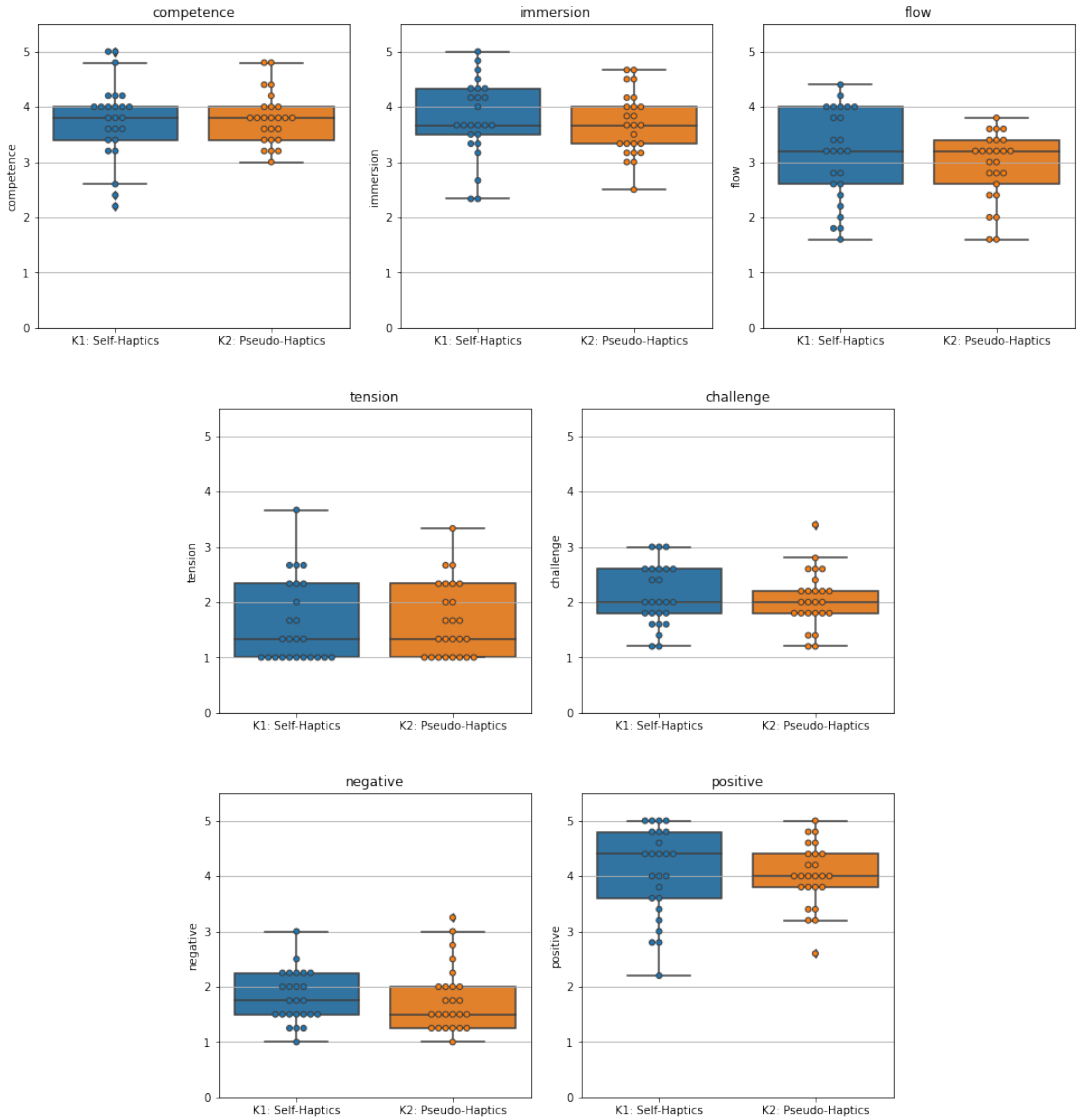


Figure 4: GEQ component scores. Error metrics (error margins at 95%c.i.).

	Jiang et al. [20]	K1 (our study)	Jiang et al. [20]	K1 (our study)
Phrase range	1-10		11-20	
WPM	6.10 - 8.13	8.90	8.54 - 9.02	10.59
CKER[a]/CER[b]	8 - 13%[a]	14.46%[b]	8 - 9%[a]	12.06%[b]

Table 2: Comparison between performance metrics in our study and Jiang et al.[20]

provide more insights into the system's usability and performance. Overall, by addressing these areas for improvement, the system can enhance user satisfaction, increase input efficiency, reduce fatigue, and provide a more seamless and immersive text entry experience in virtual reality environments.

REFERENCES

[1] Jiban Adhikary and Keith Vertanen. 2021. Text Entry in Virtual Environments Using Speech and a Midair Keyboard. *IEEE Transactions on Visualization and Computer Graphics* 27, 5 (Feb. 2021), 2648–2658. https://doi.org/10.1109/TVCG.2021.3067776

[2] Imtiaj Ahmed, Ville Harjunen, Giulio Jacucci, Eve Hoggan, Niklas Ravaja, and Michiel M. Spapé. 2016. Reach out and touch me: effects of four distinct haptic technologies on affective touch in virtual reality. In *Proceedings of the 18th ACM International Conference on Multimodal Interaction*. ACM, Tokyo Japan, 341–348. https://doi.org/10.1145/2993148.2993171

[3] Panagiotis Apostolellis and Doug A. Bowman. 2014. Evaluating the effects of orchestrated, game-based learning in virtual environments for informal education. In *Proceedings of the 11th Conference on Advances in Computer Entertainment Technology (ACE '14)*. Association for Computing Machinery, New York, NY, USA, 1–10. https://doi.org/10.1145/2663806.2663821

[4] Faisal Arafsha, Longyu Zhang, Haiwei Dong, and Abdulmotaleb El Saddik. 2015. Contactless Haptic Feedback: State of the Art. In *2015 IEEE International Symposium on Haptic, Audio and Visual Environments and Games (HAVE)*. 1–6. https://doi.org/10.1109/HAVE.2015.7359447

[5] Ahmed Sabbir Arif and Ali Mazalek. 2016. WebTEM: A Web Application to Record Text Entry Metrics. In *Proceedings of the 2016 ACM International Conference on Interactive Surfaces and Spaces (ISS '16)*. Association for Computing Machinery, New York, NY, USA, 415–420. https://doi.org/10.1145/2992154.2996791

[6] Hrvoje Benko, Christian Holz, Mike Sinclair, and Eyal Ofek. 2016. NormalTouch and TextureTouch: High-fidelity 3D Haptic Shape Rendering on Handheld Virtual Reality Controllers. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology (UIST '16)*. Association for Computing Machinery, New York, NY, USA, 717–728. https://doi.org/10.1145/2984511.2984526

[7] Carlos Bermejo and Pan Hui. 2021. A Survey on Haptic Technologies for Mobile Augmented Reality. *Comput. Surveys* 54, 9 (July 2021), 184:1–184:35. https://doi.org/10.1145/3465396

[8] Carlos Bermejo, Lik Hang Lee, Paul Chojecki, David Przewozny, and Pan Hui. 2021. Exploring Button Designs for Mid-air Interaction in Virtual Reality: A Hexa-metric Evaluation of Key Representations and Multi-modal Cues. *Proceedings of the ACM on Human-Computer Interaction* 5, EICS (Feb. 2021), 194:1–194:26. https://doi.org/10.1145/3457141

[9] Costas Boletsis and Stian Kongsvik. 2019. Text Input in Virtual Reality: A Preliminary Evaluation of the Drum-Like VR Keyboard. *Technologies* 7, 2 (March 2019), 31. https://doi.org/10.3390/technologies7020031 Publisher: Multidisciplinary Digital Publishing Institute.

[10] Yi-Ting Chen, Chi-Hsuan Hsu, Chih-Han Chung, Yu-Shuen Wang, and Sabarish V. Babu. 2019. iVRNote: Design, Creation and Evaluation of an Interactive Note-Taking Interface for Study and Reflection in VR Learning Environments. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. 172–180. https://doi.org/10.1109/VR.2019.8798338 ISSN: 2642-5254.

[11] Samir K. Dash. 2017. INPUT DEVICE INTERACTION. , 22 pages. https://image-ppubs.uspto.gov/dirsearch-public/print/downloadPdf/20170090747

[12] Tafadzwa Joseph Dube and Ahmed Sabbir Arif. 2019. Text Entry in Virtual Reality: A Comprehensive Review of the Literature. In *Human-Computer Interaction. Recognition and Interaction Technologies (Lecture Notes in Computer Science)*, Masaaki Kurosu (Ed.). Springer International Publishing, Cham, 419–437. https://doi.org/10.1007/978-3-030-22643-5_33

[13] Tafadzwa Joseph Dube and Ahmed Sabbir Arif. 2020. Impact of Key Shape and Dimension on Text Entry in Virtual Reality. In *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems (CHI EA '20)*. Association for Computing Machinery, New York, NY, USA, 1–10. https://doi.org/10.1145/3334480.3382882

[14] John Dudley, Hrvoje Benko, Daniel Wigdor, and Per Ola Kristensson. 2019. Performance Envelopes of Virtual Keyboard Text Input Strategies in Virtual Reality. In *2019 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. 289–300. https://doi.org/10.1109/ISMAR.2019.00027 ISSN: 1554-7868.

[15] Cathy Mengying Fang and Chris Harrison. 2021. Retargeted Self-Haptics for Increased Immersion in VR without Instrumentation. In *The 34th Annual ACM Symposium on User Interface Software and Technology (UIST '21)*. Association for Computing Machinery, New York, NY, USA, 1109–1121. https://doi.org/10.1145/3472749.3474810

[16] Jacqui Fashimpaur, Kenrick Kin, and Matt Longest. 2020. PinchType: Text Entry for Virtual and Augmented Reality Using Comfortable Thumb to Fingertip Pinches. In *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems (CHI EA '20)*. Association for Computing Machinery, New York, NY, USA, 1–7. https://doi.org/10.1145/3334480.3382888

[17] Aakar Gupta, Majed Samad, Kenrick Kin, Per Ola Kristensson, and Hrvoje Benko. 2020. Investigating Remote Tactile Feedback for Mid-Air Text-Entry in Virtual Reality. In *2020 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. 350–360. https://doi.org/10.1109/ISMAR50242.2020.00062 ISSN: 1554-7868.

[18] Eve Hoggan, Stephen A. Brewster, and Jody Johnston. 2008. Investigating the Effectiveness of Tactile Feedback for Mobile Touchscreens. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '08)*. Association for Computing Machinery, New York, NY, USA, 1573–1582. https://doi.org/10.1145/1357054.1357300

[19] Ching-Yu Hsieh, Yi-Shyuan Chiang, Hung-Yu Chiu, and Yung-Ju Chang. 2020. Bridging the Virtual and Real Worlds: A Preliminary Study of Messaging Notifications in Virtual Reality. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–14. https://doi.org/10.1145/3313831.3376228

[20] Haiyan Jiang, Dongdong Weng, Xiaonuo Dongye, and Yue Liu. 2022. PinchText: One-Handed Text Entry Technique Combining Pinch Gestures and Hand Positions for Head-Mounted Displays. *International Journal of Human– Computer Interaction* 0, 0 (Dec. 2022), 1–17. https://doi.org/10.1080/10447318.2022.2115333 Publisher: Taylor & Francis.

[21] Woojoo Kim and Shuping Xiong. 2022. Pseudo-Haptic Button for Improving User Experience of Mid-Air Interaction in VR. *International Journal of Human-Computer Studies* 168 (Sept. 2022), 102907. https://doi.org/10.1016/j.ijhcs.2022.102907

[22] Woojoo Kim and Shuping Xiong. 2022. Pseudo-Haptics and Self-Haptics for Freehand Mid-Air Text Entry in VR. *Applied Ergonomics* 104 (July 2022), 103819. https://doi.org/10.1016/j.apergo.2022.103819

[23] DoYoung Lee, Jiwan Kim, and Ian Oakley. 2021. FingerText: Exploring and Optimizing Performance for Wearable, Mobile and One-Handed Typing. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems (CHI '21)*. Association for Computing Machinery, New York, NY, USA, 1–15. https://doi.org/10.1145/3411764.3445106

[24] Mahdi Nabiyouni and Doug A. Bowman. 2015. *An Evaluation of the Effects of Hyper-Natural Components of Interaction Fidelity on Locomotion Performance in Virtual Reality.* The Eurographics Association. https://doi.org/10.2312/egve.20151325 Accepted: 2015-10-28T06:32:04Z ISSN: 1727-530X.

[25] Lennart Nacke and Craig Lindley. 2008. Boredom, Immersion, Flow : A pilot study investigating player experience. IADIS Press. https://urn.kb.se/resolve?urn=urn:nbn:se:bth-8394

[26] Lennart E. Nacke, Mark N. Grimshaw, and Craig A. Lindley. 2010. More than a feeling: Measurement of sonic user experience and psychophysiology in a first-person shooter game. *Interacting with Computers* 22, 5 (June 2010), 336–343. https://doi.org/10.1016/j.intcom.2010.04.005

[27] object Object. [n. d.]. AntarcticAR: An Outdoor AR Experience of a Virtual Tour to Antarctica. ([n. d.]). https://core.ac.uk/reader/35471000

[28] J. Perret and E. Vander Poorten. 2018. Touching Virtual Reality: A Review of Haptic Gloves. In *ACTUATOR 2018; 16th International Conference on New Actuators*. 1–5.

[29] Jonas Schild, Joseph LaViola, and Maic Masuch. 2012. Understanding user experience in stereoscopic 3D games. *Conference on Human Factors in Computing Systems - Proceedings* (May 2012). https://doi.org/10.1145/2207676.2207690

[30] Marco Speicher, Anna Maria Feit, Pascal Ziegler, and Antonio Krüger. 2018. Selection-Based Text Entry in Virtual Reality. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3173574.3174221

[31] Paul Streli, Jiaxi Jiang, Andreas Rene Fender, Manuel Meier, Hugo Romat, and Christian Holz. 2022. TapType: Ten-finger Text Entry on Everyday Surfaces via Bayesian Inference. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems (CHI '22)*. Association for Computing Machinery, New York, NY, USA, 1–16. https://doi.org/10.1145/3491102.3501878

[32] Keith Vertanen and Per Ola Kristensson. 2011. A versatile dataset for text entry evaluations based on genuine mobile emails. In *Proceedings of the 13th International Conference on Human Computer Interaction with Mobile Devices and Services (MobileHCI '11)*. Association for Computing Machinery, Stockholm, Sweden, 295–298. https://doi.org/10.1145/2037373.2037418

[33] Powen Yao, Vangelis Lympouridis, Tian Zhu, Michael Zyda, and Ruoxi Jia. 2020. Punch Typing: Alternative Method for Text Entry in Virtual Reality. In *Proceedings of the 2020 ACM Symposium on Spatial User Interaction (SUI '20)*. Association for Computing Machinery, New York, NY, USA, 1–2. https://doi.org/10.1145/3385959.3421722

[34] Caglar Yildirim. 2022. Point and Select: Effects of Multimodal Feedback on Text Entry Performance in Virtual Reality. *International Journal of Human– Computer Interaction* 0, 0 (Dec. 2022), 1–15. https://doi.org/10.1080/10447318.2022.2107330 Publisher: Taylor & Francis.