Text Input in Virtual Reality Using a Tracked Drawing Tablet

Seyed Amir Ahmad Didehkhorshid, Siju Philip, Elaheh Samimi,
and Robert J. Teather(✉)

Carleton University, 1125 Colonel by Dr, Ottawa, ON K1S 5B6, Canada
SijuPhilip@cmail.carleton.ca, rob.teather@carleton.ca

Abstract. We present an experiment evaluating the effectiveness of a tracked drawing tablet for use in virtual reality (VR) text input. Participants first completed a text input pre-test, entering several phrases using a physical keyboard. Participants then entered text in VR using an HTC Vive, with a tracker mounted on a drawing tablet with a QWERTY soft keyboard overlaid on the virtual tablet. This was similar to text input using stylus-supported mobile devices. Our results indicate that not only did participants prefer the Vive controller, it also offered superior entry speed (16.31 wpm vs. 12.79 wpm with the tablet and stylus) and error rates (4.1% vs. 6.4%). Pre-test scores were also correlated to measured entry speeds, and reveal that user typing speed on physical keyboards provides a modest predictor of VR text input speed (R2 of 0.6 for the Vive controller, 0.45 for the tablet).

Keywords: Text input · Virtual reality · Drawing tablet

1 Introduction

Virtual reality (VR) devices are becoming increasingly affordable and performant. Between the falling prices, and the recent emergence of wireless head-mounted displays (HMDs), VR is also becoming more accessible. Despite these recent advancements in interaction technologies for VR systems, an ongoing problem is symbolic and text input in VR. Text input has traditionally received somewhat less attention from the research community than other interaction tasks in VR [3]. This is likely because substantial text input has been a more "niche" task than selection, manipulation, or navigation. Though the exact reasons for this are unclear, it may be related to lower quality VR systems of the past that were uncomfortable to use for lengthy composition. In the past few years, however, there have been several studies on different text entry methods in VR [11, 12, 34, 41], suggesting increasing application demand.

Replacing standard, physical keyboards for heavy text-entry tasks such as writing a paper or coding would be difficult. The absence of physical embodiment and difficulty using keyboards in midair have given rise to alternative techniques to address the many use cases of short, yet arbitrary, text input. Consider, for example sending quick SMS-like messages to another user, annotating parts of a virtual environment during a design

review in VR/AR, or calling up a webpage by typing a URL. In each situation, it is undesirable to break flow by switching context from VR to using a physical keyboard in order to perform such tasks, especially when using HMDs. We thus explore alternative approaches that can be used for VR text entry that are easier to use for a novice user, and which offer acceptable performance levels. In this study, we compared the most common method of text input in VR – using a 3D tracked controller employing ray-casting – to text input using a tracked tablet with a stylus.

We present an experiment evaluating text entry using a tracked tablet and stylus. Such devices support other tasks in VR and may thus integrate into the user's workflow better than keyboards or other tracked controllers. Notably, previous work has shown keyboards offer efficient and precise text entry in VR [11], but they can be used for just that – text entry. A tablet and stylus, on the other hand, offers various functions including selection, menu navigation, swiping, drawing, etc. People are also already familiar with using styluses as text input devices due to their similarity to pencils/pens.

Using a pen and stylus with an on-screen QWERTY keyboard is common in the mobile computing domain. Many modern smartphones and tablets include a stylus (e.g., Samsung's Galaxy Note line), which among other operations (e.g., drawing) can be used with onscreen keyboards to support text input. Using the stylus has the potential for better performance than fingers due to the "fat finger" problem [37]. This style of interaction is naturally familiar from writing with a pen and paper, and it has been used in VR before [4, 10, 32]. We propose to leverage this familiarity using modern VR hardware by adding a tracker to a digital drawing tablet while using the tablet's digitizer to detect the stylus contact point. Unlike using a ray to select keys from a virtual keyboard using a tracked controller, a tablet/stylus also offers tactile feedback.

Previous work has taken a similar approach, using a 3D tracked physical pen and tablet metaphor [4], or using a wooden tablet and pen [10]. Our approach is based on the observation that simply tracking a drawing tablet yields higher precision on the contact point than using a secondary tracker on the stylus while also keeping the stylus unencumbered. Moreover, the tablet (and Vive tracker) are relatively inexpensive compared to light-weight optical trackers (e.g., Vicon) that could be used to track a stylus. The result is similar to text input on mobile devices; the main difference between our scenario and mobile devices is that the user is sitting in a virtual environment instead of the real one. In our experiment, participants used the tracked tablet in VR and entered text using a stylus by selecting characters on a virtual QWERTY keyboard displayed on the tablet screen in VR. See (Fig. 1).

However, the text entry potential of tablets and styluses in VR has not been well studied, especially in comparison to common approaches used with recent commercial VR devices. A motivating hypothesis of our work is that using a stylus and tablet may yield comparable text input performance compared to a ray/controller method. The main contribution of our work is an experiment showing that, although the tablet underperforms relative to the controller, the performance difference is small, and can be potentially improved.

Fig. 1. (Left) The VR view, showing the QWERTY soft keyboard. The "H" key is highlighted to reflect that the stylus is currently hovering over it. (Right) Participant performing the experiment with the Tablet and Stylus.

2   Related Work

Using a tablet and stylus for text entry has been studied extensively in the HCI community in non-VR scenarios [6, 9, 51, 54]. Entry rates using a stylus for input with a QWERTY soft keyboard range between 8.9 wpm and 30.1 wpm, according to Soukoreff et al. [49]. Here we focus on previous research using tablet devices and different text entry techniques for VR.

2.1   Tablets and Mobile Devices in VR

One of the earliest examples of using a tablet-like device in VR was the HARP system developed by Lindeman et al. [22]. Their results showed that a 2D stylus and tablet metaphor used in VR provided better support for precise selection actions. They argued this was a direct result of providing a tactile surface via the virtual tablet. The benefits of so-called "passive" haptic feedback are well-known in the VR research community [1, 5, 8, 15, 27]. They also showed that using a hand-held device is preferable to fixed-position devices, as they provide freedom for working effectively in IVEs.

Poupyrev et al. developed one of the earliest text entry methods in VR, the Virtual Notepad. It used a spatially tracked tablet and stylus system for taking notes in VR [32]. Using the Virtual Notepad users could take notes, modify them, add or remove pages, and manipulate the documents within the VE. The system employed character recognition to detect and issue handwritten commands in the form of individual letters. Medeiros et al. proposed using mobile devices for interaction in virtual environments [36]. They concluded that user familiarity with these mobile devices reduces their resistance to immersive virtual environments (IVEs). Other researchers have explored the use of mobiles as input devices in VR, for example, to select and manipulate objects [17].

Several other studies have explored the use of mobile devices and tablets in VR contexts [7, 14, 42, 47]. Perhaps the most similar work to ours, Kim and Kim's proposed method, using a smartphone and its hovering function for text entry in VR [18]. HoVR used a smartphone's hovering function for text entry in VR. However, they did not report text entry speed or error rate and reported only task completion time, and also did not use commonly used stimulus text [24], which makes comparing results difficult.

2.2 Text Entry Methods in VR

Compared to interaction tasks like selection and navigation, there are comparatively few studies on text input in VR. (Table 1) presents a summary of several key studies.

Table 1. Several text entry studies in immersive virtual reality environments and their performance results.

1st author	Text entry method	Entry rate (wpm)	Error rate	Notes
Poupyrev [32]	Tablet & stylus with digital ink	Not reported	Not reported	Switched between showing hands and the stylus and used character recognition for text input
Bowman [4]	QWERTY keyboard with pen and tablet metaphor	10*	7.14 errors per subject	Original result were reported in character per minute (cpm). *Note: we converted to wpm by dividing the original results by five
	Pinch keyboard	5*	43.17 error per subject	
González [10]	Pen based QWERTY keyboard	7*	7% character error rate	Used tablet and pen made out of wood, tracked via sensor. Users could see the pen. * Note: Entry rate originally reported in CPM, converted to wpm
	Pen based disk keyboard	4*	2% character error rate	
Grubert [11, 12]	QWERTY desktop keyboard	26	2.1% character error rate	Different hand representations were used. i.e. full hand vs. fingers only. Also looked into repositioning the keyboard in VR
	QWERTY touchscreen keyboard	11	2.7% character error rate	
Yu [55]	Head pointed & Gesture based	10 to 19	1.23% to 3.08% corrected error rate	Investigated TapType, DwellType, and GestureType techniques
Yu [56]	Dual joystick controller	7 to 15	1.57% to 1.59 uncorrected error rate	Used a circular keyboard layout

(*continued*)

Table 1. (*continued*)

1st author	Text entry method	Entry rate (wpm)	Error rate	Notes
Kim [18]	QWERTY touchscreen keyboard	Not reported	Not reported	Used smartphone's hovering function for finger tracking. Reported task completion time
Kuester [21]	Wearable glove	Not reported	Not reported	Used the concept of column and rows found in traditional keyboards
Rajanna [34]	Gaze typing	6 to 9	.02% to .08% rate of back space	Sitting and biking were conditions in the experiments
Xu [53]	Head motions	8 to 12	2.25% to 2.46% uncorrected error rate	Dwell and hands free interaction method, used a circular keyboard layout
Prätorius [33]	Thumb to finger taps	Not reported	Not reported for text entry.	Reported keystroke per character
Gugenheimer [13]	Split QWERTY touchscreen keyboard	10	Not reported	Used displayed fixed UIs, users wore a touch sensor on the HMD
Speicher [41]	QWERTY keyboard with Controller Pointing	15	0.97% Corrected error rate	Also looked into the physical demand required and cyber sickness in different text entry methods in VR
	QWERTY keyboard with Controller Tapping	12	1.94% Corrected error rate	

Bowman et al. empirically compared four different text entry techniques including a pen and tablet, voice recognition, a one-hand chord keyboard and a method using pinch gloves [4]. Speech recognition was fastest, at around 14 words per minute (wpm). Their pen and tablet metaphor offered entry rates of up 12 wpm. Unlike our study, which employs a tablet digitizer to "track" the stylus, their study used a 3D tracked stylus to touch letters, indicating selection by pressing a stylus button. Another example of using a pen-based approach, González et al. tracked a wooden tablet and stylus with a sensor, although the type of sensor is not reported. In a series of text entry experiments, they report entry rates between 7 and 8 wpm [10] with the stylus and tablet.

Speech recognition is a potentially attractive method of VR text input. The SWIFTER speech recognition system improved on Bowman's speech-based approach [4], achieving average entry speeds of up to 23 WPM [31]. However, although speech to text-based techniques are fast, they are not well-suited to loud environments, or in situations requiring discretion (e.g., users having private conversations, or entering password securely).

Also, editing is challenging with speech-based methods; for example, cursor positioning is problematic. Moreover, speech can interfere with the cognitive process required to enter text [38, 43].

Several studies have explored the use of game controllers as text input mechanisms both in VR, and in other similar use scenarios, such as games [20, 29, 50, 56]. Isokoski et al. used a controller and a tablet with a stylus in their experiments [16]. They reported entry rates ranging from 6 to 8 wpm using the Quickwriting method [16, 30]. Entry speed with conventional game controllers tends to range between 6 to 15 wpm [50, 56].

Other researchers explored the use of head motion and gaze direction for typing in VR [34, 53, 55]. Yu et al. explored three head-based techniques for text entry in VR [55]. They reported average entry speed of 24.73 WPM with their GestureType technique after one hour of training. Gugenheimer et al. introduced FaceTouch, which employed display-fixed UIs [13]. Their approach employed touchpads mounted on the front face of the HMD, which users touched to enter text. In an informal study on text entry using a split QWERTY keyboard, the authors reported average text entry speed of approximately 10 wpm. Rajanna et al. focused on investigating how keyboard design, selection method, and motion in the field of view impact typing performance and user experience [34]. They concluded that VR gaze typing is viable, if somewhat unnatural.

Several recent VR text input studies have investigated the use of physical keyboards with various hand visualizations [2, 11, 12, 44, 45]. Knierim et al. evaluated the effects of virtual hand representation and hand transparency on typing performance of experienced and inexperienced typists in VR [19]. Their results suggest that experienced users (e.g., touch typists) performance is not significantly affected by missing hands or different hand visualization. However, inexperienced users are impacted by these factors. Similar work by Grubert et al. also investigated methods for virtual hand representation with minimalistic fingertip visualization [11, 12]. Specifically, their minimalistic visualization showed only dots at the fingertips rather than an entire hand visualization. They report that even with minimalistic fingertip representations, entry speeds ranging from 34 to 38 wpm are possible, depending on hand and finger representation.

Other VR text input methods employing 3D tracked controllers employing direct touch, or ray-casting, to select keys from a virtual keyboard. Entry rate ranged from 12 to 15 wpm [41]. Several other studies employed gloves and hand gestures both in VR and non-VR context [21, 26, 28, 33, 35, 46, 48]. Yi et al. reported entry rates of up to 29 wpm using their hand based method in a non-VR setting [52]. As suggested by Grubert et al., methods that use a controller for text entry tend to have a higher learning curves and require more training than keyboards, and can also cause user fatigue [11].

3 Methodology

3.1 Participants

We recruited 28 participants from our local community but ended up removing four of them. Two were extreme outliers (entry speed scores more than 3 SDs from the mean), and there were logging errors with the other two. This left us with 24 participants upon which our analysis is based. There were 9 female and 15 male participants, aged between 18 and 54 (M = 26.21, SD = 8.19). Eighteen participants reported that they had not

played 3D games, or only played them infrequently. Twenty-one participants had very little or no prior experience with VR. Seven participants reported regularly using a pen or stylus for typing on their tablet or smartphone. One participant indicated that they did not text at all, while nine texted frequently during a typical day. The rest of them reported moderate texting. All participants had normal or corrected-to-normal stereo vision, assessed by having participants correctly determine the depth of two spheres presented in the scene.

3.2 Apparatus

Hardware. We used a PC with an Intel Core i7 CPU with an NVIDIA Geforce GTX 1080 graphics card. We used the HTC Vive VR platform, which includes an HMD with 1080 × 1200 per eye resolution, 90 Hz refresh rate, and a 110° field of view. The tablet was an XP-PEN STAR 06 wireless drawing tablet. Its dimensions were 354 mm × 220 mm × 9.9 mm with a 254 mm × 152.4 mm active area, and a 5080 LPI resolution. The tablet included a stylus with a barrel button and a tip switch to support activation upon pressing it against the tablet surface. The 2D location of the stylus is tracked along its surface by the built-in electromagnetic digitizer. We affixed a Vive tracker to the top-right corner of the tablet using velcro tape. See (Fig. 2).
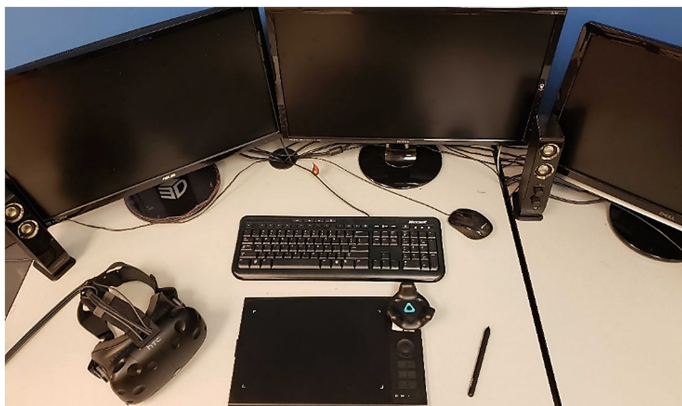

Fig. 2. Tablet and stylus with Vive tracker and Vive HMD along with the physical keyboard used in pre-tests.

Software. We used MacKenzie's "Typing Text Experiment"[1] software for the pre-test. The pre-test consisted of 30 randomly determined phrases the participants entered using a real keyboard.

The main experiment used our VR software developed in Unity3D. We developed a custom library to get stylus input from the XP-PEN STAR tablet into Unity. The tablet

---

[1] Available at http://www.yorku.ca/mack/HCIbook/.

is ordinarily seen as fitting the human interaction device (HID) profile by Windows 10, which, by default would map it to the mouse cursor, which was not desired in VR. To avoid this, we installed a custom LibUSB driver that allowed direct access to the raw data from the tablet. The library provided data such as the coordinate position of the stylus on the tablet surface, the amount of pressure applied by on the stylus tip switch, and whether the stylus was touching the tablet surface or hovering above it within approximately 2 cm.

The software polled the Vive tracker to map a virtual model of the tablet to the physical tablet, co-locating the two. The tablet stylus was used to interact with the tablet. The stylus itself was not tracked, hence tracking was limited to the tip of the stylus in a close range to the tablet surface (about 2 cm). Due to this limitation, we did not render a model of the stylus or hands. However, when the stylus was in the range of the tablet, we displayed a cursor at the stylus tip. Notably, this is how such graphics tablets are typically used, as the display is not collocated, which has the advantage of not covering part of the drawing with the hand. By applying pressure on the stylus tip switch by pressing it against the tablet surface, input events were detected for corresponding keys on the tablet and the corresponding character was entered.

Participants sat in the virtual room seen in (Fig. 3). A QWERTY soft keyboard was displayed on the virtual tablet. The keys were 1.5 cm × 1.5 cm in size. Participants sat between 30 to 40 cm from the keyboard, depending on their position. Participants were always presented with a simulated QWERTY soft keyboard displayed centered on the tablet (see Fig. 3). The tablet was positioned on a table as seen in (Fig. 3). The current target phrase appeared near the virtual keyboard to reduce the need for glancing during entry. As participants entered the phrase, each keystroke was presented, giving them immediate feedback. While hovering on keys, the letters changed color to indicate which would be selected if the tip switch was pressed. Upon pressing a key in this fashion, an auditory "click" sound was played and the key letters change colour to yellow. The SPACE bar and the ENTER key each had distinct button press sounds.

Fig. 3. View of the virtual room seen by participants. Red were spheres used for stereo viewing test (Color figure online)
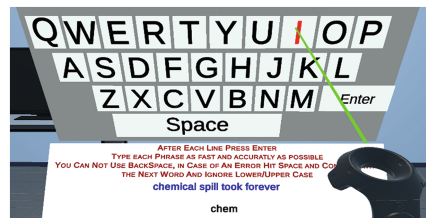

Fig. 4. Vive Controller with soft keyboard.

Figure 4 depicts the other text entry method, the Vive controller. The QWERTY soft keyboard used with the Vive controller had keys sized 10 cm × 10 cm with a 0.5 cm gap between each adjacent key. This keyboard faced the participant, and was slightly tilted towards the participant (by 10°) and was positioned about 110–120 cm from the participant's seated position. With this text entry method, participants pointed a ray from the Vive controller at the desired key and pressed the trigger button to select. Upon being

intersected by the selection ray, a key changed colour from blue to yellow. Upon pressing the trigger, the selected key would turn grey. The sound effects were the same as the tablet condition.

3.3 Procedure

Before they began, participants first read and signed consent forms and completed a pre-questionnaire to gather demographic data such as age and gaming/VR experience, stylus usage, and mobile text input habits. The experimenter then explained the procedure. Correction (i.e., backspace) was disabled with both the real keyboard during the pre-test as well as the virtual keyboard during the experiment. Auto-correction or similar features were not implemented. Participants were instructed to enter each phrase as quickly and accurately as possible, ignoring any mistakes and pressing the ENTER key to end each trial. Timing started as soon as the participant entered the first character and stopped as soon as they hit the ENTER key.

Upon starting the experiment, participants first entered 30 phrases using MacKenzie's "Typing Text Experiment" software with real keyboard as a pre-test. After the pre-test, the experimenter demonstrated how to use the Vive controller and the tablet. The participants then entered VR, and were screened for stereo viewing prior to continuing the experiment. They were presented with two red spheres at different depths (Fig. 3). They were instructed to reach out and intersect the Vive controller with the spheres to make them disappear. All participants were able to reliably detect the depth of the spheres and hence passed this screening.

The task then started without any training with the interaction devices. Participants were instructed to enter a random pool of phrases from a phrase set commonly used in text entry experiments [24]. Participants were presented with one line from the phrase set at a time, entering 30 phrases with each text input method (both in pre-test and in VR). After completing all 30 phrases, participants completed a questionnaire related to their experience of that method. In the end, they completed a post-questionnaire about their preferred text input method and any comments or suggestions they had.

3.4 Design

Our experiment employed a within-subjects design with two independent variables:

Text Input Method: Tablet and stylus, Vive Controller
Trial: 1, 2, 3, …, 30

Text input method order was counterbalanced by having half the participants use the Vive Controller then Tablet and stylus, and the other half in the reverse order. Entry speed, in words per minute (wpm), was calculated as:

$$wpm = \frac{|s|}{T} \times 60 \times \frac{1}{5}$$

where T is the text entry time in seconds, and |s| is the input string length (in characters). We used every five characters (including spaces) as a single word, consistent with the text input literature [25].

Error rates were calculated using character error rate (CER), calculated as:

$$CER\% = \frac{MSD(stimulus\ text,\ response\ text)}{CharLenght\ (stimulus\ text)} \times 100$$

CER is the minimum number of character-level insertion, deletion, and substitution operations required to transform the response text into the stimulus text, i.e., the minimum string distance (MSD) between the two, divided by the number of characters in the stimulus text [23, 39]. This metric better represents errors. For example, a single character insertion early in a phrase yields a single error, rather than a "cascade" of mismatched characters [40]. CER is expressed as a percentage of errors.

4   Results

Since participants completed only 30 trials with each text input method, we did not evaluate the effect of trial, and averaged all trials together. We compared performance using a t-test. The assumption of sphericity was met in all cases based on Mauchly's test. We were also interested in determining if the participant's touch-typing speed predicts their VR text entry speed, so used linear regression to see if they were correlated.

4.1   Performance

Figure 5 depicts average entry speed for each text entry method. The tablet and stylus had a mean entry speed of 12.79 WPM ($SE = .71$). In contrast, the Vive controller offered faster entry speed at 16.31 WPM ($SE = .44$). A t-test revealed a significant main effect of text entry method for entry speed ($t(29) = -32.3, p < .001$).
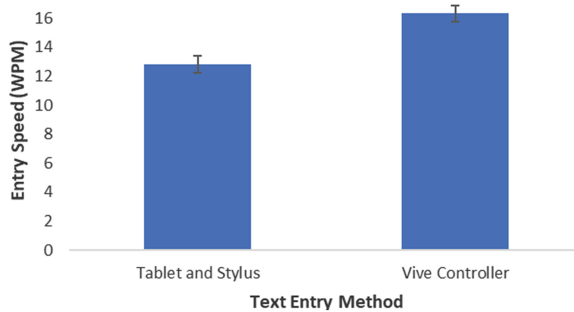

Fig. 5. Average text entry speed for each VR input method. Error bars show 95% confidence interval.

Figure 6 depicts the average error rate for each text entry method. The tablet and stylus technique had a mean error rate of 6.42% ($SE = 1.66$), and the Vive controller had a mean error rate of 4.14% ($SE = .95$). A t-test revealed that the main effect of text entry method on error rate was significant ($t(29) = 3.74, p < .001$).
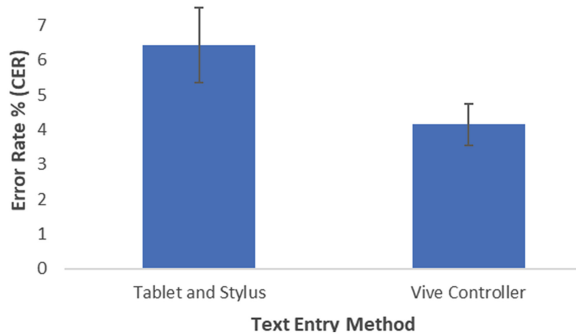
Fig. 6. Average error rate for each VR input method. Error bars show 95% confidence intervals.

Figure 7 depicts a regression analysis between pretest entry speeds and measured VR entry speed for both text input methods. As seen in the figure, there is a modest relationship between pre-test text input speed (i.e., on a standard keyboard) and VR text entry speed, for both the Vive controller and the tablet and stylus. Indeed, faster typists on a typical desktop setup had better entry speed with both VR text input methods.
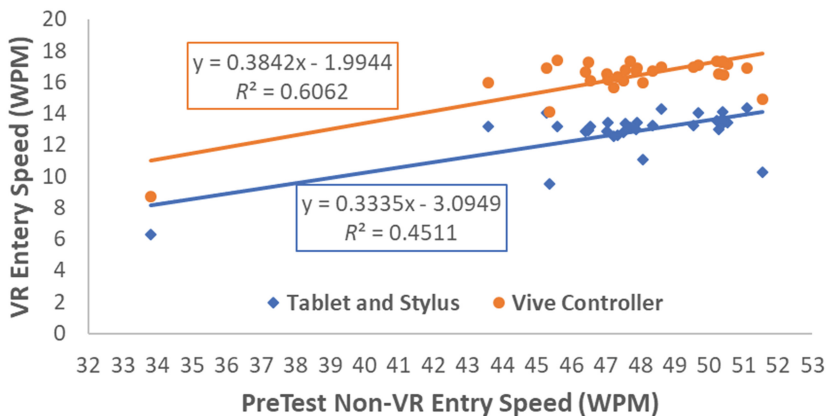

Fig. 7. Linear regression showing the correlation between pre-text entry speeds and VR entry speeds.

4.2   User Experience

All participants except one preferred the Vive controller text entry method. A few reported having trouble reading the 3D text on the tablet noting that "the text gets quite blurry." It is possible larger keys might resolve this issue. Another issue was the weight of the HMD; several participants noted it bothered them while using the tablet, which necessitated looking down. Participants also reported confusion with the sensitivity of the pen and tablet, they were not sure about the amount of tip switch pressure required

to register input. Most of them found it hard without knowing where the cursor and the stylus were when tracking was lost and reported they wanted to see the stylus at all times. One participant stated that the tablet was "good to use when you get the hang of it, but the distance and specific angle you have to hold the stylus at is a little difficult to get used to". One of them also suggested that implementing two styluses could have improved the speed and efficiency of typing as one could at least be used for spacing.

5   Discussion

Our performance results (16.32 vs. 12.80 wpm) indicate that our proposed method performed worse than the Vive controller. Notably, the tablet and stylus performance is comparable to several previous text input methods seen in Table 1. In particular, its performance is comparable to Bowman's tracked stylus and tablet [4], several game controller methods [56], head motion [53] and touchscreen typing on a soft keyboard [12]. It performs better than several previous techniques, including an alternative tracked tablet and stylus [10] and gaze typing [34].

Despite these results, we believe with improvements, there is still potential for the tablet and stylus to be considered a viable text entry method in VR. In particular, participants noted several issues that could improve the design of tablet-based text input schemes, including larger keys and more ergonomic positioning of the tablet, perhaps letting participants hold the tablet or move it where comfortable. Participant comments also suggest that adding the stylus and hand visualization and improving the tip switch sensitivity could further improve the tablet and stylus performance.

Some participants leaned forward and moved very close to the tablet with their head down to tap on the tablet; this could have caused the HMD to move slightly on their head and cause the blurry effect they reported while using the tablet. Some participants also reported noticing the weight of the HMD only while using the tablet. This also might have to do with the fact that they were hunching over the tablet. In contrast, with the Vive controller condition, they held their heads up to see the soft keyboard.

Participants also reported their arms getting tired because of tapping, and that it also caused finger fatigue. This was mainly because more hand/arm movement was required with the tablet keyboard. While using the Vive controller with ray-casting, participants could easily move the cursor across the keyboard via small wrist movements. We believe this could be improved by implementing a swiping text entry method for the tablet, or by using a different soft keyboard layout. Notably, the Vive controller can also be used bimanually, which could potentially have increased typing performance relative to the one-handed operation with the stylus. We opted to give them two controllers to more accurately simulate the real experience of text input on commercial VR systems. Participants noted that they liked the tactile feedback provided by the tablet, in line with previous work on haptics in VR [5, 15, 27].

6   Conclusion

In this paper, we evaluated the effectiveness of using a tablet and stylus for VR text input. We designed and developed a text entry method using a QWERTY virtual keyboard on

a tablet in VR. We found that the Vive controller performed faster, had lower error rates, and was preferred by participants. We also found that VR text input speed can be – to a modest extent – predicted by touch typing entry speed with a conventional keyboard. We believe that by improving some limitations of our experiment, we can improve the tablet and stylus efficiency might be better. Also, if users are already using a tablet for other functions in VR, like a VR design session, using the tablet instead of a controller for text entry may be inherently preferable and feel more natural.

7   Limitations and Future Work

There are a few limitations with the current experiment. First, tablet position was always fixed. We had chosen this option, rather than allowing the user to hold the tablet, as we suspected the alternative would increase arm fatigue. However, because of this decision, the tablet's virtual keyboard and the target phrases were not in the same location, necessitating that participants look up and down to see the sentence first, and then type it with the keyboard. In contrast, this head motion was not required with the Vive controller condition, which may partly explain the difference observed. A future implementation would better visually co-locate the keyboard and stimulus phrases.

A second limitation is that the stylus itself was not tracked. Several participants commented on this. This was a limitation of the type of tablet we used (i.e., no in-air tracking) and could be addressed by using an optical tracker to maintain a lightweight tracker on the stylus. New devices like Logitech's VR Ink stylus may address this.

Several other comparisons are possible, but were excluded from the current experiment to keep it simple. Future studies might, for example, focus on stylus vs. finger input, holding the tablet in 3D space vs. resting on a surface, and the effect of scaling stylus motion when entering text (i.e., applying CD gain to the stylus). Other options including using different keyboard layouts and swipe-based text input. We are also considering using a new HMDs with higher resolutions, lighter designs, and a wider field of view to address the ergonomic concerns mentioned by participants of this study.

References

1. Aguerreche, L., Duval, T., Lécuyer, A.: Reconfigurable tangible devices for 3D virtual object manipulation by single or multiple users. In: Proceedings of the 17th ACM Symposium on Virtual Reality Software and Technology, pp. 227–230 (2010)
2. Bovet, S., et al.: Using traditional keyboards in VR: steam VR developer kit and pilot game user study. In: IEEE Games, Entertainment, Media Conference, pp. 132–135 (2018)
3. Bowman, D.A., Kruijff, E., LaViola, J.J., Poupyrev, I.: 3D User Interfaces: Theory and Practice. Addison Wesley Longman Publishing Co., INC (2004)
4. Bowman, D.A., Rhoton, C.J., Pinho, M.S.: Text input techniques for immersive virtual environments: an empirical comparison. Proc. Human Factors Ergon. Soc. Ann. Meeting **46**(26), 2154–2158 (2002)

5. Brooks, J.F.P., Insko, B.E.: Passive Haptics Significantly Enhances Virtual Environments. The University of North Carolina at Chapel Hill

6. Cechanowicz, J., Dawson, S., Victor, M., Subramanian, S.: Stylus based text input using expanding CIRRIN. Adv. Vis. Interfaces, pp. 163–166 (2006)

7. Chen, T.-T., Hsu, C.-H., Chung, C.-H., Wang, Y.-S., Babu, S.V.: iVRNote: design, creation and evaluation of an interactive note-taking interface for study and reflection in VR learning environments. In: IEEE Conference on Virtual Reality and 3D User Interfaces, 172–180 (2019)

8. Franzluebbers, A., Johnsen, K.: Performance benefits of high-fidelity passive haptic feedback in virtual reality training. In: ACM Symposium on Spatial User Interaction, pp. 16–24 (2018)

9. Goldberg, D., Richardson, C.: Touch-typing with a stylus. In: Proceedings of the INTERACT 1993 and Conference on Human Factors in Computing Systems, pp. 80–87 (1993)

10. González, G., Molina, J.P., García, A.S., Martínez, D., González, P.: Evaluation of text input techniques in immersive virtual environments. New Trends on Human-Computer Interaction: Research, Development, New Tools and Methods. Springer. 109–118

11. Grubert, J., Witzani, L., Ofek, E., Pahud, M., Kranz, M., Kristensson, P.O.: Effects of hand representations for typing in virtual reality. In: IEEE Conference on Virtual Reality and 3D User Interfaces (VR), pp. 151–158 (2018)

12. Grubert, J., Witzani, L., Ofek, E., Pahud, M., Kranz, M., Kristensson, P.O.: Text entry in immersive head-mounted display-based virtual reality using standard keyboards. In: IEEE Conference on Virtual Reality and 3D User Interfaces (VR), pp. 159–166 (2018)

13. Gugenheimer, J., Dobbelstein, D., Winkler, C., Haas, G., Rukzio, E.: FaceTouch: enabling touch interaction in display fixed uis for mobile virtual reality. In: Proceedings of the 29th Annual Symposium on User Interface Software and Technology, pp. 49–60 (2016)

14. Henrikson, R., Araujo, B., Chevalier, F., Singh, K., Balakrishnan, R.: Multi-device storyboards for cinematic narratives in VR. In: Proceedings of the 29th Annual Symposium on User Interface Software and Technology, pp. 787–796 (2016)

15. Hoffman, H.G.: Physically touching virtual objects using tactile augmentation enhances the realism of virtual environments. In: Proceedings of the Virtual Reality Annual International Symposium, pp. 59–63 (1998)

16. Isokoski, P., Raisamo, R.: Quikwriting as a multi-device text entry method. In: Proceedings of the Third Nordic Conference on Human-Computer Interaction, pp. 105–108 (2004)

17. Katzakis, N., Teather, R.J., Kiyokawa, K., Takemura, H.: INSPECT: extending plane-casting for 6-DOF control. In: Proceedings IEEE Symposium on 3D User Interfaces, pp. 165–166 (2015)

18. Kim, Y.R., Kim, G.J.: HoVR-Type: smartphone as a typing interface in VR using hovering. In: IEEE International Conference on Consumer Electronics (ICCE), pp. 200–203 (2017)

19. Knierim, P., Schwind, V., Feit, A.M., Nieuwenhuizen, F., Henze, N.: Physical keyboards in virtual reality: analysis of typing performance and effects of avatar hands. In: Proceedings of the Conference on Human Factors in Computing Systems, pp. 1–9 (2018)

20. Költringer, T., Isokoski, P., Grechenig, T.: TwoStick: writing with a game controller. In: Proceedings of Graphics Interface, 103–110 (2007)

21. Kuester, F., Chen, M., Phair, M.E., Mehring, C.: Towards keyboard independent touch typing in VR, p. 86, February 2006

22. Lindeman, R.R.W., Sibert, J.J.L., Hahn, J.K.J.J.K.: Towards usable VR: an empirical study of user interfaces for immersive virtual environments. In: Proceedings of the SIGCHI conference on Human Factors in Computing Systems, pp. 64–71 (1999)

23. MacKenzie, I.S., Soukoreff, R.W.: A character-level error analysis technique for evaluating text entry methods. In: Proceedings of the Second Nordic Conference on Human-Computer Interaction, pp. 243–246 (2004)

24. MacKenzie, I.S., Soukoreff, R.W.: Phrase sets for evaluating text entry techniques. In: Extended Abstracts on Human Factors in Computing Systems, pp. 754–755 (2003)
25. MacKenzie, I.S., Soukoreff, R.W.: Text entry for mobile computing: models and methods, theory and practice. Hum.-Comput. Interact. **17**(2–3), 147–198 (2002)
26. Markussen, A., Jakobsen, M.R., Hornbæk, K., Markussen, A., Jakobsen, M.R., Hornbæk, K.: Vulture: a mid-air word-gesture keyboard. In: Proceedings of the 32nd Annual ACM Conference on Human Factors in Computing Systems - CHI 2014, pp. 1073–1082 (2014)
27. McClelland, J.C., Teather, R.J., Girouard, A.: Haptobend: shape-changing passive haptic feedback in virtual reality. In: Proceedings of the 5th Symposium on Spatial User Interaction, pp. 82–90 (2017)
28. Mehring, C., Kuester, F., Singh, K.D., Chen, M.: KITTY: keyboard independent touch typing in VR. In: Virtual Reality Annual International Symposium, pp. 243–244 (2004)
29. Natapov, D., Castellucci, S.J., MacKenzie, I.S.: ISO 9241-9 evaluation of video game controllers. In: Proceedings of Graphics Interface, pp. 223–230 (2009)
30. Perlin, K.: Quikwriting: continuous stylus-based text entry. In: Proceedings of the 11th Annual ACM Symposium on User Interface Software and Technology, pp. 215–216 (1998)
31. Pick, S., Puika, A.S., Kuhlen, T.W.: SWIFTER: design and evaluation of a speech-based text input metaphor for immersive virtual environments. In: IEEE Symposium on 3D User Interfaces (3DUI), pp. 109–112 (2016)
32. Poupyrev, I., Tomokazu, N., Weghorst, S.: Virtual notepad: handwriting in immersive VR. In: Proceedings IEEE Virtual Reality Annual International Symposium, pp. 126–132 (1998)
33. Prätorius, M., Burgbacher, U., Valkov, D., Hinrichs, K.: Sensing thumb-to-finger taps for symbolic input in VR/AR environments. IEEE Comput. Graph. Appl. **35**(5), 42–54 (2015). https://doi.org/10.1109/MCG.2015.106
34. Rajanna, V., Paulin Hansen, J.: Gaze typing in virtual reality: impact of keyboard design, selection method, and motion. Proc. ACM Sympos. Eye Track. Res. Appl. **15**(1–15), 10 (2018)
35. Reyal, S., Zhai, S., Kristensson, P.O.: Performance and User Experience of Touchscreen and Gesture Keyboards in a Lab Setting and in the Wild, pp. 679–688, April 2015
36. De Sa Medeiros, D.P., De Carvalho, F.G., Raposo, A.B., Dos Santos, I.H.F.: An interaction tool for immersive environments using mobile devices. In: XV Symposium on Virtual and Augmented Reality, pp. 90–96 (2013)
37. Shibata, T., Afergan, D., Kong, D., Yuksel, B.F., MacKenzie, S., Jacob, R.J.K.: Text entry for ultra-small touchscreens using a fixed cursor and movable keyboard. In: Proceedings of the Conference Extended Abstracts on Human Factors in Computing Systems, pp. 3770–3773 (2016)
38. Shneiderman, B.: The limits of speech recognition. Commun. ACM, **2000**, 319–365 (2000)
39. Soukoreff, R.W., MacKenzie, I.S.: Measuring errors in text entry tasks: an application of the Levenshtein string distance statistic. Extended Abstracts Hum. Factors Comput. Syst., pp. 319–320 (2001)
40. Soukoreff, R.W., MacKenzie, I.S.: Metrics for text entry research: an evaluation of MSD and KSPC, and a new unified error metric. Proceedings of the ACM Conference on Human Factors in Computing Systems – CHI **2003**, 113–120 (2003)
41. Speicher, M., Feit, A.M., Ziegler, P., Krüger, A.: Selection-based text entry in virtual reality. In: Proceedings of the Conference on Human Factors in Computing Systems, pp. 1–13 (2018)
42. Tuttle, A.J., Savadatti, S., Johnsen, K.: Facilitating collaborative engineering analysis problem solving in immersive virtual reality. In: American Society for Engineering Education (2019)
43. Vertanen, K.: Efficient Correction Interfaces for Speech Recognition. University of Cambridge (2009)

44. Walker, J., Kuhl, S., Vertanen, K.: Decoder-assisted typing using an HMD and a physical keyboard. In: Extended Abstracts of the ACM Conference on Human Factors in Computing Systems, p. 16 (2016)
45. Walker, J., Li, B., Vertanen, K., Kuhl, S.: Efficient typing on a visually occluded physical keyboard. In: Proceedings of the Conference on Human Factors in Computing Systems, pp. 5457–5461 (2017)
46. Wang, C.-Y., Chu, W.-C., Chiu, P.-T., Hsiu, M.-C., Chiang, Y.-H., Chen, M.Y.: PalmType: using palms as keyboards for smart glasses. In: Proceedings of the 17th International Conference on Human-Computer Interaction with Mobile Devices and Services - MobileHCI 2015 (2015)
47. Wang, J., Lindeman, R.W.: Object impersonation: towards effective interaction in tablet- and HMD-based hybrid virtual environments. In: IEEE Virtual Reality (VR), pp. 111–118 (2015)
48. Whitmire, E., et al.: DigiTouch: reconfigurable thumb-to-finger input and text entry on head-mounted displays. Displays. PACM Interact. Mob. Wearable Ubiquitous Technol. **1**, 113 (2017)
49. William Soukoreff, R., Scott Mackenzie, I.: Theoretical upper and lower bounds on typing speed using a stylus and a soft keyboard. Behav. Inf. Technol. **14**(6), 370–379 (1995)
50. Wilson, A.D., Agrawala, M.: Text entry using a dual joystick game controller. In: ACM Conference on Human Factors in Computing Systems, 475–478 (2006)
51. Wobbrock, J.O., Myers, B.A., Kembel, J.A.: EdgeWrite: a stylus-based text entry method designed for high accuracy and stability of motion. In: ACM Symposium on User Interface Software and Technology, pp. 61–70 (2003)
52. Xin, Y., Chun, Y., Mingrui, Z., Sida, G., Ke Sun, Y.S.: ATK: enabling ten-finger freehand typing in air based on 3D hand tracking data. In: ACM Symposium on User Interface Software & Technology, pp. 539–548 (2015)
53. Xu, W., Liang, H.N., Zhao, Y., Zhang, T., Yu, D., Monteiro, D.: RingText: dwell-free and hands-free text entry for mobile head-mounted displays using head motions. IEEE Trans. Visual. Comput. Graph. **25**(5), 1991–2001 (2019)
54. Yatani, K., Truong, K.N.: An evaluation of stylus-based text entry methods on handheld devices studied in different user mobility states. Pervasive Mobile Comput. **5**(5), 496–508 (2009)
55. Yu, C., Gu, Y., Yang, Z., Yi, X., Luo, H., Shi, Y.: Tap, Dwell or Gesture?: exploring head-based text entry techniques for HMDs. In: Proceedings of the Conference on Human Factors in Computing Systems, pp. 4479–4488 (2017)
56. Yu, D., Fan, K., Zhang, H., Monteiro, D., Xu, W., Liang, H.N.: PizzaText: text entry for virtual reality systems using dual thumbsticks. IEEE Trans. Visual. Comput. Graph. **24**(11), 2927–2935 (2018)