Gaze Typing in Virtual Reality: Impact of Keyboard Design, Selection Method, and Motion

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ABSTRACT

Gaze tracking in virtual reality (VR) allows for hands-free text entry, but it has not yet been explored. We investigate how the keyboard design, selection method, and motion in the field of view may impact typing performance and user experience. We present two studies of people (n = 32) typing with gaze+dwell and gaze+click inputs in VR. In study 1, the typing keyboard was flat and within-view; in study 2, it was larger-than-view but curved. Both studies included a stationary and a dynamic motion conditions in the user's field of view.

Our findings suggest that 1) gaze typing in VR is viable but constrained, 2) the users perform best (10.15 WPM) when the entire keyboard is within-view; the larger-than-view keyboard (9.15 WPM) induces physical strain due to increased head movements, 3) motion in the field of view impacts the user's performance: users perform better while stationary than when in motion, and 4) gaze+click is better than dwell only (fixed at 550 ms) interaction.

CCS CONCEPTS

• **Human-centered computing → Text input**; *Virtual reality*; *User interface design*; *Mobile devices*; Accessibility systems and tools;

KEYWORDS

Virtual reality; gaze typing; keyboard design; motion; VR sickness, multi-modal input; dwell; mental and physical workload.

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1 INTRODUCTION

Communicating through chat, executing commands, taking notes, completing input fields, naming objects in a game, and so on require the user to be able to enter text in VR [Guttentag 2010; Mujber et al. 2004; Rizzo et al. 2004]. Increasingly, VR applications for gaming, training, entertainment, e-learning, collaborative work, and therapy have introduced complex interactions including text entry [Löchtefeld et al. 2016; Ribarsky et al. 1994; Wexelblat 2014]. Currently, there are four main options used for text entry in VR: 1) removing the headset and using a physical keyboard to enter text, 2) pointing with an external controller to activate the keys on an on-screen virtual keyboard (VKB), 3) speech-to text-conversion, and 4) pointing by head motion. Taking the headset off and using a physical keyboard to enter text breaks the experience of immersiveness and the user may need to re-adjust the fit of the headset on their face.

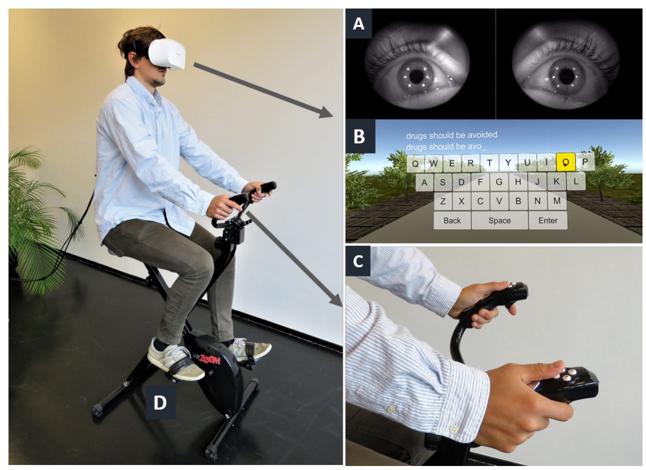

Figure 1: A user gaze typing in a VR environment: A) FOVE VR headset with an eye tracking unit, B) a virtual keyboard displayed inside the headset, C) the trigger buttons on the bike simulator, D) peddling the bike simulator moves the user along a straight road in the virtual world.

Using an external controller that can project rays at a VKB needs special hardware setup, and the user's hands are then occupied with operating the controller. In addition, since the position of the controllers in 3D space is tracked by fixed cameras (intrusive), the controllers need to be used within a limited space (VR rig) which seriously reduces mobility [Walker et al. 2017]. Hence, these controllers do not offer a true 3D experience in VR. Using speech-to-text conversion in VR relies heavily on the accuracy of the speech recognition system, and also, the speech input may not work well in noisy environments [Deng and Huang 2004; O'Shaughnessy 2008]. Head-tracking has shown potential for text entry on 2D surfaces (desktop) [Hansen et al. 2004], and VR-headsets provide head tracking input. Head movements, however, also impact the scene-view in VR and thus add an additional layer of motion to the experience. Hence, we need a text entry method in VR that supports immersiveness, enables text entry at an acceptable speed, should be

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easy to learn, should not require external hardware setup, should keep the user's hands free, and that may be used without the risk of discomfort. Gaze typing appears to be an appropriate solution in this regard. However, to our best knowledge, there exists no gaze typing study in VR. Also, there is no literature on the primary gaze typing metrics like Words Per Minute (WPM) and Rate of Backspace Activations (RBA) [MacKenzie and Tanaka-Ishii 2010] using fundamental key selection methods such as dwell and click. Hence, the main aim, which is also the contribution of this work, was to conduct a gaze typing study in VR to investigate if gaze typing in VR is at all viable. In addition, we wanted to explore how the typing performance might be impacted by keyboard design, selection method, and motion in the user's field of view.

Basic design considerations for gaze interactive VR-interfaces include questions related to the size of the input area: Is it important to keep it within just one field of view or may it be spatially distributed outside a single view? (see Figure 2 and Figure 3 for a within-view and a larger-than-view typing interface). A larger-than-view interface requires head movements to attend keys outside the current perspective, and thus impose the risk of making some users feel uncomfortable. On the other hand, this leaves more space around each key, which could reduce the negative impact of low precision on the tracker - a problem common to many of the remote gaze tracking systems. Thus the key research question of this paper is how within-view gaze interactive interfaces compare to larger-than-view interfaces in terms of productivity, comfort, and effort. Additionally, as motion in the field of view is common in VR applications, e.g., when driving or flying, it is relevant to consider both the impact that visual and head movements might have on gaze interaction.

Hence, to understand how keyboard design, selection method, and motion in the field of view influence a user's performance while gaze typing, we conducted two experiments (n = 32 participants). Figure 1 demonstrates the experimental setup where a user is sitting on a bike simulator and wearing a VR headset. The VKB is displayed inside the headset, and the user enters a set of phrases through multiple key selection methods. In the first experiment, we used a flat keyboard, and it was within the view field of the user as shown in Figure 2. The user can focus on any key with minimal to no head movements. In the second experiment, we used a larger, curved keyboarded as shown in Figure 3. Hence, to focus on the keys on the left and right sides of the keyboard, the user was required to make head movements. The keys on both flat and curved keyboards had the same dimension, but the spacing (horizontal and vertical) between the keys was narrower for the flat keyboard but larger for the curved keyboard. Furthermore, we tested two selection methods on both the keyboards: 1) gaze+dwell, and 2) gaze+click, and used two environments: 1) a stationary field of view (sitting), and 2) motion in the field of view (biking). Overall, we investigated gaze typing in VR with an aim to develop initial insights that would encourage and assist further research in VR text entry methods.

2 PREVIOUS WORK

Gaze typing has been applied since 1990 [Frey et al. 1990], and is one of the most well-studied gaze interaction tasks [Hansen et al. 2002; MacKenzie and Zhang 2008; Majaranta and Räihä 2002]. Thousands of people with severe motor disabilities use gaze typing every day [Hansen et al. 2003; Majaranta 2011; Rajanna 2016]. Numerous novel interfaces have been designed for this purpose, in particular to address the need for more large input buttons that the low precision of gaze trackers raise and addressing the so called Midas-touch challenge - that everything looked at may unintended get activated [Jacob 1991]. However, the most common layout design is still the qwerty format because it is well-known and because it is effective with just one activation per character. Often, this format is operated with dwell activation to overcome the Midas touch problem by offering a time clutch; a key should be looked at for e.g. 500 milliseconds before it gets activated [Hansen et al. 2003; Majaranta and Räihä 2007]. If people master a single-switch well, gaze interaction may then also be performed by just looking at the button and then making a click for confirmation [Göbel et al. 2013; Kumar et al. 2007; Rajanna and Hammond 2016, 2018].

Gaze typing in VR has not yet been explored but a few studies of fingertyping has been published. Wu et al., developed a 3D VR keyboard that provides haptic feedback for keypress events [Wu et al. 2017]. The fingers position and postures are tracked by two data gloves worn one on each hand, and the haptic feedback is generated through micro-speakers. The authors found that the VR keyboard, either with or without haptic feedback, performs better than a physical keyboard. This is because, to use the physical keyboard the users had to take off the headset which incurs extra time.

Walker et al., developed a system that provides visual feedback of a user's hands position on a physical keyboard inside the VR headset [Walker et al. 2017]. In a study with 24 participants, who were touch typists, the authors found that the participants typed over 40 WPM with less than 5% error on a visually-occluded keyboard. Bowman et al., studied four text input techniques for virtual environments, namely, a pinch keyboard, a one-hand chord keyboard, a soft keyboard using a pen and tablet, and speech [Bowman et al. 2002]. The authors found that none of them exhibited high levels of performance, usability, or user satisfaction. Jimenez et al., implemented a swype keyboard for VR [Jimenez 2017]. The path of a user's fingers on the VKB presented inside the HMD is tracked with a LEAP motion controller. Since this was a prototype system, no gaze typing metrics were presented.

In summary, previous text entry studies have focused on the use of a VKB and various key selection methods to enter text by a hand-operated device but no studies implying gaze has been found. In our work, we investigated how the gaze input can be used to enter text in VR through two experiments, and the questions we wanted to address were: 1) Is gaze typing viable in VR environments? 2) What are the average gaze typing speed (WPM) and error rate (i.e., RBA) in VR? 3) Since gaze tracking is susceptible to accuracy issues, does a larger-than-view (increased spacing between keys), curved VKB have lower error rate than within-view flat VKB (reduced spacing between keys)? 4) Does motions in the user's field of view impact gaze typing performance? 5) Does a multi-modal gaze plus click interaction method suit better than gaze plus dwell interaction? 6) Do we observe learning effects? 7) How does the keyboard design impact physical and mental workload on the user? 8) What are the general limitations of gaze typing in VR?

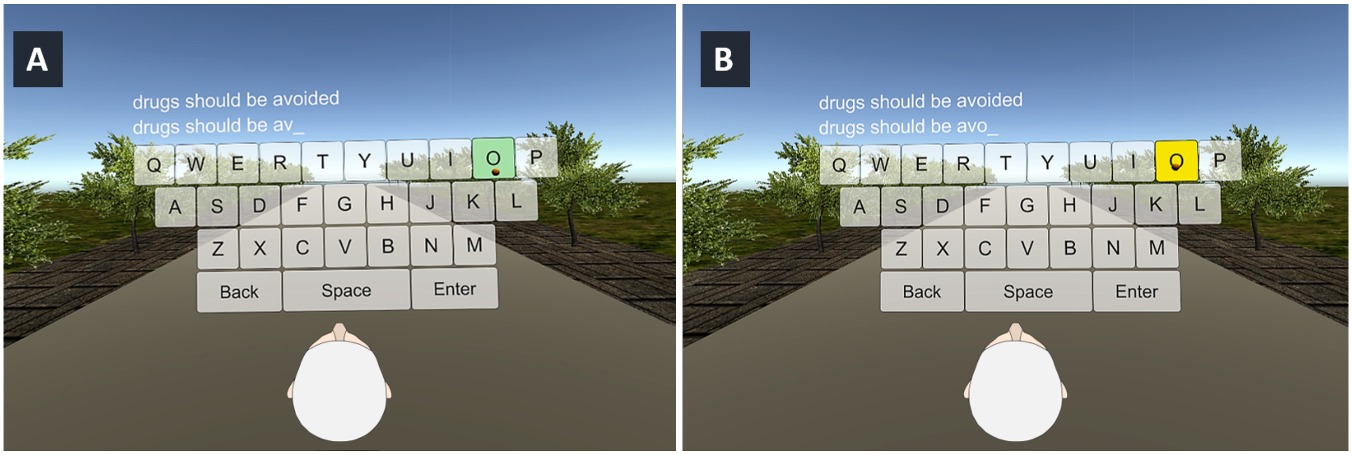

Figure 2: Flat, Within-View Keyboard: on this flat keyboard, the user needs minimal to no head movements to focus on any key on the VKB, since it is entirely within the user's field of view. To select a character, the user first focuses on the key, then the background changes to green (A). When the key is selected either by dwell or click the background changes to yellow (B). Note: this image was captured on a desktop, the field-of-view will be smaller inside the VR headset.

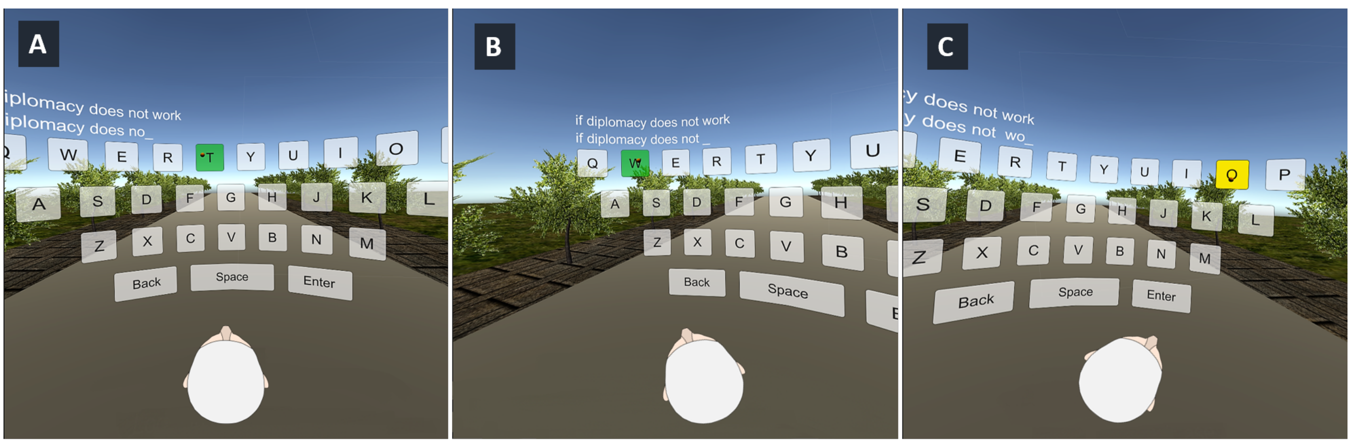

Figure 3: Curved, Larger-than-View Keyboard: Only central 2/4 of the keyboard is within the view, 1/4 of the keyboard on both left and right sides of the keyboard are out of the view. In 'A' the user is about to type character 'T', this requires no head movements. In 'B' the user is trying to type character 'W'. Since 'W' is out of the user's field of view the user is forced to turn her head to left so that 'W' can be focused. Similarly, in 'C' the user has entered character 'O'. Since 'O' was out of the user's field of view, the user had to turn her head to right to focus on the key. Note: this image was captured on a desktop, the field-of-view will be smaller inside the VR headset.

3 SYSTEM IMPLEMENTATION

The system implementation is described across three main aspects: 1) Keyboard Design, 2) Selection Method and Feedback, and 3) Environment.

3.1 Keyboard Design

We implemented a standard QWERTY keyboard for VR using the Unity game engine [1], and the keyboard was rendered in world space. A keyboard in world space is similar to looking at a billboard, and the position and orientation of the keyboard remain unaltered even when the orientation of the headset changes due to head movements. We used FOVE, a VR headset with an integrated eye tracking unit [2]. FOVE has a resolution of 2560 X 1440 px, renders at 70fps, and has a field of view of 100 degrees. The binocular eye tracking system runs at 120 Hz, and the manufacturer indicate tracking accuracy to be < 1°of visual angle. We designed two different interfaces for the QWERTY keyboard: 1) a flat, within-view keyboard (Figure 2), and 2) a curved, larger-than-view keyboard (Figure 3). The flat, within-view keyboard occupies the entire horizontal view field of the VR headset, such that the character 'Q' and 'P' are aligned along the

[1]unity3d.com [last accessed - Jan 23rd '18]

[2]www.getfove.com [last accessed - Jan 23rd '18]

left and right most edges of the display. Hence, the user needs to perform minimal to no head movements to focus at any key on the keyboard. The size of an alphabetical key was 6.5°of visual angle, and gap between the keys was 0.5°.

When typing with low tracking accuracy, the system was susceptible to inadvertent activations, and also if the point of gaze was exactly on the edges of two characters, both keys would get activated. To counter these limitations with low tracking accuracy, we designed a curved, larger-than-view keyboard first by increasing the inter character spacing both in horizontal and vertical directions (3.5°). Second, the interface was curved toward the user such that the perceived size of all the eyes on the keyboard were the same. We ensured that the dimension of the keys on the curved keyboard remained exactly the same as the flat keyboard (6.5°). The resultant curved keyboard was such that approximately the center portion of the keyboard (center 2/4 of the keyboard) was within the user's view, and the remaining 1/4 of the keyboard on both left and right sides were out of the field of view. Hence, to see and interact with characters on the left and right sections of the keyboard, the user was required to tilt their head as shown in Figure 3. The curved, larger-than-view keyboard prevents inadvertent activations and erroneous double activations due to increased spacing between the characters, we expected. In a few sections of this paper, for convenience, we will refer to flat, within-view keyboard as just the 'flat' keyboard, and curved, larger-than-view keyboard as just the 'curved' keyboard.

3.2 Selection Method and Feedback

While there exists multiple advanced key selections methods such as adjustable-dwell [Majaranta et al. 2009], cascading-dwell [Mott et al. 2017], dwell-free [MacKenzie and Zhang 2008; Pedrosa et al. 2015; Urbina and Huckauf 2010], and so on, since our work was the first gaze typing study in VR, we selected the two fundamental, gaze-based key selection methods: 1) gaze+dwell input, 2) gaze+click input. In gaze+dwell based selection method, the user fixates on the target key for a duration of 550 ms (dwell time) to select it. The dwell time value was selected based on multiple pilot trials, and the reasons for selecting a fixed dwell time are discussed section 6 - limitations and future work. While it is possible to type with a lower dwell time (e.g., 400 ms), users with poor tracking would likely experience inadvertent activations.

The background color of every key looked at by the user changes to green color (Figure 2.A), and the color is retained while the user's gaze is still pointed at the key. If the user chooses to enter the specified key, she continues dwelling on the key, and the key is activated once the dwell time elapses. Upon activation, the background of the key changes to 'yellow' color, providing a visual feedback (Figure 2.B), and a click sound is generated to provide an auditory feedback. The background of the key restores to its original color once the user's gaze moves away from the key. The gaze+click based selection functions similar to the gaze+dwell based selection. However, the key activation is achieved by clicking on an external button on the handle of the bike instead of dwelling. Hence, when using the multi-modal gaze+click method, it is crucial to achieve the synchronization between focusing on the character and pressing an external button.

3.3 Environment

As VR environments range widely from a stationary setup to dynamic setup involving motion in the field of view [Burdea and Coiffet 2003; Duchowski 2017; Krueger et al. 2017; Messier et al. 2016; Sherman and Craig 2002], we considered gaze typing tasks in both stationary and dynamic environments. To simulate the two environments, we used a VR bike simulator from VirZOOM (model VZ_EA2) featuring 5 control buttons integrated in each handle. In a stationary setup, a user will be sitting on a bike on the street, and a translucent keyboard is displayed in front of the user. Throughout the gaze typing task, neither the user nor the VKB change their position in 3D space. This set up is similar to scenarios where the text is entered in VR while the user is stationary, for example, document editing, chatting, gaming, and so on.

In a dynamic setup, we introduce motion in the user's field of view. In this scenario, similar to the stationary setup, a user will be sitting on a bike on the street, and a keyboard is rendered in front of the user. However, the user pedals the bike while gaze typing, and the peddling action translates to linear motion of the user in VR. As the user bikes, she starts moving along a straight road and the keyboard also moves with respect to the user's position such that the distance between the user and the keyboard remains constant. The motivation for including the biking condition was primarily based on a futuristic scenario where we envision that people could type in an augmented reality (AR) headset while experiencing motion in the user's field of view (driving, biking). We observed, many Europeans already type on their phones while biking. Hence, an AR headset with gaze typing abilities appears to be a likely option in the future. Also, many VR applications for training, therapy, gaming, etc., expect the user to enter text while the VR environment is changing (i.e. in motion). Since we considered a basic motion condition, the road did not have curves or obstacles which may further impact the typing performance. To ensure that all participants biked with a comparable speed, a speed-bar was placed under the VKB as shown in Figure 4. Each user must bike such that the speed indicator was always in green zone (Figure 4.A), biking slow turns the indicator red (Figure 4.B). Furthermore, we controlled that biking did not strain the participants, but only introduced motion. Hence, on a 1 to 8 resistance level on the bike, the resistance was set to 2, and the user had to hit only 50% of the speed to remain in the green zone.

4 EXPERIMENT DESIGN

To address the research questions listed in section 2, we conducted two different experiments using a within-view (16 participants) and a larger-than-view keyboard (16 participants). In both the experiments, we considered two environments: sitting and biking, and two selection methods: dwell and click. The two factors 'environment' and 'selection method' resulted in four different combinations: 1) sitting+dwell, 2) sitting+click, 3) biking+dwell, and 4) biking+click. In sitting+dwell combination the participant will be sitting on a bike, but does not peddle, hence, the user's position in VR remains constant. The user activates a key by dwelling on it. The sitting+click combination is similar to the sitting+dwell combination, but, the user selects a key by pressing a button on the bike's controller. In biking+dwell combination the participant will be sitting on a bike, and also peddles while gaze typing. This introduces linear motion in the user's field of view, and the key selection is achieved by dwelling on the keys. Lastly, biking+click combination is similar to biking+dwell, but, the key selection is achieved by pressing a button on the bike's controller.

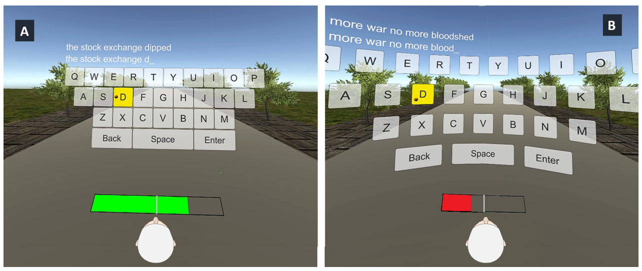

Figure 4: Biking Condition: in the biking condition, the user will be peddling while gaze typing. The peddling action moves the user along a road in the virtual world. A speed-bar was displayed at the bottom of the interface, and the users were required to maintain the speed range in 'green' (A). Speed range in 'red' (B) indicates that the user should be biking faster to get back in the green zone.

Each participant performed gaze typing through four different sessions, and in each session one of the four environment+selection combination was used. The order of the environment+selection combination presented to each user was counterbalanced using a Latin Square design. Before the start of each session, the participant was calibrated on the FOVE's standard calibation procedure. Also, the calibation accuracy was recorded on a 9 point calibration interface we developed. In each session, a participant typed four phrases (a total of 16 phrases from 4 sessions) chosen randomly from the set of 500 phrases for evaluation of text entry techniques by MacKenzie et al. [MacKenzie and Soukoreff 2003].

While we wanted the users to type more than four phrases per session, the procedure of consenting, experiment briefing, calibrating before each session, gaze typing, and post study interviews made the study last for nearly 1 hour, and the participant was wearing a VR headset for the majority of the time. Therefore, by having them type more sentences, we had a chance of participants not completing the study due to strain. Hence, based on a few pilot trials, we chose an optimum number of 4 phrases per condition. Out of the 4 phrases typed, the first phrase was considered as the training phrase and hence not included while computing the gaze typing metrics. Furthermore, we considered only those phrases entered by the users that had a similarity of 95% and above to the phrase presented based on the Levenshtein string similarity ratio [Levenshtein 1966]. Based on this measure, out of 192 phrases entered (16 participants × 4 sessions × 3 phrases) on a given keyboard, 1 phrase was rejected on the within-view keyboard, and 6 phrases were rejected on the larger-than-view keyboard. The participants corrected most of the errors in the text entered since they were instructed to do so.

To evaluate a participant's gaze typing performance in a given session, we considered a text-focused and a key-activation-focused metrics [Majaranta 2011], namely typing speed: Words Per Minute (WPM), and error rate: Rate of Backspace Activation (RBA). Also, we computed the total head movements during a session as the percentage of the number of characters entered. The head movements were recorded through the on-device orientation tracking IMU. Data from four participants (not included in the count of 32 participants) were discarded as they did not complete the study for reasons explained in section 6 - limitations and future work.

5 RESULTS AND DISCUSSION

5.1 Experiment 1: Within-view Keyboard

In this experiment, the participants typed on the flat, Within-view Keyboard. A total of 16 volunteers (13M, 3F) took part in the study, whose ages ranged from 20 to 33 (μ_{age} = 25.75). 6 participants had a corrected vision (glasses or contact lenses), and 7 had used VR at least once. Table 1 summarizes the mean typing speed, error rate, and the amount of head movements for 16 participants.

Table 1: Within-view Keyboard: Gaze typing metrics - mean WPM, error rate, and head movements

		WPM	Error	Head Movements%
Sitting	Dwell	9.36	0.02	580.37
	Click	10.15	0.07	764.46
Biking	Dwell	8.07	0.04	1242.52
	Click	8.58	0.08	1292.26

From Table 1 we observe that the highest typing speed of 10.15 WPM was achieved with the sitting+click combination. Also, the least error of 0.02 was achieved with the sitting+dwell combination. Furthermore, to understand how the environment and selection method impact gaze typing performance on the within-view keyboard, we conducted two-factor ANOVA with replication. The two independent factors were 'environment' and 'selection method', and each factor further had two levels. Environment: sitting, biking, and selection method: dwell, click. A total of three ANOVA tests were performed, and for each ANOVA test we considered one dependent variable of the three dependent variables: WPM, error, and head movements. The results of the three ANOVA tests are presented in Table 2.

Table 2: Within-view Keyboard: ANOVA tests on the three gaze typing metrics (p values highlighted in gray indicate significance at $\alpha = 0.05$).

	Environment [sitting, biking]	Selection [dwell, click]	Interaction
WPM	$F(1,60) = 8.92$, $p = 0.00$	$F(1,60) = 1.84$, $p = 0.18$	$F(1,60) = 0.09$, $p = 0.77$
Error	$F(1,60) = 1.06$, $p = 0.31$	$F(1,60) = 13.24$, $p = 0.00$	$F(1,60) = 0.02$, $p = 0.89$
Head Movements	$F(1,60) = 16.87$, $p = 0.00$	$F(1,60) = 0.65$, $p = 0.42$	$F(1,60) = 0.22$, $p = 0.64$

From Table 2, we observe that 'environment' is a significant factor for WPM. This is because, while sitting there is minimal or absence of head movements, and since the the whole keyboard remains within the view, the user types faster. However, when biking the user's body starts leaning left and right causing increased head movements, which makes focusing the keys harder resulting in lower typing speed. As a support for this observation, we see that the difference in the amount of head movements between sitting and biking conditions is also significant. Furthermore, the difference in error rate is significant between dwell and click selection. With dwell-based input, the user waits until the dwell time elapses for a key activation, hence, inadvertent activations are minimal. However, with click, the user's gaze sometimes shifts to the next character in the word while the user presses the button to enter the current character. This mismatch in the synchronization between looking at the target key and clicking a button to select it causes more error with click activation. Lastly, we observe that there is no interaction between the factors.

To understand the learning effects of gaze typing across the four sessions we conducted a two-factor ANOVA without replication, where one factor was 'participants' and the other 'sessions.' There were a total of 16 participants and 4 sessions. Table 3 presents the results of the ANOVA tests for the three dependent variables: WPM, error, head movements. We observe that the difference in the gaze typing speed (WPM) across sessions is significant. The typing speed increases from 8.28 WPM in the first session to 9.89 WPM in the fourth session. Also, the difference in typing speed and head movements among the participants is significant.

Table 3: Within-view Keyboard: ANOVA tests to understand learning effects across the sessions (p values highlighted in gray indicate significance at $\alpha = 0.05$).

	Sessions [S1, S2, S3, S4]	Participants [P1 to P16]
WPM	$F(3,45) = 3.40$, $p = 0.03$	$F(15,45) = 3.16$, $p = 0.00$
Error	$F(3,45) = 1.23$, $p = 0.31$	$F(15,45) = 1.83$, $p = 0.06$
Head Movements	$F(3,45) = 1.00$, $p = 0.40$	$F(15,45) = 3.70$, $p = 0.00$

5.2 Experiment 2: Larger-than-view Keyboard

In experiment 2, the participants typed on a curved, larger-than-view keyboard. The protocols followed for experiment 2 were exactly same as experiment 1. For the study we recruited 16 volunteers (12M, 4F), whose ages ranged from 22 to 47 ($\mu_{age} = 29$). 5 participants had a corrected vision (glasses or contact lenses), and 9 had used VR at least once. To avoid any biases, no participant from experiment 1 was a subject in experiment 2. Each participant typed 4 phrases in each of the four sessions: 1) sitting+dwell, 2) sitting+click, 3) biking+dwell, 4) biking+click. The order of the environment+selection combination presented to each user was counterbalanced using a Latin Square design. Table 4 summarizes the mean typing speed, error rate, and the amount of head movements for 16 participants.

Table 4: Larger-than-view Keyboard: Gaze typing metrics - mean WPM, error rate, and head movements

		WPM	Error	Head Movements%
Sitting	**Dwell**	7.48	0.06	1680.75
	Click	9.15	0.03	1821.84
Biking	**Dwell**	6.77	0.04	2592.95
	Click	8.29	0.03	2508.22

From Table 4 we observe that the highest typing speed of 9.15 WPM was achieved with the sitting+click combination. Also, the least error of 0.03 was achieved both with sitting+click and biking+click combinations. Furthermore, to understand how the environment and selection method impact gaze typing permanence on the larger-than-view keyboard, we conducted two-factor ANOVA with replication. The independent factors and dependent variables were same as experiment 1. The results of the three ANOVA tests are presented in Table 5.

Table 5: Larger-than-view keyboard: ANOVA tests on the three gaze typing metrics (p values highlighted in gray indicate significance at $\alpha = 0.05$).

	Environment [sitting, biking]	Selection [dwell, click]	Interaction
WPM	$F(1,60) = 2.57$, $p = 0.11$	$F(1,60) = 10.46$, $p = 0.00$	$F(1,60) = 0.02$, $p = 0.88$
Error	$F(1,60) = 1.33$, $p = 0.25$	$F(1,60) = 2.04$, $p = 0.16$	$F(1,60) = 0.68$, $p = 0.41$
Head Movements	$F(1,60) = 13.06$, $p = 0.00$	$F(1,60) = 0.02$, $p = 0.9$	$F(1,60) = 0.26$, $p = 0.61$

Unlike the within-view keyboard, 'environment' is not a significant factor for WPM (Table 5). This is because, to reach all the keys on the larger-than-view keyboard the user was forced to perform head movements irrespective of the environmental conditions (sitting, biking). But, we observe that the selection method is a significant factor, and this is due to the fact that the combination of head movements and click is much faster than head movements and dwell in selecting the target key on the larger-than-view keyboard. When considering the error, unlike the within-view keyboard, selection method is not a significant factor since irrespective of the selection method being dwell or click, on the larger-than-view keyboard the user is forced to perform head movements to reach different characters as not all characters are within the user's field of view. Hence, the chance of mis-synchronization between focusing on the target character and pressing a button is significantly less. Similar to the within-view keyboard, we do not see any interactions between the factors on larger-than-view keyboard.

Furthermore, to understand the learning effects of gaze typing across the sessions we conducted a two-factor ANOVA without replication. The independent factors, dependent variables, number of participants, and number of sessions were same as experiment 1. Table 6 presents the results of the ANOVA tests. We observe that the difference in the gaze typing speed (WPM) across sessions is significant. The typing speed increases from 6.9 WPM in the first session to 9.03 WPM in the fourth session. Unlike the within-view keyboard, where the error did not change across sessions, on the larger-than-view keyboard difference in error across sessions is significant. The error decreases from 0.063 in the first session to 0.022 in the fourth session. Similar to the within-view keyboard, the difference in typing speed and head movements among the participants is significant.

Table 6: Larger-than-view Keyboard: ANOVA tests to understand learning effects across the sessions (p values highlighted in gray indicate significance at $\alpha = 0.05$)

	Sessions [S1, S2, S3, S4]	Participants [P1 to P16]
WPM	F(3,45) = 5.13 *p = 0.00*	F(15,45) = 3.92 *p = 0.00*
Error	F(3,45) = 2.92 *p = 0.04*	F(15,45) = 1.73 *p = 0.08*
Head Movements	F(3,45) = 1.00 *p = 0.40*	F(15,45) = 4.06 *p = 0.00*

5.3 Tracking Accuracy and Performance

In experiment 1 (within-view keyboard) a total of 64 tracking accuracy values (16 participants x 4 sessions) were recorded (1 value = mean accuracy of 9 points) post calibration, and the mean tracking accuracy was 3.9°, min 2.1°, and max 9.34°of visual angle. Also, in experiment 2 (larger-than-view keyboard) a total of 64 tracking accuracy values were recorded post calibration, and the mean tracking accuracy was 4.26°, min 1.96°, and max 7.76°of visual angle. While we expected that better calibration accuracy would result in higher WPM and lower error rate, we found no correlation both on the flat and curved keyboards. The reason is that though a user starts typing with good accuracy, even a minor disturbance (smiling, cheeks raising) to the calibrated position of the headset on the user's face significantly impacts gaze tracking accuracy. Furthermore, before comparing the gaze typing metrics across the experiments (keyboard designs), we wanted to check if the gaze tracking accuracies between the two groups were the same. From a t-Test for two samples with equal variances, we found that the difference in tracking accuracy between the two groups was not significant (P = 0.14 > 0.05).

5.4 Keyboard Design: Typing Performance

To understand how does the keyboard design impact gaze typing performance, we performed three-factor mixed model ANOVA with replication on the dependent variables: WPM, error, and head movements. The three factors (independent variables) we considered were: 1) keyboard design, 2) environment, and 3) selection method. The factor 'Keyboard design' is a between-subjects factor and it has two levels: 1) flat (within-view), and 2) curved (larger-than-view). 'Keyboard Design' is a between subjects factor since the participants who gaze typed on the flat keyboard did not participate in the evaluation of the curved keyboard and vice versa. 'Environment' is a within-subjects factor and has two levels: 1) sitting, and 2) biking. Lastly, 'selection method' is also a within-subjects factor and has two levels: 1) dwell, and 2) click. A total of 3 ANOVA tests were performed, and for each ANOVA test we considered one dependent variable of the three dependent variables. Table 7 shows the results of the ANOVA tests for 3 dependent variables.

Table 7: Interface Design: ANOVA tests on the 3 gaze typing metrics (p values highlighted in gray indicate significance at $\alpha = 0.05$)

	Keyboard [flat, curved]	Environment [sitting, biking]	Selection [dwell, click]
WPM	F(1,30) = 4.58 *p = 0.041*	F(1,30) = 18.99 *p = 0.00*	F(1,30) = 20.21 *p = 0.00*
Error	F(1,30) = 1.28 *p = 0.26*	F(1,30) = 0.02 *p = 0.88*	F(1,30) = 1.77 *p = 0.19*
Head Movements	F(1,30) = 28.9 *p = 0.00*	F(1,30) = 54.31 *p = 0.00*	F(1,30) = 0.81 *p = 0.37*

From Table 7, we observe that 'keyboard design' is a significant factor that would influence the typing speed (WPM). Typically users type faster on the flat, within-view keyboard compared to the curved, larger-than-view keyboard. As expected, we observe that the amount of head movements is also influenced by the keyboard design. Users perform more head movements on the curved keyboard than on the flat keyboard.

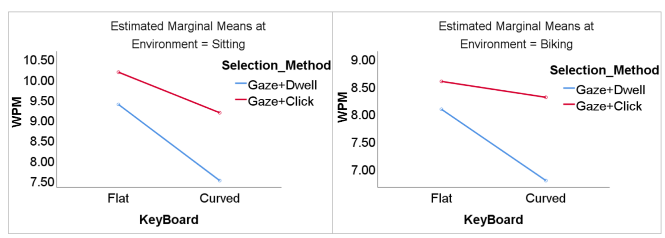

Figure 5: Interaction for WPM: *selection_method* × *keyboard*

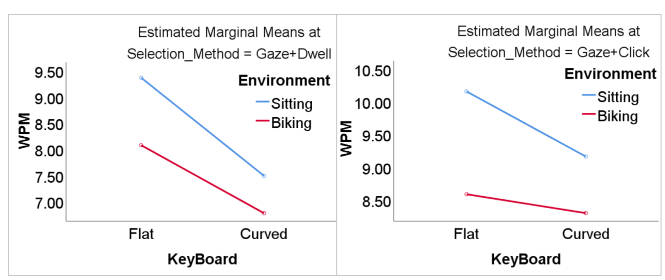

Figure 6: Interaction for WPM: *environment* × *keyboard*

Lastly, contrary to our expectation, the keyboard design did not influence the error rate. The difference in the error rate between the flat and curved keyboards was not significant. Hence, we infer that increasing the spacing between interface elements in 3D, with an intent of reducing inadvertent activations may not reduce the error rate. Figure 5 and 6 visually represents the statistical result that there is no interaction between the factors selection method (P = 0.06 > 0.05) and environment (P = 0.218 > 0.05) on the typing speed (WPM) on flat and curved interfaces. From Figure 7 and 8 we observe a significant interaction between the factors selection method (P = 0.00 < 0.05) and environment (P = 0.03 < 0.05) on the error rate (RBA) on flat and curved interfaces. As previously discussed, click-based selection results in more error than dwell on the flat keyboard, but relatively less error than dwell on the curved keyboard. Also, motion in the field of view impacts performance on the flat keyboard, but does not impact much on the curved keyboard as the users will always be moving their head while typing irrespective of the environment.

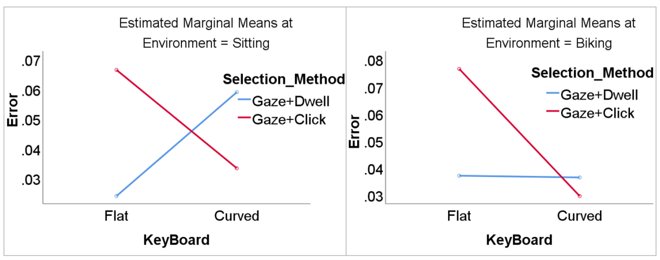

Figure 7: Interaction for Error: *selection_method* × *keyboard*

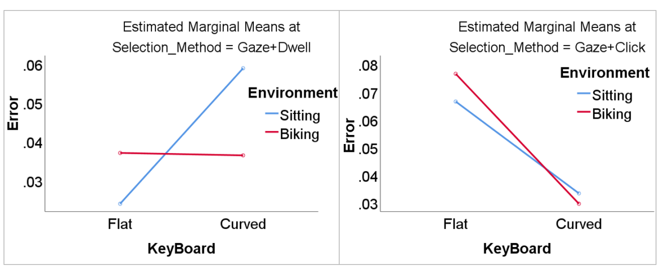

Figure 8: Interaction for Error: *environment* × *keyboard*

5.5 Keyboard Design: Workload

We wanted to understand if the interface design impacts users' perceived mental and physical workload. During both experiment 1 and 2, after completion of each session, the participants rated for the mental and physical workload measures on a 10 point scale. Where, 1 being the least and 10 being the highest workload. From a Mann-Whitney U test, we found that the physical work load differs between the keyboards (p = 0.01 < 0.05), however the mental workload does not (p = 0.401 > 0.05).

To further explore the workload on participants when considering two factors 'keyboard' and 'sessions,' we performed two-factor mixed ANOVA with replication. The dependent variables were physical workload, and mental workload. The factor 'Keyboard' is a between-subjects factor and it has two levels: 1) flat (within-view), and 2) curved (larger-than-view). 'Sessions' is a within-subjects factor and has four levels: session1 through session4. A total of 2 ANOVA tests were performed, and for each ANOVA test we considered one dependent variable of the two dependent variables. Table 8 shows the results of the ANOVA tests.

Table 8: Interface Design: ANOVA tests on the mental and physical workload (p values highlighted in gray indicate significance at $\alpha = 0.05$)

	Keyboard [flat, curved]	Sessions [S1, S2, S3, S4]	Interactions
Physical Workload	F(1,30) = 4.51 *p = 0.04*	F(3,90) = 2.83 *p = 0.04*	F(3,90) = 2.18 *p = 0.09*
Mental Workload	F(1,30) = 0.48 *p = 0.49*	F(3,90) = 1.94 *p = 0.12*	F (3,90) = 0.40 *p = 0.74*

From Table 8 we observe that keyboard design is a significant factor for physical workload. This might be due the fact that users perform more head movements on the curved keyboard than on the flat keyboard. However, the keyboard design is not a significant factor for mental workload. We believe, this is due the fact that irrespective of the keyboard design the amount of mental work required, i.e., finding the target key and activating it is the same. Similarly, 'sessions' is a significant factor for physical workload, but not mental workload. Lastly, Figure 9 visually represents the statistical result that the interaction between factors 'sessions' and 'keyboard' for both the dependent variables are not significant ($p > 0.05$).

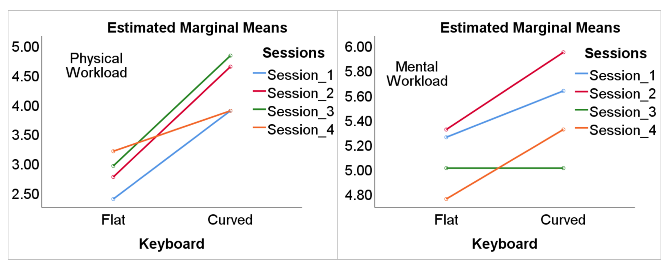

Figure 9: Interactions for mental and physical workload: *sessions* × *keyboard*

5.6 Qualitative Feedback

During the post-study interview, we asked participants which of the two selection methods they prefer? and why? On the flat keyboard, 50% preferred dwell and 50% preferred click; on the curved keyboard, 31% preferred dwell and 69% preferred click. Following are some of the reasons explaining why a participant either preferred or did not prefer a selection method.

Reasons for dwell being the preferred method.

F3: *less failure in task execution.*

F6: *dwelling feels natural, I don't have to worry about multiple controls (like button clicks).*

F8: *it was easy, when you look at a letter and heard the sound you*

know it's registered. I make less mistakes.
F19: *dwell is better, with dwell you don't have to think, you can just look, it's more immediate.*
F21: *it's faster, but you need some practice first, once you know how many seconds you look at a character it becomes easier. It is easier than clicking. Dwelling is one less function. Clicking involves multiple functions.*

Issues with dwell-based selection.
F14: *I had to close my eyes to avoid activations of the keys.*
F15: *with dwell you have to wait, which is not good.*
F20: *dwelling is more cognitively demanding because it requires more attention.*

Reasons for click being the preferred method.
F10: *it is fast, you use less effort while looking at the target.*
F20: *dwelling is more cognitively demanding because it requires more attention. With clicking, you can look at the button and just choose right away.*
F21: *click is better since you are in movement on a bike. It then becomes easier to control with the click.*
C1: *with dwell it is a frustration that you have to gaze for some time before the characters are chosen. With click you are more in control.*
C12: *when biking I had a feeling that I should focus on the body movement. So, I couldn't use gaze well. The body was shaking. So point and click is better.*

Issues with click-based selection.
F6: *it is overwhelming (while biking), I need to focus on head movement, biking, and clicking. Hence, dwell is preferred.*
F8: *with click activation the synchronization between looking and clicking is hard. I was fast, I move out of the character before even clicking it and make more mistakes.*
F17: *when using clicking, I looked at the character, and before clicking I had moved to the next character. Hence I mistyped.*
C17: *clicking is doing two things at once which is extra work. Couldn't see any advantage.*

Lastly, when asked about the general feedback about the whole gaze typing experience in VR, the participants shared the following details.
F5: *elements on the boundary are hard to type.*
F8: *calibration was frustrating.*
C7: *central area is better, it seems more accurate.*
C8: *moving eyebrows impacts the calibration.*
C13: *while biking, moving feet, shaking of the head, body makes it difficult to focus the gaze on the characters.*

6 LIMITATIONS AND FUTURE WORK

The main limitation of our study design is that a fixed dwell time was used since each participant typed 4 phrases per condition, and this was a less number of sentences to test different dwell times. Since the dwell time was fixed, it allowed us to compare the impact of keyboard design (flat vs curved) and environment (sitting vs biking). With a fixed dwell time of 550 ms though we observed that gaze+click selection performs better than gaze+dwell, additional studies with varying dwell times need to be conducted to validate this observation. Regarding the limitations of gaze typing in VR, first, as many participants shared, gaze tracking accuracy is crucial, and it impacts performance. With a good accuracy (better calibration), dwell becomes a preferred selection method, and a dwell time of less than 550 ms is preferred. Though, participants with poor accuracy tend to choose click as the activation method, they feel it is overwhelming, specially, when biking. Second, gaze tracking accuracy relies heavily on maintaining the fit of the headset on the user's face following calibration. Even with a tight fit, the headset shifts when the cheeks are raised (speaking, smiling) or when eyebrows are raised and lowered. A minor shift in the headset fit from the calibrated fit reduces the tracking accuracy.

Third, we observed that the tracking accuracy also relies on the length of the eyelashes. Longer eyelashes and mascara–which may darken, thicken, lengthen–on the eyelashes significantly reduces accuracy (IR light blocked) to a point that tracking becomes impossible. While some female participants experienced tracking issues, two of them did not complete the study due to the above reasons. Fourth, motion in VR makes it more uncomfortable to gaze type. In our study, three participants experienced discomfort (excessive sweating, giddiness, nausea, vomiting) when they tried gaze typing while biking. Two of them did not complete the study, but one completed the study after a long break. Fifth, gaze typing for extended period causes uneasiness. This is more due to having a headset on their face than gaze typing task itself. Lastly, the interaction space in VR is limited, hence, overlaying a VKB in VR space would occupy much of screen-space and leave a little space for other objects in the scene.

Considering some of the future enhancements for gaze typing in VR, it is crucial to maintain a good tracking accuracy post calibration, hence, the system should dynamically calibrate [Binaee et al. 2016] itself at regular intervals. This reduces the user from experiencing poor accuracy even when the headset shifts minimally on the face. To enable using VR headset and gaze typing for longer periods, the headsets must be made lighter and untethered. Motion sickness in VR still remains a problem to be addressed [Tanaka and Takagi 2004]. Solutions like controlling velocity and visual angle of the visual information [Tanaka and Takagi 2004], dynamic field of view [Fernandes and Feiner 2016], virtual nose [Whittinghill et al. 2015], gaze-contingent depth-of-field [Duchowski et al. 2014], etc., have shown to reduce VR motion sickness and visual discomfort, and these can be adopted in gaze typing. Lastly, we will be conducting studies including more complex motion conditions like roads with curves and obstacles, and varying dwell times which would likely influence the typing performance.

7 CONCLUSION

Text entry in virtual reality still remains a problem to be addressed. We investigated the feasibility of gaze typing in VR. We found that though gaze typing in VR is viable, it is constrained. Users perform better when the entire keyboard is within-view. Motion in the user's field of view negatively impacts performance, induces strain, and some individuals may experience motion sickness. Though gaze+dwell based selection feels natural and easy, gaze+click is the most preferred way of interaction.

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