ABSTRACT

JAKOB KIRBY, B.S(May 2025) COMPUTER SCIENCE

VR TYPING FOR HAPTIC GLOVES: A COMPARISON STUDY OF VR TEXT ENTRY METHODOLOGIES (54 pp.)

Thesis Advisor: Kwangtaek Kim

The goal of my thesis is to investigate and develop a virtual haptic keyboard using available commercial haptic gloves with a focus on ten-finger typing within a Virtual Reality environment. Previously, only text-entry studies performed with bare-handed typing within VR were conducted. A new haptic glove-based text entry system was created. In the new system, two glove-optimized virtual keyboard layouts were designed: a flat layout, and an ergonomic split layout (a decision based on two studies conducted to find measurements of users' typing postures while wearing haptic gloves.) Additionally, tactile feedback simulating realistic key pressing was developed using the unique force feedback mechanism of each glove system. An additional comparative user study was conducted to find what level of haptic feedback is most preferred by users. The resulting data determined that a single-phase feedback system was favored. The study was created to assess usability, typing performance, and to measure performance against current standard VR typing methods. Also of interest, was the determination of any differences between the two commercial haptic gloves, Dexmo and Nova. The experiment compared six different VR typing methods: the VR controller, the physical keyboard, the Dexmo glove with each of the two keyboard layouts (flat

and split) and the Nova glove with the same two keyboard layouts (flat and split.) This study measured four typing metrics: Words Per Minute, Keystrokes Per Character, Corrected Error Rate, and Uncorrected Error rate, to determine the typing efficiency and accuracy of the typing methods. Participants in the study also filled out a NASA Task Load Index and System Usability Scale form to determine if the system led to a likeable or unlikeable experience for the user. The results indicated that while users appreciated the novelty of glove-based typing and were able to achieve proficient speed and accuracy, the typing performance of the controller and physical keyboard was higher than the glove methods. Users reported that the primary drawback of haptic glove-based typing is the weight of the gloves. The weight contributed to lower typing speed and accuracy, limiting the effectiveness of haptic feedback in typing performance.

VR TYPING FOR HAPTIC GLOVES: A COMPARISON STUDY OF VR TEXT ENTRY METHODOLOGIES

A thesis submitted.

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Jakob Kirby

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Thesis written by

Jakob Kirby

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Approved by

Dr. Kwangtaek Kim, Advisor

Dr. Mikhail Nesterenko, Interim Chair, Department of Computer Science

Mandv Munro-Stasiuk Ph.D., Dean, College of Arts and Sciences

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CHAPTER 1

Introduction

In Virtual Reality (VR), various hand interaction devices enable users to engage in virtual environments. These devices can range from basic controllers provided with the Head-Mounted Display (HMD) to advanced wearable haptic gloves. While all these devices serve the primary function of facilitating user interaction within VR, they each come with distinct advantages and limitations. For example, traditional VR controllers, though simple and widely used, offer limited interaction capabilities, primarily relying on buttons for input.

One critical task in VR that has been getting attention but remains underexplored with newer hand interaction devices is VR typing. Despite the emergence of advanced devices like haptic gloves, there is a gap in research concerning realistic key typing feedback for VR typing, or overall haptic glove-based typing overall. Haptic gloves, with their ability to provide localized finger haptic feedback, present a promising method for enhancing typing performance in VR. Unlike VR controllers, which lack the capability for ten-finger typing and realistic key typing feedback, haptic gloves can deliver tactile sensations that mimic the feel of physical key presses.

Research indicates that haptic feedback can significantly improve typing performance [19,20], suggesting that haptic gloves could offer superior typing experiences in VR environments. However, designing a haptic virtual keyboard that effectively utilizes the haptic feedback capabilities of these gloves poses unique challenges. The mechanical functioning of haptic gloves varies, requiring specific modifications to achieve a realistic key typing experience. Additionally, haptic gloves do not provide global hand tracking with reference to the world coordinate system in VR, as they are not grounded devices. Despite their potential, there is limited knowledge on how to design and develop a haptic virtual key typing interface using haptic gloves for VR or AR environments.

Several studies have demonstrated that ten-finger typing in VR can be achieved through various methods, such as designing wearable electronic sensing systems to detect finger contact motion [1], incorporating conductive fabric strips along the fingers [2], or utilizing VR data glove [3], to provide typing sensing and confirmation. However, these studies primarily focus on finger motion sensing for text input without considering haptic feedback. A straightforward approach to adding tactile feedback cues for key typing confirmation is attaching vibrators to existing data input devices. For instance, one study explored the use of micro speakers in VR data gloves [18] to provide tactile feedback. Despite this, such methods fail to deliver a realistic haptic typing experience comparable to that of a physical keyboard due to the limited haptic feedback capabilities of vibrators.

Therefore, there is a need to develop new ten-finger typing interfaces that leverage the advantages of haptic glove technologies in VR. With this being the first efforts of research and development, many different steps were taken to ensure that the best typing experience could be made with haptic gloves, along with finding any current issue inherent to haptic gloves not found in any other VR typing methods. The first main goal of this study as stated is to create an in-air typing interface within VR that will be able to provide realistic keyclick haptic feedback using the haptic gloves, and explain the steps taken to ensure that any developments and decisions around the design are explained and understood. The in-air glove keyboard will also ensure that in-air free typing will be allowed with full user personalization and movement as seen fit, while still ensuring that the typing experience is as efficient and comfortable as possible. This focus on comfort and getting the best possible keyboard dimensions will be shown in tests and measurements, from user typing posture measurements so the keyboard will be as comfortable as possible. This information will be crucial in creating a keyboard layout that will be as comfortable and efficient for user typing performance as possible. As mentioned before, there has been no research done on creating a haptic glove keyboard, having these user measurements will be invaluable. There will also be steps taken to investigate the effects that haptic force feedback will have upon users typing performance, as well as users' subjective preference for its inclusion, to see how impactful this haptic glove exclusive feature will be.

Secondly there will also be an investigation into whether different keyboard layouts may be preferable to haptic glove typing. With multiple new issues exclusive to haptic gloves appearing through development, we want to see if a keyboard developed exclusively around the haptic glove may assist in improving the typing experience. For this we will go over the development, and what issues are being addressed by this new layout, as well as the ergonomic methodologies chosen specifically to adapt and address these haptic glove limitations.

Finally, with there being no research upon haptic glove typing, there is no measurement of how haptic glove VR typing compares to other common and established typing methodologies. With this gap in knowledge, we will conduct a comparative typing study between the different established VR typing methods to see how efficient haptic gloves initial typing performance compares to the current standard VR methodologies.

Organization

The structure of this thesis has been created so that the steps taken to develop the glove-based typing methods can be fully understood as well as to give a deep understanding of how the glove-based methods function. Chapter 2 will go over works related to the different typing methods featured within this thesis as well as reviewing the additional non-VR studies that influenced the design of the typing methods, and comparative experiment conducted within this thesis. Chapter 3 will go over how each typing method was developed starting with the glove keyboard, and how its two different layouts differ, along with the goals of each layout. These sections will also feature the pilot studies conducted to ensure the best possible keyboard layouts were made with the two pilot studies being over the keyboard layout dimensions and the user's preference for haptic key click effects. The final base VR typing methods will then have their developments reviewed and explained in the order of the controller method first then physical keyboard method second. Chapter 4 will explain the comparative typing study that was conducted to evaluate the newly developed haptic glove keyboards against established VR methods. This will go over how many users took part, what the experiment featured and how users were tested so that there will be a better understanding of the methods and reasoning behind each part of the experiment. Chapter 5 will go over the results of the study explaining any data that was collected and what it means for each typing method, as well as how each typing method ranked in comparison to each other. Chapter 6 will go into a more depth discussion of the findings of this experiment and what each finding means and how it can be applied to any current of future work. Finally, chapter 7 will conclude the thesis by giving a small review of the main findings within this thesis.

CHAPTER 2 Related Works

2.1 Wearable VR Methods

Various attempts to create wearable typing methods for virtual reality (VR) existed before the widespread use of commercial VR headsets [1]. These early solutions involved custom data gloves that allowed typing by touching different finger joints to produce specific characters [1,2,4]. For instance, typing Q, A, and Z could involve touching different joints of the pinky finger with the thumb of the glove. Interest in these gloves declined as technology advanced, leading to more familiar typing methods. Some approaches adapted this style without wearables, using hand-tracking technology to enable finger-tap typing with one hand [5]. However, these systems do not fully leverage VR and would not have any major differences outside of a VR environment. This may be because many of these data glove methods were developed before VR devices became widely available, and a significant knowledge gap remains for these initial data glove-based methods as there are few studies on their typing efficiency or usability.

Some other wearable or attached methods aim to create VR-specific typing experiences. These approaches focus on placing the keyboard interface on the user's limbs within VR [6,7,8]. They either use the standard commercial controllers of VR headsets with a virtual keyboard on the user’s arms or track the user’s bare hands through hand-tracking capabilities or a Leap Motion device [47]. These methods demonstrated relatively high words-per-minute (WPM) rates and highlighted the advantages of fully virtual systems with the flexibility and positioning of VR typing methods. They also highlighted the benefits of hand interaction within VR, as the virtual keyboard and other visuals allow for greater adaptability to the limitations of virtual schemes. Other methods aim for even more freedom by removing the physical keyboard altogether [9], using finger movements and positioning to type, or incorporating wearable trackers that do not require covering the entire hand [10]. The main issue with these methods is that they are still not able to give any form of haptic feedback to the user's hands and fingers because of the methods being bare handed methods as well as the tracking being camera based. Outside of any additional attachments to the user these methods are incapable of providing haptic feedback from the typing interface itself.

There have been several studies that have explored adding bare-hand tracking to commercial VR headsets or using a Leap Motion device for the same tracking [47]. Many of these studies did not investigate ten-finger typing or the addition of haptic feedback as they focused on poke-style typing [11,12,8,13], usually only allowing the pointer finger to be able to type which offered consistency across different hand-tracking methods. The major limitations of these approaches is their inability to support ten-finger typing with some of the tracking methods being generally unable to support 10-finger typing if a free moving keyboard was wanted, along with the lack of haptic feedback removing all of the potential benefits that tactile sensations could offer for typing. Some methods combined finger-based data glove techniques with Leap Motion tracking [14], which was able to make up somewhat for the lack of a 10-finger style method although still differing from normal 10-finger typing. These methods, however, still lacked tactile feedback of any form to the fingers. Additionally, there is a notable lack of research on the effectiveness of haptic glove devices and their potential for finger typing in VR [15,16,17].

The few studies on haptic glove-based typing either use motors for vibration feedback or require additional haptic feedback devices which varies greatly from the haptic glove devices used within our study. One study by C.-M. Wu et al. [17] presented a concept similar to our own, where a glove controlled haptic button allows for realistic key clicks in VR. However, they used a data glove without built-in haptic feedback, relying only on limited finger motion tracking and camera-based hand tracking. For haptic feedback, they employed micro-speakers to simulate a button-click effect when pressing the virtual buttons. Their focus, however, was on 3D button clicks for user interfaces, not ten-finger text entry. This highlights a gap in analyzing the haptic capabilities of current VR gloves and the steps needed to improve VR typing efficiency.

2.2 Standard VR Methods

Unlike novel glove-based typing methods, multiple studies have explored typing with standard hand interaction devices that come with VR Head Mounted Displays (HMDs), primarily using base VR controllers. A few of these investigate the efficiency of the "Raycasting" or point-and-click style of typing featured within our own study [18,19]. While these systems are usable, they do not match the typing speeds possible with traditional typing methods, and if any haptics are provided, they are not any form of force feedback but instead vibration style feedback from the controllers. There is also interest in alternative keyboard and typing styles to improve typing speed and efficiency. Some feature novel text entry systems using either different postures for holding the controllers [20] or taking advantage of the thumb trackpads on the controller [21]. One such style is "Percussive" style typing, where the controller acts as a virtual drumstick or general object to strike shapes serving as keys [22, 23,24]. These methods attempt to mimic drumming motions, with some showing improved typing speeds, typically around twenty words per minute. However, they face challenges, including the lack of force feedback and potential variability in performance due to differences in controllers for different HMDs. Additionally, percussive typing may not be suitable for all environments, as it requires sufficient space for the striking motions notably limiting the freedom that other VR typing methods are able to have.

The problems shown with the “percussive” controller typing is why we decided to proceed with the “Raycasting” style of controller typing in the study. Another factor is also because there is a much larger precedent for the point-and-click style of typing, as it is the standard method within almost all VR HMD’s when interacting with their menus or typing within them.

2.3 Featured Haptic and Typing Studies

Several additional studies played a crucial role in shaping the development of the glove-based virtual keyboards used in this study, particularly those focused on the effects of haptics and various types of visual feedback. For the glove keyboard, it was essential to incorporate realistic audio, visual, and tactile haptic feedback, as emphasized in a study by Han et al. [25,26]. They demonstrated the effectiveness of haptic key click feedback as a form of multimodal feedback for virtual QWERTY keyboards on the touchscreens of commercial phones and tablets. Similarly, W. Kim et al. [11,28] explored the impact of pseudo-haptic feedback on enhancing a user's sense of touch and feedback when interacting with or pressing a virtual key or button in VR. Furthermore, audio feedback has been shown to improve users' typing skills [29]. These studies highlight the significant impact of haptic and multimodal feedback in virtual typing and other mediums, offering a strong precedent for including these elements in the typing methods for haptic gloves. To the best of our knowledge, no study has previously designed or evaluated a virtual keyboard for haptic glove-based ten-finger typing, which adds considerable value to our research. This approach has the potential to improve mid-air typing performance in VR, offering an alternative to current VR controller-based or eye-gaze typing methods, both of which do not support ten-finger typing, in addition to continuing the advantages of VR typing in having a mobile and adjustable typing platform.

CHAPTER 3

VR Typing Method Developments and Designs

Now we will go over the different typing methods implementations for this study. The order for them will be the haptic glove-based method, the VR controller-based method, and the physical keyboard-based method. The glove based method will be split up into three section with the first focusing on the design and creation of the different keyboard layouts, the second will then focus on the steps taken to create the haptic feedback for the keys and why the specific implementation was chosen, and the final section will go over the differences between each haptic glove in the final version of the glove based keyboard. The VR controller and physical keyboard-based methods will be explained in only one section as there were no novel improvements or changes made to them, as they are pre-established and standard methods for VR.

3.1 Development of Virtual Keyboard Layout Designs for Haptic Gloves

Haptic gloves required a brand-new keyboard layout as there has been no literature or programs that feature 10-finger typing with commercial haptic gloves. With each glove having its own defined features and limitations there was a need for a new virtual keyboard that could act as a universal typing scheme and platform.

When creating a virtual keyboard for the haptic gloves, we designed a flat standard QWERTY keyboard referred to as the flat keyboard layout. When typing with the gloves on this layout, the main issues that appeared were the larger space each glove took up on the keyboard from the attached haptic components on the gloves, and the limited degrees of freedom allowed by the fingers when typing. These issues made it so dual hand 10-finger typing was actively

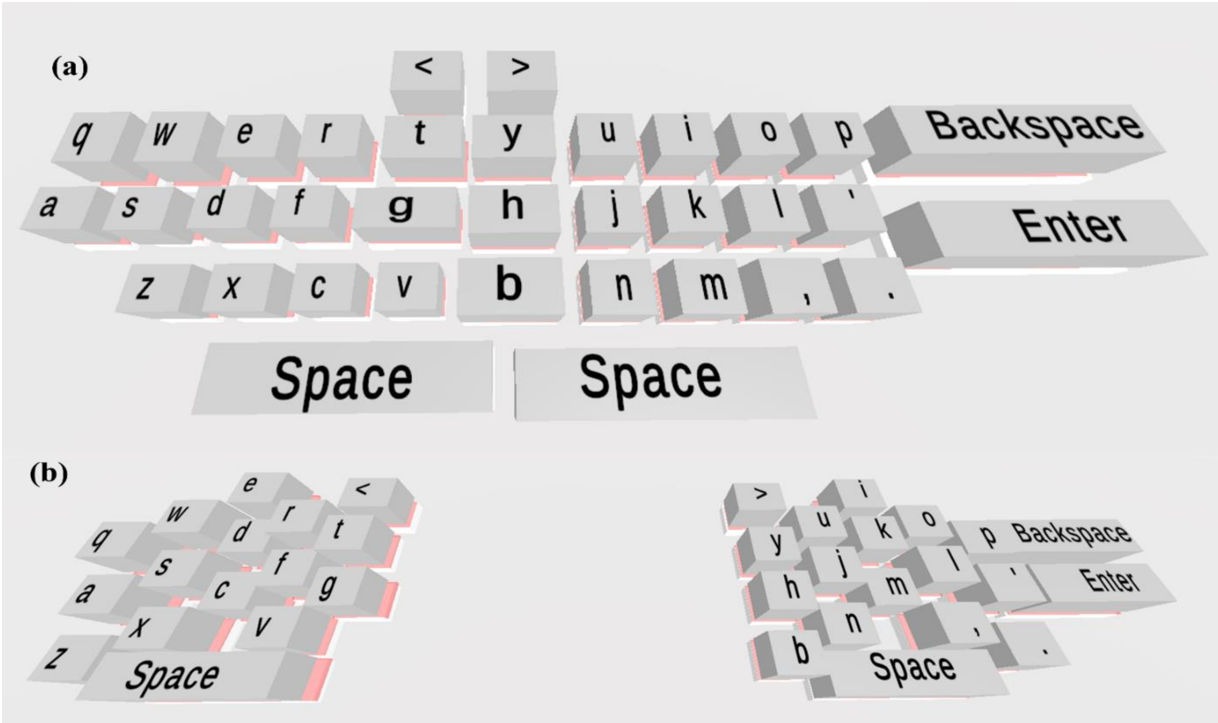

Figure 1. Glove keyboard layouts.

discouraged. Adjustments to the flat keyboard layouts center keys were made to have them larger than the other keys to allow for two hands to be used comfortably on the keyboard. An inclusion was also made to allow for the keyboard to be adjusted and moved anywhere on the X and Y axis to allow for runtime user adjustments. It was limited to no rotation to allow for a more simple approach for the future typing experiment.

To better address these issues noted with the gloves in the flat layout, we created a second layout referred to as the split layout. The split keyboard layout follows an ergonomic style flow with the rows being arched to assist finger placement, as well as the keys being split down the center with a large empty space between the halves to give each glove more typing room. This layout followed an ergonomic style design because there is research showing that ergonomic keyboards can increase or enhance typing efficiency for a user [30,31,32] as well as increasing the comfort for users while typing [31]. It was also made so that this layout would be as adjustable as the previous flat layout with the included additions of being able to adjust the distance between the two halves to be farther or closer at any time when typing.

For the actual keys in the layouts the dimensions were based upon research by Zhou [33] and Park [34] to find the optimal or most usable size of virtual button for bare-handed VR interaction. Considering the results of this research, the keys had a dimension of 17x20 mm for the width and height along with spacing between the keys of ~8mm.

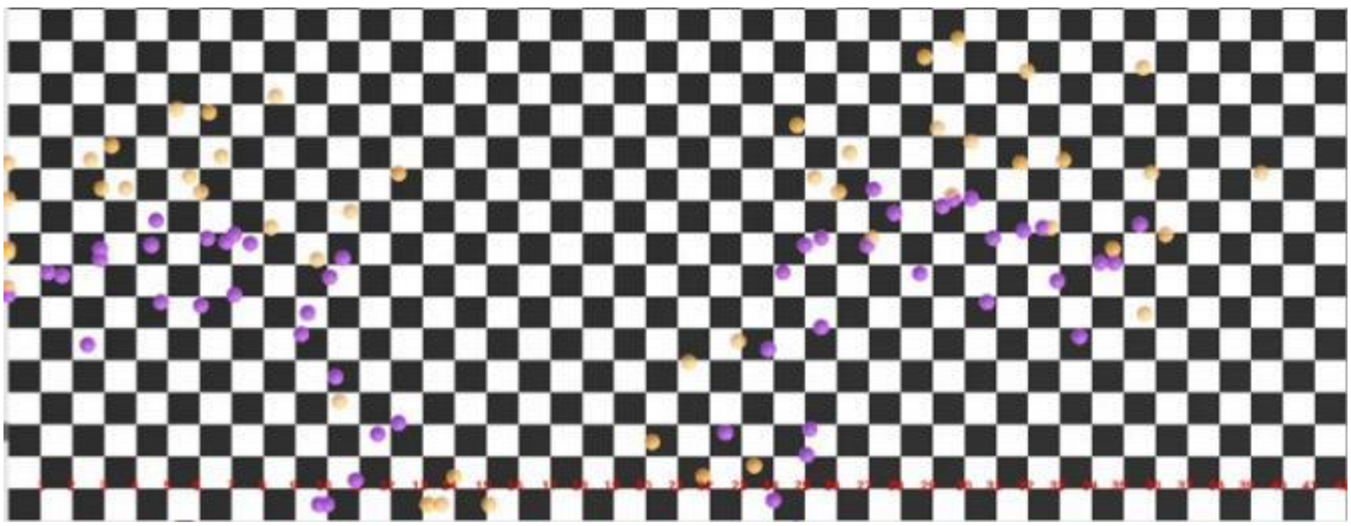

Figure 2. Visualization of finger posture positions of all users taken on paper within unity. The purple dots represent the typing posture and orange dots represent the full spread.

3.2 Glove Keyboard Layout Pilot Study

To be able to find the most efficient and accurate keyboard dimensions for the flat and split layouts, a pilot study was conducted to gather this information from user typing postures. This information is important for both the new development of the layouts, but also for the new split layout needing to be within dimensions that will allow for the best user experience and comfort possible for users.

3.2.1 Procedure

For the experiment, participants placed their hands on a piece of paper in both typing posture and having full finger extension. For these postures, each fingertip position was marked and labeled for each finger. These positions were then measured to find the widths between each finger from the farthest marked points. The points that were used as edges were usually the left pinky for the left hand and full measurements, and the right thumb for the right-hand distance measurements. In the measurements these edge points were marked as the zero points for the X axis distance measurements and the lowest marked position was used as the zero point for the Y-axis measurements. These positions were taken and then transferred to Unity to see if the distances matched, and how the measurements lined up with the virtual hands as seen inf Figure 2.

3.2.2 Participants

5 participants participated in this study all being male with ages ranging from 20-30 years. Participants were not selected based upon any particular identifying features or skills they had. As this was not a formal experiment, no IRB approval was needed. All participants were still informed of what the study entailed and agreed to take part.

3.2.3 Results and Discussion

Table 1 Hand posture measurement results

Left Hand			Right Hand			Merged Measures		
	Type	Spread		Type	Spread		Type	Spread
	10.72	14		9.6	13.85		35.5	39.3
	9.35	15.1		9.1	16.1			
	10	13.15		11.65	14.5			
	9.65	13.6		9.65	12.9			
	11.6	10.4		13.2	14.45			
Averages:	10.264	13.25		10.64	14.36			

The results showed that the average typing width for the left hand was 10.264cm with the average spread distance being 13.25cm. The right hand had an average typing posture width of 10.64cm and an average max finger spread of 14.36cm. The total average combined spread of the typing posture was 35.5cm, with the finger spread average being 39.3. These widths were within the allowable spread of the Dexmo gloves and were also within acceptable and comfortable movement distances of the Nova haptic glove as they did not allow for the same finger movements. The final measurements of each keyboard half within the split keyboard were 13.30cm with the buttons having a spacing of 2.20. The larger measurement was chosen as it was found that having slightly more room given to the keyboard resulted in a more comfortable and efficient typing experience. The height of the rows was the same spacing as the buttons and were additionally changed based upon the positioning of the measured points as seen in Figure 2.

These new measurements allowed for much more consistent developments. As whenever new issues were discovered, it allowed for much smoother changes to the keyboard layouts now that there was a permanent measurement for the keyboard, based within actual user data. Another small note about hand position data is the fact that in the virtual scene there will be different

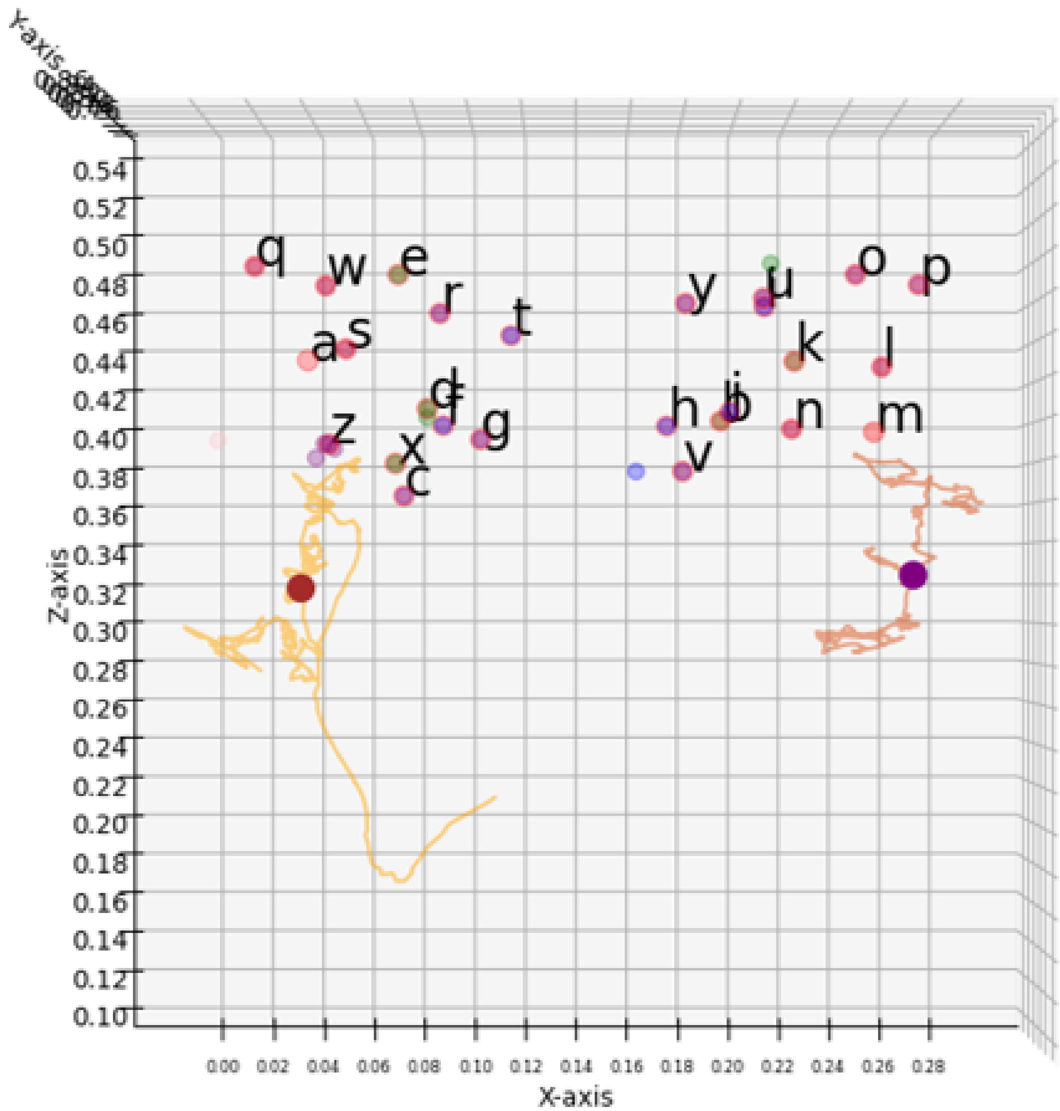

Figure 3. Virtual finger contact points on plain to real world locations and hand trajectory. The red dots designate where each collision for each respective key was. The yellow and brown lines indicate the left and right hands with the dots on them indicating the average center of each of the hands.

virtual hands used to represent the users' hands. This may change the users' typing positions and postures, so it was necessary to see if there are any changes to the positioning of a user's hands and fingers when transferred to the virtual environment. This was tested by checking if the virtual hands points lined up with its dimensions and the dimensions input into the virtual environment by typing upon a virtual plane object. The collision points on this plane were noted and then measured to see if they lined up with the points done within real life. A visualization of these points can be seen in Figure. 3. These positions lined up with the virtual hands dimensions and movements done by the user. Even though the hand of the user typing may not exactly be that of the virtual hand, it was found that the virtual hand is accurate to the movements done for the users real hand. The virtual hand is still limited to the movements and limitations of the users real hand even with a difference in size. This meaning that the measurements taken of the users typing posture positions are able to be reflected within the virtual world, and any large changes in hand measurements should not affect the users typing efficiency.

3.3 Development of Haptic Feedback Design for Two Commercial Haptic Gloves

When typing using the haptic gloves force feedback was included to function as an additional confirmation for the user that a key type action had finished. Each glove allowed a large number of modifications to the actual haptic effects, as well as allowing force feedback to be added at different stages of the typing interaction such as at touch, press, and typing completion. With all the different number of possible instances of feedback and the level of that feedback being available, another user pilot study was conducted to find out what was most preferred by users.

3.3.1 Key Haptic Feedback Users Preference Study

This user study will have the goal of finding what amount of haptic feedback users prefer as well as what number of haptic feedback stages users prefer to recreate a realistic clicking feel. It was decided that it would be better to recreate the feeling of a mouse click as opposed to a keyboard key. This is because it allows for the simplest recreation of feedback with their being two main stages of touch and press, as well as not needing to perform an even larger study on keyboard styles and switch types to find additional user preference and feedback recreation. It was also decided that because of the Nova gloves more limited haptic options that this style of click effect would be the best option to realistically recreate. This is also why the Nova glove was selected as the haptic glove to be used in the study as the Dexmo gloves can recreate any haptic effects done by the Nova gloves, but the reverse is not possible.

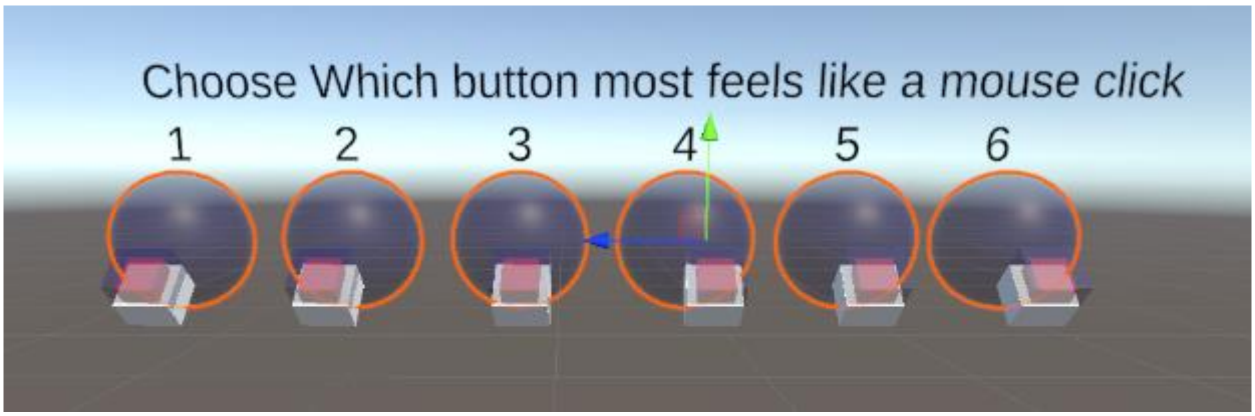

Figure 4. Buttons users could press within the study in addition to selection spheres.

3.3.2 Procedure

For the experiment users would wear a single Nova glove to interact with the haptic buttons. The user would have six haptic buttons in front of them. These buttons are made up of two different sections, a top section that would have variable haptic feedback effect for a touch/press haptic effect referred to as a breakthrough effect, where when pressed enough on the object it would disappear and allow the user to hit and touch a second unpassable haptic barrier object. There was the option additionally to make it so that the finger stoppage was only visual with no barrier haptic object plus the inclusion of the breakthrough. Each of the haptic conditions were randomized between the six buttons. Users would press each button then select which button most felt like a mouse click. This was done for a total of ten trials for each user which would result in ten total selections possible for each user. Each experiment had an average length of 2 minutes.

3.3.3 Participants

This user preference study involved five users who were chosen for their abilities to discern different haptic feedback effects and changes. These users were made up of males all within the age range of 20-29 years. This was an informal study so no IRB forms or applications were needed, but the users were informed of what may occur during the study and what it entailed and agreed to participate.

3.3.4 Results and Discussion

The results found that the most preferred haptic feedback condition was that of a single stage haptic effect with visual only key-top and a haptic feedback barrier. The second most preferred was the two-stage haptic model with the light breakthrough. With more users overwhelmingly choosing the one stage haptic effect this was the haptic design that would be included for the keys going forward.

Even with the touch effect on the keys being visual there was precedence behind this style of feedback allowing for improved typing experiences within VR [10, 11, 28]. The buttons used in the study would be changed to a different design for the actual keyboard as the keys used within this study provided a very small amount of visual feedback as well as having limited features.

Table 2 Haptic button feedback ranges and results

Users	Force Feedback	Force Feedback & .02 Breakthrough	Force Feedback & .04 Breakthrough	Visual	Visual & .02 Breakthrough	Visual & .04 Breakthrough
User 1	5	5	0	0	0	0
User 2	6	1	3	0	0	0
User 3	2	4	4	0	0	0
User 4	6	4	0	0	0	0
User 5	0	3	1	0	5	1
Results	19	17	8	0	5	1

3.4 Finalized Glove Key Design

For the finalized glove key design, the process of glove interactions which is displayed in Figure 5, the key would include a moving top object that provides the visual feedback of typing, and upon performing a key type haptic force feedback would be delivered and lock the object in place. This would function as both a visual indicator for a key type with the locking in addition to a change in color for the moving object, and as a protective measure against mistypes. The haptic delivery system differed between gloves with the moving object being the haptic object for the Dexmo gloves and an invisible haptic barrier being the haptic object for the Nova gloves. This is because the Dexmo gloves allow for togglable haptics while the Nova gloves do not allow for the same style of toggle. Within unity the haptic object for Dexmo gloves has a force value of 0.45/1.0 which approximately corresponds to the maximum output of the gloves of 0.5N but the gloves rarely deliver the full force to stop the finger. The Nova gloves haptic object has a force value of 100/100 resulting in the maximum force the Nova glove can administer per frame being 0.2N.

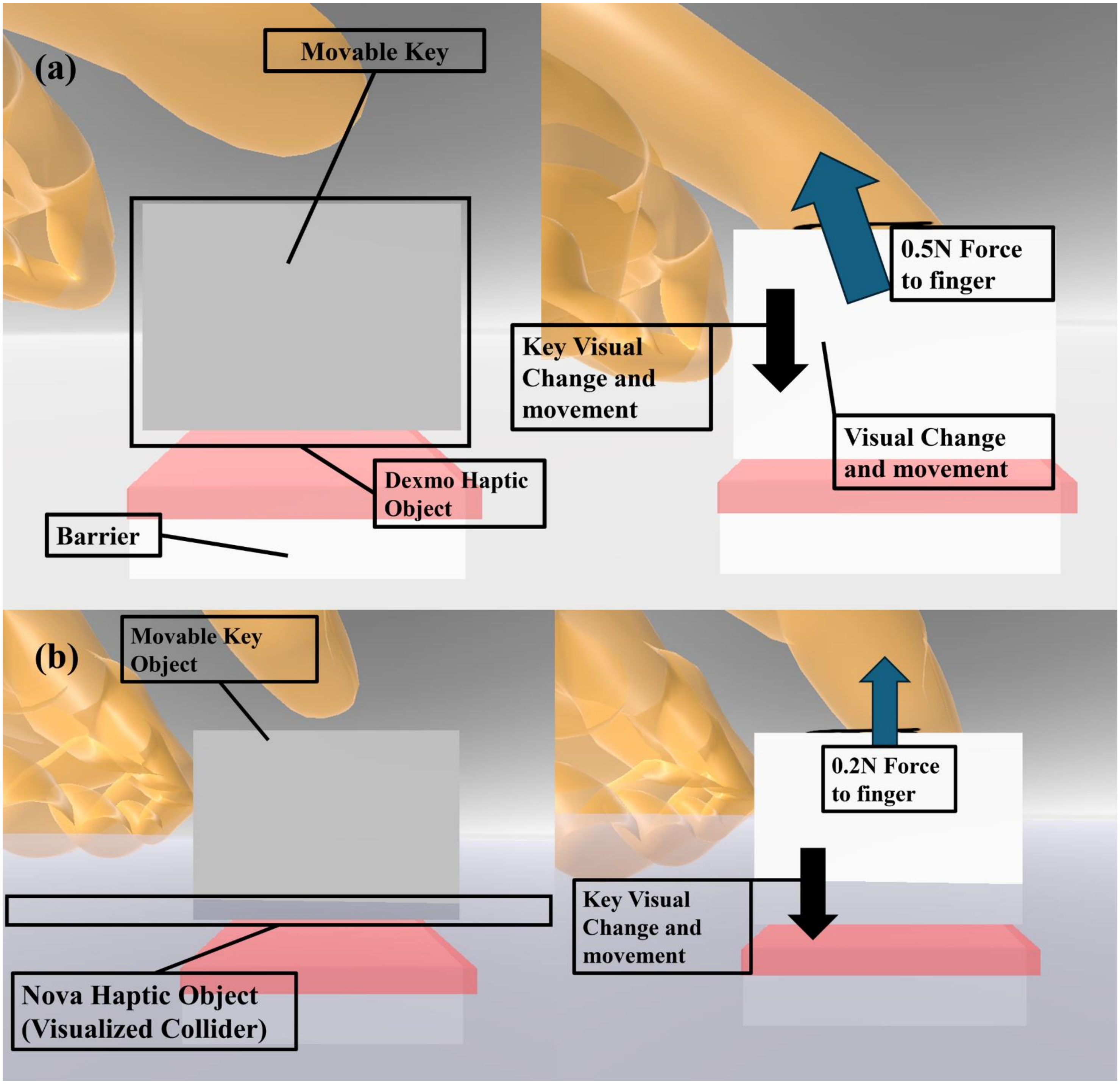

Figure 5. Visualized process of glove button touch and force feedback process. (a) Dexmo glove process. (b) Nova glove process

Figure 6. Users typing on virtual glove keyboards and images of different gloves. (a) Dexmo Glove. (b) Nova Glove.

3.5 VR Controller Based Typing Integration

VR controller typing is the current standard for VR typing with many HMDS using the controllers in a manner similar to a TV remote or pointer and is usually integrated into interface and menu navigation as well. The VR controller-based method was chosen as it is beneficial to have a method that was already available in VR and could act as a reference or common benchmark when comparing against other VR methods. This method was developed using the same MRTK Keyboard package [35] and making inclusions for "Raycasting" based interactions for key selection and typing. The back trigger button of the VR controllers was used as the activation and click button as that is the general standard of most VR controller-based methods. When typing, both controllers are allowed to be used in tandem to allow for even faster typing. There is also the same provided audio, and visual selection feedback as provided in other typing methods to give even greater feedback to the user when using this method.

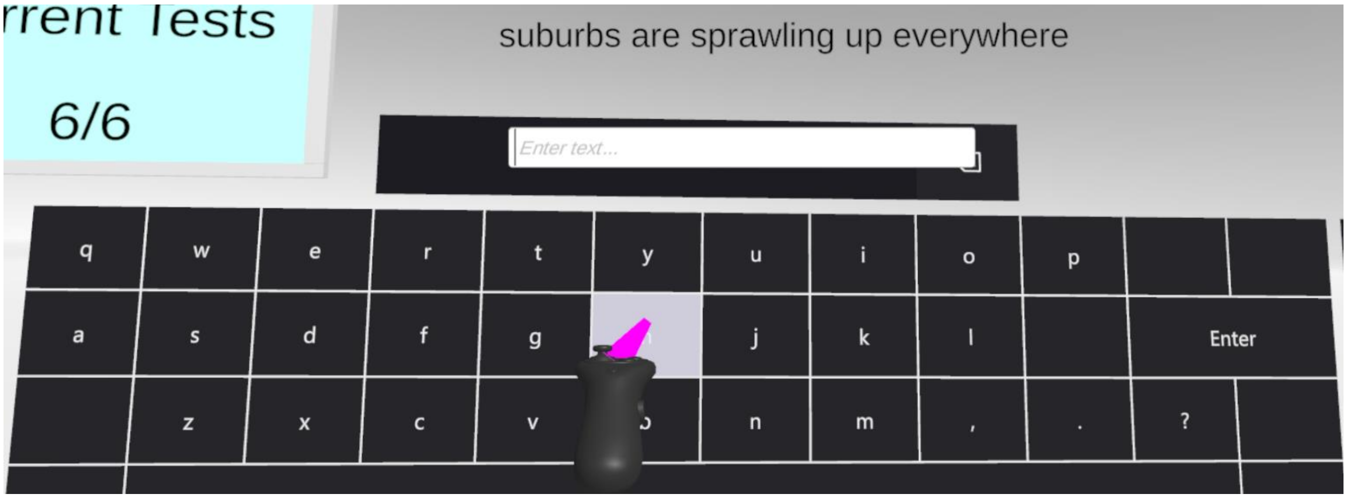

Figure 7. Users view in the VR Controller method.

3.6 Physical Keyboard Based Typing Integration

A final method of a physical keyboard was also included to give a final method of typing that was already established to get a better idea of a user's typing ability. One major thing to know about this method is that although it features a physical keyboard as its main method of typing and interaction the user is still wearing the VR HMD and entirely in VR when typing. There is a visual provided to them of what they are typing similar to the controller method as seen in Figure 6, but the users are unable to see the keyboard and their hands when typing. Although typing with the VR headset on is not how most physical keyboard typing is done, it allows for the inclusion of another comparative method, as well as giving and idea for the typing skills of users.

Figure 8 MTKR-Keyboard View without UI and Physical Keyboard Used in Study.

CHAPTER 4 Experiment

Table 3 Experiment conditions.

Typing Methods	Haptic Feedback for Key Press	
Dexmo (Layout: Flat, Split)	Yes (our design)	No
Nova (Layout: Flat, Split)	Yes (our design)	No
Meta VR Controller	Yes (built-in vibration)	N/A
Physical Keyboard	Yes (mechnical keys)	N/A

To measure typing performance of our developed haptic glove-based typing method with two glove-best-fit keyboard layouts (split and flat ergonomic keyboards), we designed and conducted a user study, following an IRB approved protocol (761). For a thorough data analysis of the effectiveness of haptic glove-based typing with and without haptic feedback, compared to other finger typing methods (VR controller and physical keyboard), different experiment conditions were designed and summarized in Table 3.

4.1 Participants

A total of 22 participants (18 males, 4 females, average age 23 ± 5.8 years old) took part in the experiment. All participants were skilled typists on physical keyboards but had no experience with haptic gloves. Some users had a large amount of experience with virtual reality but overall, the majority of users were inexperienced with Virtual Reality. All users volunteered and were compensated $30 for their participation.

4.2 Procedures

Participants were instructed to wear VR glasses (Meta Quest 2) and use one of the typing methods summarized in Table 3. For the haptic glove conditions, participants wore either Dexmo or Nova gloves as shown in Figure 6. Users were also allowed to have the glove keyboards position moved before typing to allow for the best typing position for each user. The adjustment of the keyboard was also allowed during runtime if requested by the user. In the no haptic feedback condition, the haptic feedback functionality was turned off, so participants received no haptic feedback from the gloves when pressing virtual keys, although visual and sound feedback were still provided. In contrast, the VR controller's built-in vibration was always provided for key pressing as the VR controller method with vibration feedback was included as a reference since it is a common data input method for VR devices, and we wanted to compare its performance with haptic glove typing. As mentioned in the methods section two controllers are used during the test and typing is possible with both controllers at the same time but is not required if users do not do so. The physical keyboard condition served as a baseline that haptic gloves typing aims to achieve. For this condition, participants typed using their bare hands, providing baseline performance data, even though a physical keyboard is impractical for a mid-air typing environment in VR. Before typing users were allowed to find the home row positioning for both of their hands, and the physical keyboard used had the normal notched keys tops for the F and J keys. The entire experiment was divided into two sessions, each lasting approximately 1.5 hours. In each session, participants tested a randomized glove and non-glove typing method by typing phrases randomly selected from a phrase dataset [36]. For each condition, 20 sentences were tested, resulting in a total of 200 sentences per participant. After completing the experiment, all participants filled out two subjective questionnaires, System Usability Survey (SUS) [37] measuring usability and NASA Task Load Index (NASA TLX) [38] measuring workloads.

During the experiment users were allowed to take small breaks if needed and were also provided with arm rests to try to mitigate any pain that would come from users having to hold their arms and hands in the air for a prolonged period. It was also made that the user could not accidentally submit a sentence that was incomplete or may result in inaccurate typing data. The only time it was allowed for a sentence being transcribed to be recorded as a submission was if 80% of the sentence was finished. This was done to maintain that each data measurement was consistent in each sentence being a fully complete and purposefully submitted sentence from the users.

CHAPTER 5

Results

This section will review the results of the typing experiment. It will go over the typing metrics and data collected as well as any subjective questions or forms user responded to after completing the experiment. Any data or measurements calculated or measured will be explained as to what they are and how they are used. All discussions will be within the next chapter.

5.1 Data measurements taken

We measured typing speed using Words Per Minute (WPM), efficiency using Key Strokes Per Character (KSPC), and accuracy using Corrected Error Rate (CER) and Uncorrected Error Rate (UER), following the literature [25, 26, 27, 39]. Higher values in WPM and CER indicate faster typing speed and more corrected errors, respectively. Conversely, lower values in UER represent higher accuracy with fewer uncorrected errors. CER reflects the rate of corrected errors, while UER indicates the rate of uncorrected errors. For optimal efficiency, KSPC should be close to 1.0, as it measures the key-stroke effort required to complete a sentence. A KSPC value of 1.0 means the number of keystrokes matches the number of characters transcribed without mistakes. Note for KSPC all keystrokes are used in the calculation of this value, and this does include any special keys such as backspace or arrow keys. A paired T-Test was also performed to see if there was any significant difference between methods. Typing data was also checked for outliers with any that were found being removed from any evaluation and averages [40].

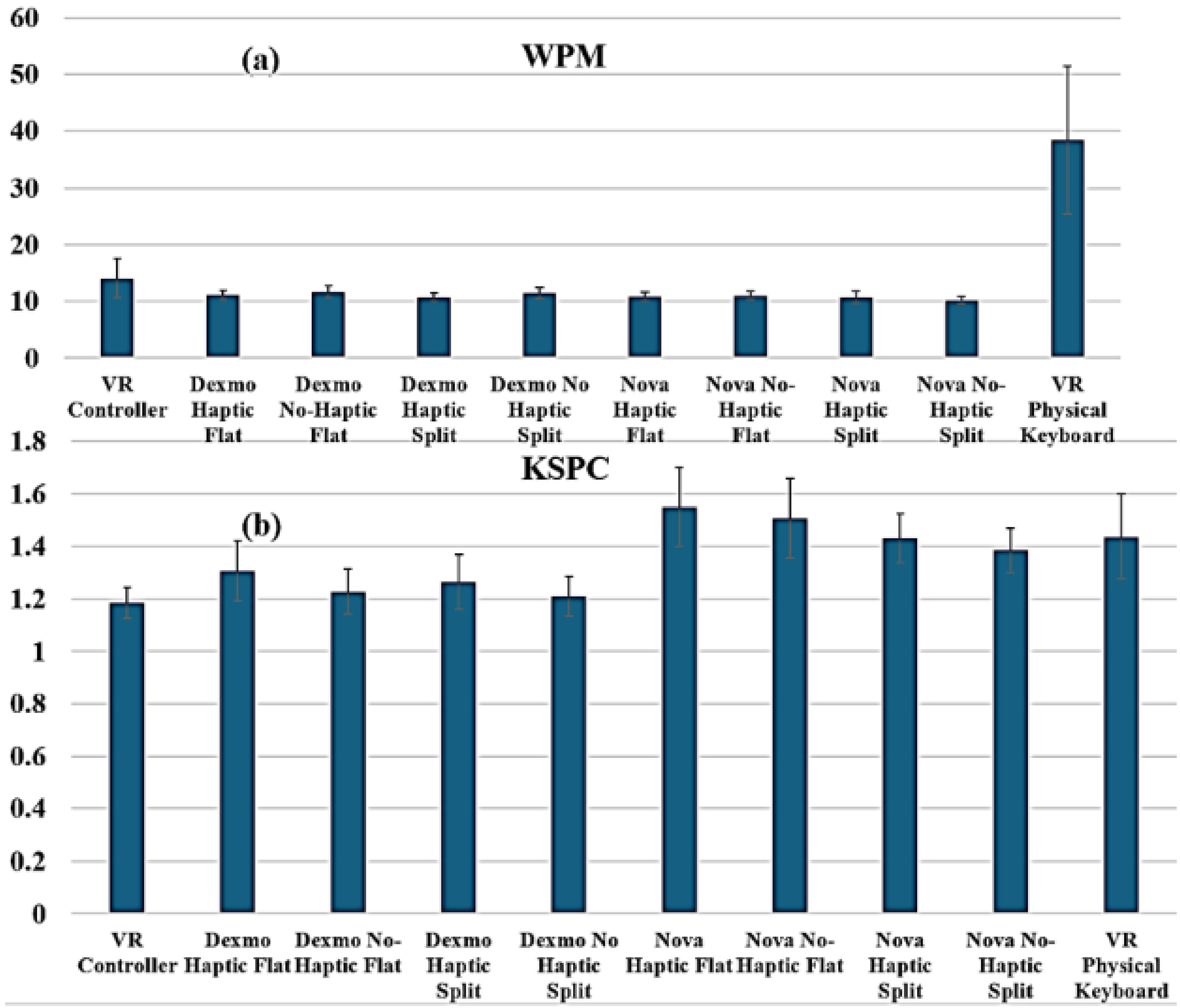

Figure 9. Average results of Words Per Minute and Key Strokes Per character for each method.

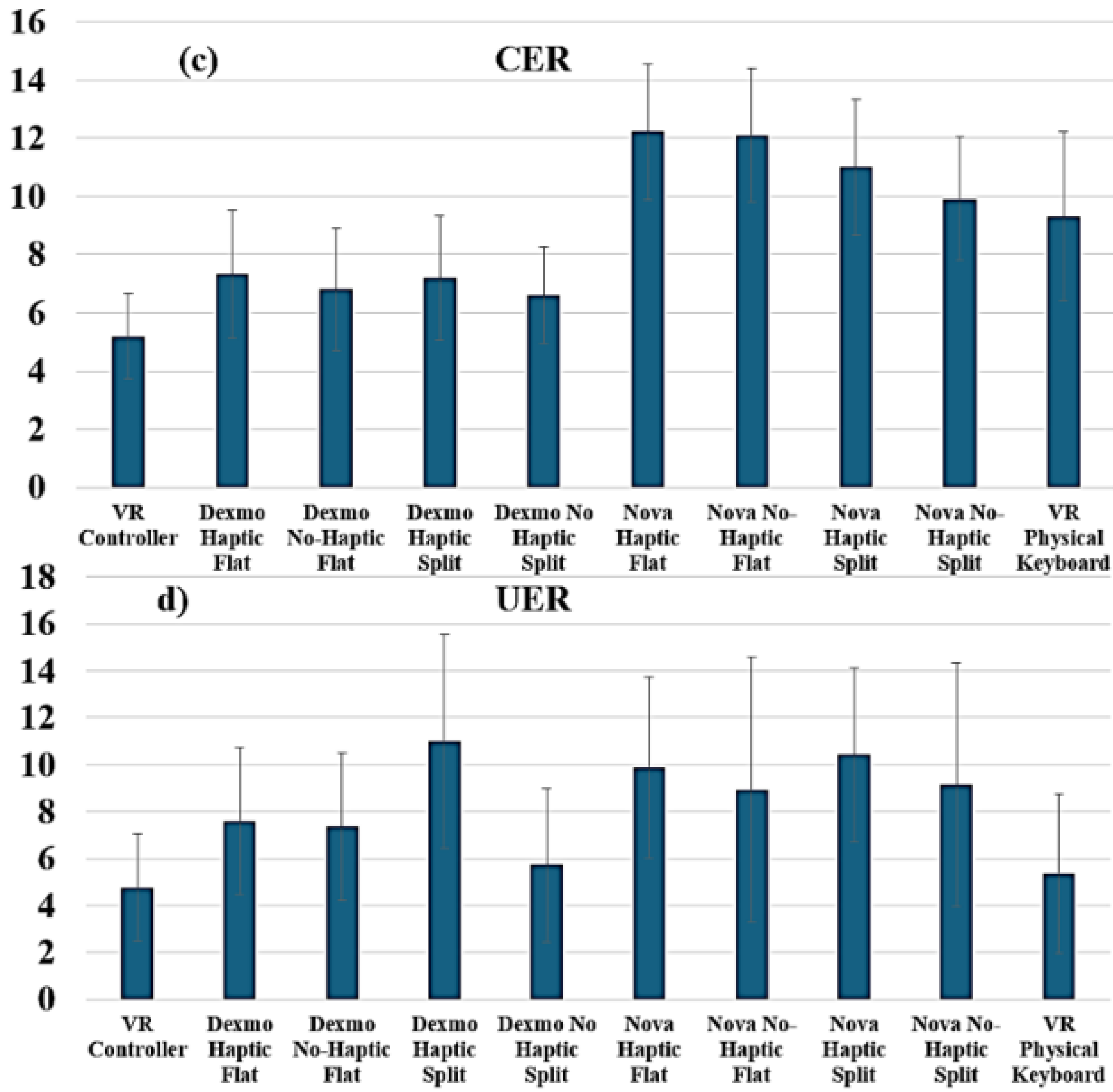

Figure 10. Average Results of Corrected Error Rate and Uncorrected Error Rate for each method.

5.2 Quantitative results: Typing Performance

As shown in Figure. 7, the fastest typing method was the VR physical keyboard, achieving a WPM of 37.98, a KSPC of 1.42 and a CER/UER of 9.3/5.37. The next fastest method was the VR controller-based method, with a WPM of 14.03, a KSPC of 1.18, and a CER/UER of 5.19/4.76.

Among the Dexmo glove methods using the flat layout, the fastest was the non-haptic version, with a WPM of 11.65, KSPC of 1.23 and a CER/UER of 1.23/6.81. Although slightly slower, the haptic version had a WPM of 11.47 (2% slower), a KSPC of 1.28 (4% less efficient), and a CER/UER of 7.32/7.6 (an 8% and 3% increase respectively). These results suggest that haptic feedback in Dexmo gloves flat layout is more effective at increasing error corrections (as indicated by a higher CER value) compared to non-haptic feedback. This improvement is likely due to the key pressing confirmation provided by the haptic feedback. However, the differences between the haptic and no haptic conditions for Dexmo gloves were not found to be statistically significant with respective p-values of .35, .09, and .27/.43. The split layout with the Dexmo, the non-haptic method was the fastest, with a WPM of 10.63, a KSPC of 1.21, and a CER/UER of 6.6/5.7. The haptic version had a WPM of 9.89, which is 7% slower than the non-haptic feedback, a KSPC of 1.269 (5% less efficient), and a CER/UER of 7.19/11.01 (9%/92% more prone to errors, respectively). It was found that KSPC and UER were significantly different between the methods with p-value of .04 and .003. WPM and CER had p-values of .06, and .201. This indicates that haptic feedback in the split layout was less efficient and more error-prone, while providing more error corrections compared to no haptic feedback. This result is likely due to the split layouts, where typists may feel uncomfortable locating individual keys occluded by haptic gloves on the split layout. This was also the only comparison where any points of data were found to be significantly different.

For the Nova glove flat layout, the non-haptic method was the fastest, with a WPM of 11.03, a KSPC of 1.51, and a CER/UER of 12.11/8.94. The haptic version had a WPM of 10.94 (1% slower), a KSPC of 1.54 (2% less efficient), and a CER/UER of 12.2/8.9 (an increase of 1%/11% respectively). Just like the Dexmo gloves the haptic versions appear to be overall slower on average than the haptic version. For the split layout, the haptic method was the fastest, with a WPM of 10.76, a KSPC of 1.41, and a CER/UER of 11/10.4. The non-haptic was 4% slower, with a WPM of 10.34, a KSPC of 1.37 (3% more efficient), and a CER/UER of 9.91/9.13. These results suggest that haptic feedback provides faster typing speed and more error corrections, although it is less efficient. The Nova gloves overall had a lower performance compared to the Dexmo gloves. This is in speed, accuracy, and error correction. It did generally have an overall lower average UER than the Dexmo methods but this may be attributed to the slower typing speeds and when looking at the much larger KSPC and CER it can be assumed that it's not that it was more accurate but there was much more time taken to correct errors leading us to assume there was a larger error rate overall.

Comparing the layouts regardless of haptic glove types and haptic feedback, the flat layout provided higher typing speed, greater efficiency, and more accurate typing when typists wore haptic gloves in VR. The haptic and non-haptic methods for the Dexmo gloves had a 7% and 2% decrease in WPM going from the flat method for the haptic and non-haptic methods respectively. There was an increase in KSPC of 1% and 2% for the haptic and non-haptic methods, meaning that the split was slightly more efficient, along with there being a CER/UER increase for the flat layout of 2%/31% and 3%/22%. The Nova gloves had a 2% and 6% decrease in WPM scores for the haptic and non-haptic methods going from flat to split, and also having the same trend as the Dexmo gloves in KSPC with the scores for the flat being 8% and 9% higher for the haptic and non-haptic once again. The CER/UER for the flat was slightly different with the haptic flat CER being 10% larger than the split but also had a 5% smaller UER than the split. The non-haptic versions followed this same trend with the flat having an 18% larger CER, while also having a 2% decrease going from the flat to the split in UER.

5.3 Qualitative Results: User preference

Each typist completed a SUS form [37] to assess system usability, and a NASA TLX [38] form to measure workload and frustration after each session (Figure. 8). The non-glove-based methods had the controller with a SUS of 74.65 and the VR Physical keyboard having a score of 82.72. These scores are within the range to have acceptable usability. For Dexmo- based methods, as shown in Figure. 8, the scores were 45.9, 46.93, 43.18, and 42.84. For Nova gloves, the scores in the same order were 45.79, 44.54, 37.38 and 40.11. These SUS scores for both glove devices are all considered unacceptable by standard SUS usability scores.

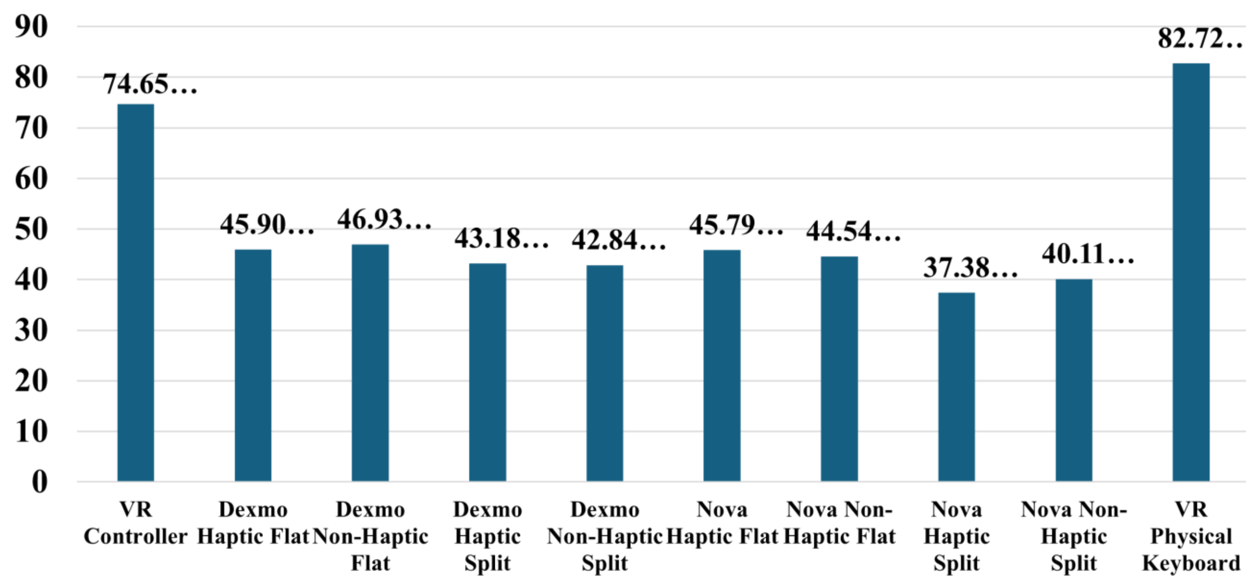

Figure 11. Average System Usability Survey scores per method

For the NASA TLX responses measuring workloads, the non-glove methods had scores of 49.11 for the VR controller and 46.22 for the physical keyboard, both considered low workload. For the glove-based methods, starting with Dexmo gloves, the scores as shown in Fig.8 were 76.38, 77.66, 77.44, 80.16, 79.44, and 80.16. For the Nova Gloves, the scores in the same order were 79.5, 81.83, 78.1 and 82.4. All of these scores indicate a higher workload, outside the acceptable range of 25 to 50. Additionally, all flat methods had better scores than all split layouts in both SUS and NASA TLX assessments.

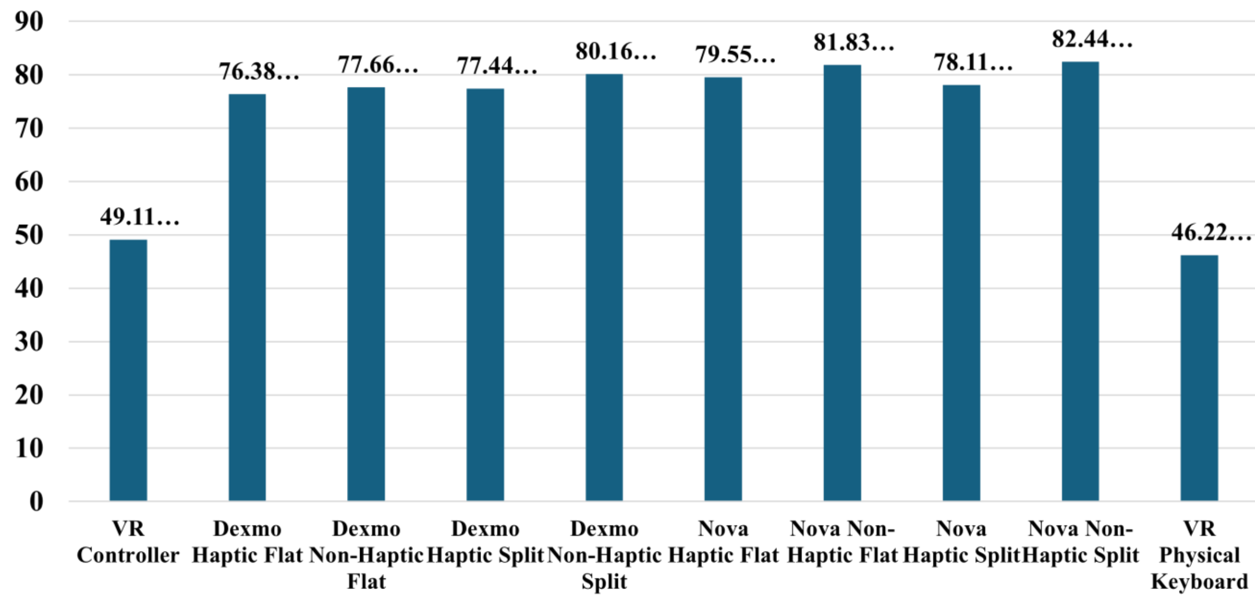

Figure 12. Average results of NASA TLX per method.

Users were asked about if the inclusion of haptic feedback affected their typing experience. Of the 22 users, 11 felt that the haptic feedback improved their experience, with one noting that haptics “Helped tell if a key was typed by just the touch” and made them “[feel] less frustrated and make less errors”. For the users who disliked the haptics, when asked why they felt the removal of them affected their typing experience one user responded saying: “The haptics often bounced my fingers into other keys I didn’t mean to press.” This was also a common complaint amongst the users who had negative feelings towards the inclusion of the haptics with any other comment being that they did not have a specific opinion. Some users mentioned that while the Dexmo gloves had more responsive haptics, they were uncomfortable due to their heavy weight.

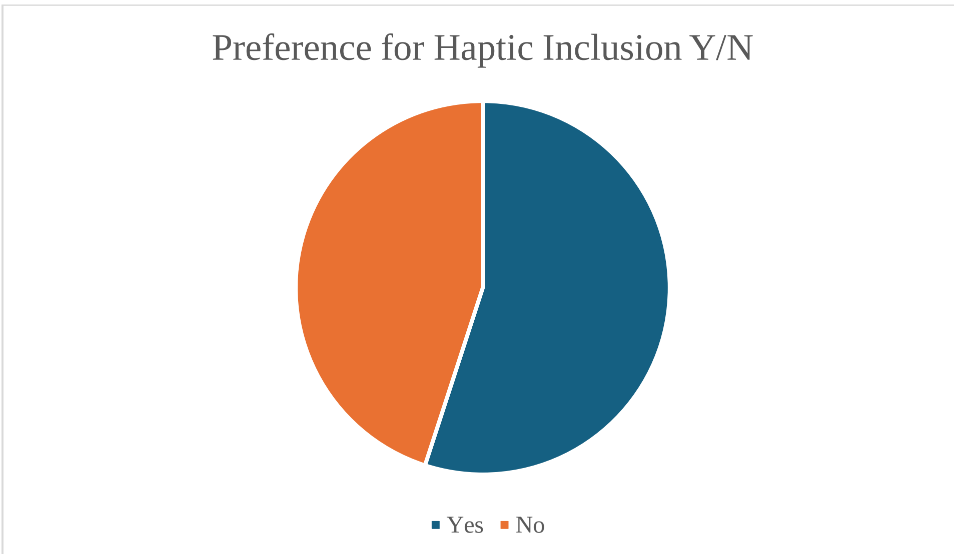

Figure 13. Users preference for haptic feedback from questions

This was another common complaint amongst most gloves but was mainly aimed towards the Dexmo gloves. This is not because of any additional conditions but because the Dexmo gloves feature more tracking finger tracking, and haptic capabilities resulting in many more components on the glove making it heavier than the Nova gloves. For favorite methods as seen in Figure 13, 11 users preferred the VR physical keyboard, while 9 users chose the VR controller. The remaining users favored the Dexmo and Nova flats.

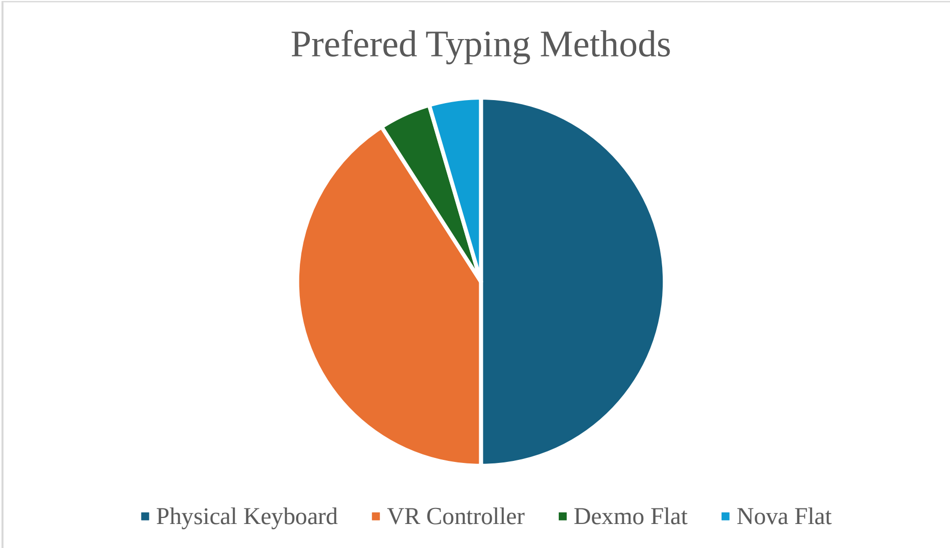

Figure 14. Users preferred typing methods.

CHAPTER 6

Discussion

6.1 Qualitative Results: Flat layout VS Split Layout

Quantitative typing performance data showed that between the flat layout and the split layout, the WPM speeds are able to show the different speeds with the flat being faster but the other metrics of KSPC, CER/UER, need to be look at together to get a full understanding. Although the split layout altogether had better KSPC and CER/UER scores, an insight that can be gotten from this is that the that the large UER scores in comparison to a slightly larger KSPC and UER actually show that the split methods are much less efficient than the flat. This is mainly because the CER rates show that users were able to make many quick corrections, while not largely impacting their WPM. The split method, however, has very small KSPC values which would normally be a benefit to a method, but when also looking at the low CER values and the much larger UER values show that not only does the split layout led to less corrected errors but many more errors to get through in total. WPM also is affected even when knowing that the users are not taking time to correct errors when using the methods showing that the split method is just less efficient overall. The split method sadly was unable to improve or assist with the finger tracking or provide better ergonomics to the glove, as the difference between the split layout and a regular keyboard may have been too much for users.

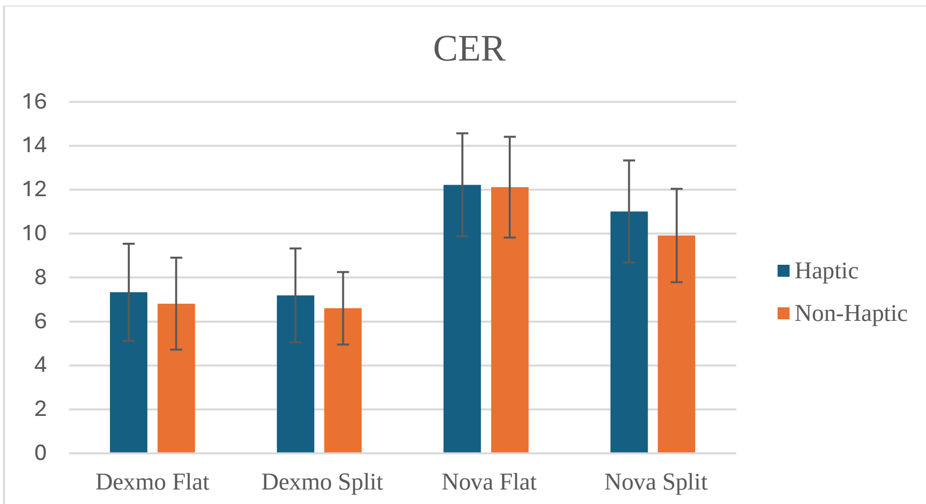

Figure 15. Average CER scores between Haptic and Non-Haptic Glove Methods

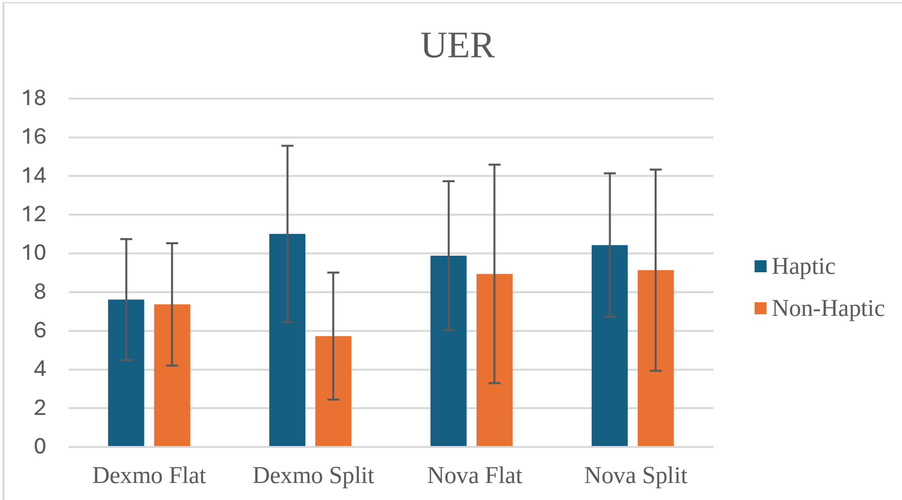

Figure 16. Average UER of Haptic and Non-Haptic Glove methods

6.2 Qualitative Results: Haptic VS Non-Haptic

The haptic differences give insight into how haptics may need to not be removed entirely but have the goals of the haptics be changed to a different format. Almost all the non-haptic methods had faster WPM values compared to their haptic counterparts, no measurements of haptic to non-haptics were found to be significantly different. This also cannot be attributed in the same way to error correction or revisions because not only did the haptic method have much slower WPM and higher KSPC but also had larger CER/UER scores in comparison to the haptics. One thing that can be noted about the CER/UER, in association with what was said by users from their responses, to questions about haptics, is how the haptics assisted them in identifying errors. If we want to see what a truly error prone method would be the Dexmo haptic split can be a good example of this, as it was significantly different, but as shown if figures 14 and 15 although the haptic methods may have caused mistypes in the Dexmo gloves causing more errors as can be seen in the UER, the CER of the Nova gloves haptic typing methods, which had no report of haptics causing errors, in comparison to their non-haptic versions shows that the feeling of haptics can provide a much clearer identification of when an error has occurred. This can be seen in their CER results as they were on average lower than the non-haptic version, and although the UER on average was higher the general range of UER values is much smaller than that of the non-haptic version. Since the user feels the key pressed in their fingers it is much easier to identify errors and correct them. Although even if the CER/UER scores were not found to be significantly different, we can still see that the haptics do allow for an improved typing experience, and the user preference discussed in the next section will also show this user preference.

6.3 Qualitative Results

The main issue with haptic gloves was their weight, which many users cited as the primary reason for disliking Dexmo gloves. One user noted, “If Dexmo released a lighter alternative, my opinion may change.” This weight stems from extra tracking and haptic components, compounded by the need for more hand movement due to the lack of finger articulation. The weight also may have exacerbated the issues users had with haptics, as the large strain the users had on their arms and hands may have resulted in poor hand positioning and typing motions on the virtual keyboard, resulting in the glove needing large movements to halt the finger and applying the necessary haptic force feedback effects. Another noted issue of gloves is the placement of the controllers for tracking. Since the haptic gloves do not provide hand tracking, controllers are needed to be used to allow for hand movements within the scene. As seen in figure 6 there are different mounting points on both gloves, but users did not respond well to the controller point for the Dexmo gloves as they felt it would weigh their hands down and cause mistypes when typing. This also is affected by the weight issue, as needing to change the most natural position to fight against the gloves weight to one side or the other as we have seen leads to lower typing performance.

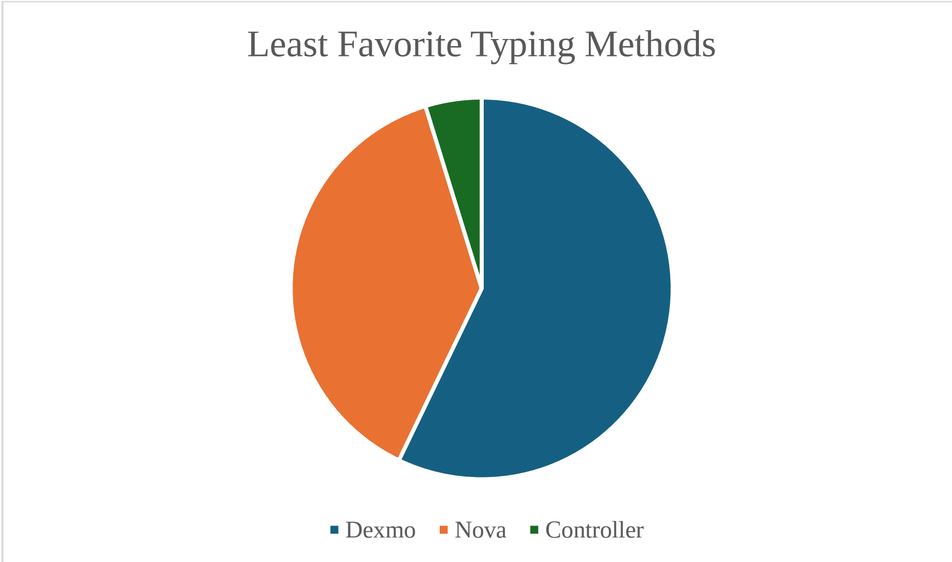

Figure 16. Least favorite typing method with glove methods grouped by glove.

While the response from users about haptic feedback was positive as seen in figure 13 with 11/22 saying it positively impacted their typing experience and 9/22 saying it negatively affected their experience and 3 responded with no feeling, it showed that a number of users had something they disliked about the haptic feedback. When looking at the exact responses an overwhelming majority of the users that responded negatively to the haptic feedback said that the haptics specifically on the Dexmo gloves would result in a mistype. This meant that the force feedback provided may be too strong, and could be adjusted to a lighter style of haptic feedback. One user who responded positively to the haptic feedback said the haptics "made it feel less like my hand floating in space, and more like they were resting on a keyboard." The haptic effects made their contact feel much more tactile which was the intended feel for the glove-based keyboard. The mistype issue mentioned may also come from the weight of the gloves, as after a period of time users may not have been able to keep good typing postures which had the haptic gloves administer much more force than realistically needed resulting in the bounce effect and the mistypes. Future haptics for air keyboards may simply add resistance to users' fingers rather than the finger stopping in the current experiment. This issue of weight can also be seen much more prominently in the users' choices of least favorite typing method, as if we group by glove, as seen in Figure 16, the Dexmo is chosen overwhelmingly as their least favorite. This is surprising as it scored better in both the SUS and NASA TLX but it appears that users found the weight added to the gloves by the additional haptic components to be much more straining than the Novas, and affected their typing experience making it a lot of users least favorite glove and general method.

Even with the large issue of weight mentioned if adjustments are made to either the gloves to remove the method, or changes to the system as mentioned to adapt to the weight, glove based typing had the potential to have much larger scores, as even the limited tracking in the Novas resulted in WPM scores similar to that of methods featuring the base controllers [20,30].

CHAPTER 7

Conclusion

In conclusion we developed various VR typing methods using different VR hand interaction devices and assessed their impact on typing performance and experience. We found that standard VR typing methods, using controllers and physical keyboards, remain the fastest, outperforming haptic glove-based methods in nearly every typing and usability metric. This highlights current challenges with haptic gloves, including their weight, the strain they cause during typing, and their limited range of movement. While controllers are limited in expression but enable simple and quick inputs, and physical keyboards allow normal typing without the restrictions of haptic gloves, there is still room for improvement. Even with these drawbacks to the haptic glove-based methods of weight and tracking, the potential to allow for typing metrics that can rival that of the faster methods is there. The current glove keyboard created within the virtual environment features not only haptic feedback that is able to be adjusted, to better correct the issues shown from users for the amount of force, but also allows for extreme customization and movement. This movement of the keyboard as well as the creation of these items even with their slower speeds is still important as this is the first rendition of any glove based virtual keyboard, be that with the current gloves used (Dexmo, and Nova), or any haptic gloves within VR at all. These developments show the necessary inclusions needed for a virtual keyboard that can be moved anywhere to the user, as well as universal implementation for all gloves. We will also be able to mark any future improvements as this study may act as a benchmark to any future haptic glove-based typing metrics, or button-focused works, as we are the first research put forth to compare the current standard VR typing methodologies to the glove-based keyboard we created.

Although the haptic feedback may have resulted in mistypes, there is user preference for its inclusions. There is also evidence to show that if the mistype causing force feedback was switched for a different less intrusive haptic method, then the potential for haptics to offer a much more reliable and accurate typing method is there as was shown within the discussion and in the Figure 13 and 14 looking directly into the CER and UER. Although the averages may show a large difference, the general spread of users experience shows that some users had extremes much different than to that of the UER extremes of the same methods within both haptic and non-haptic, showing the potential if these changes are made. Future research will focus on whether skilled 10-finger typists can enhance the typing performance of glove-based methods and explore new haptic feedback technologies or lightweight tracking methods to attempt to better address the weight issues in haptic glove-based typing.

LIST OF PUBLICATIONS

[1] J. Kirby K. Kim, “Virtual Ten-Finger Typing: Evaluating Haptic Gloves for VR Text Input”, ISMAR 2025 (Manuscript under Review)

[2] J. Kirby K. Kim, “Design and Evaluation of Haptic Glove-Based Text Inputs in Virtual Reality”, 25th International Conference on Digital Signal Processing (Accepted)

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APENDIX I

1. System Usability Scale (SUS)

a. I think I would like to use this system frequently.
b. I found the system unnecessarily complex.
c. I thought the system was easy to use.
d. I think that I would need the support of a technical person to be able to use this system.
e. I found the various functions in this system were well integrated.
f. I thought there was too much inconsistency in this system.
g. I imagine that most people would learn to use this system very quickly.
h. I found the system very cumbersome to use.
i. I felt very confident using the system.
j. I needed to learn a lot of things before I could get going with this system.

2. How did you like the system?

a. What was your favorite Typing method
b. Why?
c. What was your least favorite typing method?
d. Why?

3.) **NASA Task Load Index**. Please rate your level of mental demand, physical demand, temporal demand, performance, effort, and frustration from number 0 to 21 after experiencing the task.

Conditions	*Mental Demand	*Physical Demand	*Temporal Demand	*Performance	*Effort	*Frustration

APENDIX II

1. System Usability Scale (SUS)

   a. I think I would like to use this system frequently.

   b. I found the system unnecessarily complex.

   c. I thought the system was easy to use.

   d. I think that I would need the support of a technical person to be able to use this system.

   e. I found the various functions in this system were well integrated.

   f. I thought there was too much inconsistency in this system.

   g. I imagine that most people would learn to use this system very quickly.

   h. I found the system very cumbersome to use.

   i. I felt very confident using the system.

   j. I needed to learn a lot of things before I could get going with this system.

2.)

   a.) Did you find the haptics useful?

   b.) Did you feel the lack of haptic feedback affected your typing experience?

   If so, why?

3.)

   a.) What glove-based method was your favorite?

   b.) Why?

4.) **NASA Task Load Index**. Please rate your level of mental demand, physical demand, temporal demand, performance, effort, and frustration from number 0 to 21 after experiencing the task.

Conditions	*Mental Demand	*Physical Demand	*Temporal Demand	*Performance	*Effort	*Frustration

APPENDIX III

User Haptic experience	VR and Haptic Experience	Gender	Age
User 1	Minor Experience	M	25
User 2	No Experience	M	23
User 3	Minor Experience	M	22
User 4	Experience	M	20
User 5	No Experience	M	21
User 6	No Experience	M	21
User 7	Minor Experience	M	23
User 8	Minor Experience	F	25
User 9	Experience	M	24
User 10	Experience	M	20
User 11	Experience	M	19
User 12	No Experience	F	20
User 13	Experience	M	26
User 14	Experience	M	23
User 15	Experience	F	24
User 16	Minor Experience	M	23
User 17	No Experience	M	23
User 18	Minor Experience	M	21
User 19	Minor Experience	M	23
User 20	Minor Experience	F	48
User 21	Experience	M	27
User 22	Minor Experience	M	20

WPM	VR Controller	Dexmo Haptic Flat	Dexmo No-Haptic Flat	Dexmo Haptic Split	Dexmo No Split	Nova Haptic Flat	Nova No-Haptic Flat	Nova Haptic Split	Nova No-Haptic Split	VR Physical Keyboard
User 1	12.29827	12.78944	11.87226	11.05604815	9.767752	11.97764	13.92183	9.927942	11.61786	81.43571
User 2	14.63504	10.50746	10.70467	10.5594708	10.93356	7.781566	9.555123	12.7091	9.321301	34.69432
User 3	17.5967	10.24574	13.2384	11.2556463	11.67169	10.07551	10.54237	9.809296	10.35632	11.0456
User 4	12.89521	11.79933	11.19227	8.9731315	12.38465	10.3565	10.21836	9.402253	10.10938	57.59074
User 5	12.71272	11.67763	13.79364	13.72238874	10.97868	12.49222	14.4418	8.504905	10.63107	103.1376
User 6	12.07418	11.98075	10.12833	9.503930789	8.990972	9.285231	9.368844	11.03671	9.088059	32.35269
User 7	14.15414	13.2338	11.70617	10.96511675	12.22643	10.45915	10.11415	8.784214	9.22237	26.87599
User 8	10.42153	8.926775	10.63683	12.07716438	9.0223	10.90297	10.58869	11.37745	8.41579	24.31753
User 9	9.590696	11.94141	13.18898	12.2714058	9.535554	11.93635	11.63976	11.20151	14.11537	13.46338
User 10	11.85246	14.56744	9.795393	12.08863415	15.9407	14.2227	10.83536	7.881586	8.132249	18.33123
User 11	42.83524	10.55386	9.784436	11.61851405	10.15571	9.587468	10.2361	15.16828	10.50073	52.14048
User 12	13.0543	10.0462	8.108966	9.21730205	8.108966	11.11776	11.54785	8.998196	9.156353	19.86244
User 13	11.70258	12.56912	13.63936	8.890551579	10.3549	9.835951	12.18706	9.960881	10.37517	12.28227
User 14	12.33573	10.73075	10.47065	8.356898789	13.80913	11.4838	9.694254	9.822709	9.880295	61.24381
User 15	13.90387	11.37045	11.13577	9.631731526	10.77346	10.01029	11.03493	9.467953	8.787007	49.84238
User 16	13.31656	12.96968	10.15203	11.8420525	10.60183	10.29242	8.850414	9.651937	10.65858	40.16198
User 17	10.61537	10.1484	10.29619	9.01043525	12.90633	7.829799	11.10286	10.35874	9.565763	15.51674
User 18	13.84772	7.27893	9.580159	10.37513068	12.74521	10.02074	10.6368	14.96072	9.948517	15.14828
User 19	12.63194	10.20576	16.94718	10.3341375	13.68804	12.91944	13.03469	12.20975	11.32246	71.40099
User 20	11.34538	11.2431	12.18943	12.2024742	12.42564	12.22284	9.359389	12.09625	11.84172	24.02027
User 21	13.85541	16.71864	16.20194	10.81625259	12.84597	12.69051	14.07917	13.01788	13.3689	51.1763
User 22	11.17257	10.85696	11.68518	9.159460579	11.40839	13.35655	9.736005	10.46808	11.25286	19.58662

KSPC	VR Controller	Dexmo Haptic Flat	Dexmo No-Haptic Flat	Dexmo Haptic Split	Dexmo No Split	Nova Haptic Flat	Nova No-Haptic Flat	Nova Haptic Split	Nova No-Haptic Split	VR Physical Keyboard
User 1	1.121033	1.169541	1.054679	1.0584402	1.13474	1.325309	1.118944	1.20221	1.098459	1.043014
User 2	1.114072	1.67808	1.494084	1.47479105	1.411505	1.989812	1.773994	1.779773	1.45999	1.466847
User 3	1.143283	1.251108	1.110491	1.2140408	1.099879	1.722721	1.357541	1.394527	1.246901	1.589284
User 4	1.157332	1.8619	1.446404	1.7911478	1.317905	1.908533	1.534128	1.496755	1.409725	1.569483
User 5	1.080321	1.047823	1.040447	1.08603845	1.011191	1.914406	1.916077	1.495299	1.696937	1.078115
User 6	1.250343	1.123058	1.27329	1.2295013	1.086189	1.130188	2.077352	1.203735	1.403019	1.25486
User 7	1.117213	1.182249	1.395488	1.3516347	1.386524	1.397884	2.126341	1.282702	1.31848	1.550578
User 8	1.102053	1.24884	1.122599	1.22950875	1.14408	1.477413	1.469833	1.597121	1.214602	1.498578
User 9	1.102513	1.059787	1.140108	1.0483	1.146965	1.811577	1.3416	1.370219	1.280766	1.224644
User 10	1.083123	1.060257	1.031241	1.0438581	1.089253	1.251003	1.436108	1.210103	1.253812	1.800566
User 11	1.07156	1.4705	1.401165	1.4810985	1.261854	1.571991	1.632278	1.639156	1.690008	1.07156
User 12	1.361832	1.336182	1.593304	1.22151105	1.593304	1.920152	1.49378	1.402178	1.59495	1.590725
User 13	1.188667	1.062161	1.096081	1.10616185	1.080765	1.21956	1.153779	1.152759	1.243741	1.98944
User 14	1.206293	1.564875	1.155243	1.57274005	1.41671	1.22919	1.185189	1.327791	1.22522	1.053245
User 15	1.257175	1.315211	1.261884	1.334653895	1.198281	1.374687	1.688172	1.240955	1.34814	1.189593
User 16	1.544921	1.14479	1.132574	1.118608	1.147634	1.314357	1.257563	1.318947	1.279829	1.315781
User 17	1.197751	1.27694	1.387732	1.29450055	1.194951	1.891114	1.34096	1.732714	1.279537	2.164437
User 18	1.248651	1.134093	1.203046	1.0757006	1.126006	1.343337	1.388257	1.384259	1.548269	1.367172
User 19	1.20444	1.60627	1.154586	1.2741913	1.204633	1.452525	1.299162	1.395012	1.439753	1.166055
User 20	1.129509	1.245033	1.155754	1.2718711	1.179836	1.856043	1.757714	2.085788	1.628551	1.697137
User 21	1.177117	1.122408	1.141996	1.255009213	1.153664	1.43775	1.314911	1.240367	1.195693	1.113805
User 22	1.255424	1.311411	1.279197	1.3973786	1.240613	1.401907	1.598761	1.210303	1.333573	1.48076

CER	VR Controller	Dexmo Haptic Flat	Dexmo No-Haptic Flat	Dexmo Haptic Split	Dexmo No Split	Nova Haptic Flat	Nova No-Haptic Flat	Nova Haptic Split	Nova No-Haptic Split	VR Physical Keyboard
User 1	4.32242	5.46383	1.669208	2.1243182	6.992908	7.278184	4.039235	7.457723	4.087363	1.757543
User 2	3.107986	15.11854	15.69006	13.46695415	12.47478	21.57501	18.44969	16.39012	13.41772	10.90966
User 3	4.092035	7.337483	4.213762	6.07631415	4.05036	19.44165	12.0998	12.73312	8.298204	17.19796
User 4	4.372771	11.41837	10.65943	11.4946773	6.596514	14.43926	15.17888	13.82146	11.16077	11.29586
User 5	2.965018	1.905193	1.617579	2.5396835	0.338889	8.918733	19.94758	8.664121	10.44055	1.84401
User 6	4.15239	4.965174	9.687842	8.22063305	3.878856	4.96837	6.898741	6.884639	7.6155	6.685995
User 7	3.869185	6.264207	11.9794	10.72694115	11.28617	11.86327	12.48931	8.682824	8.692427	12.01842
User 8	2.754114	6.610113	5.12516	8.73776945	5.65872	14.32284	13.97936	12.83821	7.48224	10.96866
User 9	3.674227	0.97519	3.566592	1.730438	3.47009	10.42152	6.186665	8.879549	3.684002	6.390926
User 10	3.256205	2.082183	1.449536	1.4754105	3.709374	8.979336	14.39408	5.874628	8.456339	16.77174
User 11	2.33532	14.14761	10.69797	14.3518028	8.812128	14.59581	17.03171	17.45067	18.51082	2.33532
User 12	9.919424	9.864057	13.52189	5.2671559	13.52189	19.00233	14.45248	11.63598	16.93307	9.401123
User 13	6.885825	0.973972	3.147495	2.5230412	3.281521	6.268555	5.857717	5.936296	10.36173	22.31372
User 14	6.44689	12.40559	3.853472	15.9226748	11.65871	6.680976	5.892844	10.61771	8.35252	1.79779
User 15	8.948764	10.62321	7.207866	7.960806684	6.87621	13.33192	19.59159	9.157838	11.15046	5.942406
User 16	13.86479	5.195171	4.466003	4.83900855	5.549352	11.44618	8.673171	10.06077	9.181942	9.191099
User 17	5.594675	8.019511	12.50107	10.6931808	7.672726	18.11436	11.27079	18.80002	1.279537	19.15513
User 18	6.306385	4.659838	8.699503	2.8045577	4.81169	9.182574	10.73379	12.44334	15.73829	10.19341
User 19	5.525337	15.98497	5.521008	8.82278975	7.807813	13.0287	10.49323	11.70494	14.66018	4.361596

User 20	3.314989	6.518954	4.796007	5.37029775	5.240508	15.80308	14.87773	22.15685	12.61529	11.6565
User 21	1.177117	5.544126	5.141241	6.934623158	6.291107	12.7432	10.15425	6.889666	7.179284	3.108275
User 22	7.486923	5.14595	4.676211	6.11817505	5.250596	6.543712	13.82363	3.118821	8.841295	9.680918

UER	VR Controller	Dexmo Haptic Flat	Dexmo No-Haptic Flat	Dexmo Haptic Split	Dexmo No Split	Nova Haptic Flat	Nova No-Haptic Flat	Nova Haptic Split	Nova No-Haptic Split	VR Physical Keyboard
User 1	4.41875	3.993213	6.252982	7.50924405	19.61934	11.31687	6.762473	6.460606	0.178571	0.669118
User 2	8.508929	20.53741	6.243445	13.33036345	5.340272	13.11925	6.047619	17.55963	17.85788	2.5315
User 3	8.813512	5.531035	12.06143	2.031920211	0.862069	5.726458	5.396963	13.30426	11.46201	2.927577
User 4	1.15323	18.05447	10.10317	24.5563323	19.19709	17.46542	4.259768	5.803419	19.72397	4.292878
User 5	3.170732	0.192308	17.30722	27.6280815	0.178571	17.67133	8.698546	25.02229	25.05929	10.27092
User 6	11.33455	4.480296	4.0932	15.60064305	9.931052	5.949295	23.54313	7.103528	5.669599	1.601307
User 7	13.19836	8.207136	10.45974	7.9290779	9.391573	10.97669	13.19749	5.800548	23.21249	11.01439
User 8	2.678572	14.82574	5.034202	3.6572623	1.013652	5.213377	0.151515	13.4354	9.557744	5.329004
User 9	15.55784	14.7525	11.37103	18.82179665	12.44958	29.5844	51.9615	26.81196	41.5676	4.064564
User 10	4.002849	0.178571	0	3.17619065	2.114827	6.797869	0.147059	8.8125	8.067193	4.189189
User 11	3.857143	6.891204	11.83482	5.07816875	4.200089	8.429251	7.330357	13.80973	4.485395	3.857143
User 12	10.97448	17.11181	19.21346	27.73597895	19.21346	13.94741	11.77441	12.01009	6.151321	16.8649
User 13	0.595238	10.82166	6.835584	25.5657765	0.925926	4.662829	0.853077	3.775269	0.278797	0.280303
User 14	2.319028	9.14394	5.603255	3.61696875	3.809773	6.384354	16.23615	10.26592	5.88855	0.178571
User 15	2.895515	0	4.035087	13.36197268	4.12037	0.295139	0.298574	0	2.12144	2.727273
User 16	5.293988	4.530298	0.333333	0.5300128	0.284455	0.2	3.593074	4.080152	3.593074	0.394057
User 17	0	3.585687	1.398488	0.43621015	0.320513	13.03107	4.131879	10.92138	0.277778	7.376133
User 18	1.013072	9.029173	4.5	9.7540043	0.399267	13.38514	7.809146	6.975525	2.6	2.575757
User 19	0.450086	1.964001	0.352734	3.5660788	0.945638	1.075269	0.673741	6.372545	0.452713	0.464744
User 20	1.339129	3.1703	0.638436	8.621847875	0.588235	5.493493	14.0064	7.090805	5.705648	7.058271
User 21	2.190208	0.16129	2.103849	2.883055326	2.901791	1.789176	2.638486	0.318979	1.292735	0.363757
User 22	0.989542	10.39675	22.28532	16.97373686	8.270677	25.02287	7.244451	23.8964	5.805717	29.21052