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# HiKeyb: High-Efficiency Mixed Reality System for Text Entry

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## Abstract

Text entry is an imperative issue to be addressed in current entry systems for virtual environments (VEs). The entry method using a physical keyboard is still the most dominant choice for an efficient interaction regarding text entry. In this paper, we propose a typing system with a style of mixed reality, which is called HiKeyb, and it possesses a similar high-efficiency with the single physical keyboard in the real environment. The HiKeyb system consists of a depth camera, a pose tracking module, a head-mounted display (HMD), a QWERTY keyboard and a black table mat. This system can guarantee the entry efficiency and the amenity by not only introducing the force feedback from a movable physical keyboard, but also improving the immersion with the real hand image. In addition, the infrared absorption material helps improve the robustness of the system against different lighting environments. Experiments have proved that users wearing HMDs in Virtual Phrases session can achieve an entry rate of 23.1 words per minute and an error rate of 2.76%, and the rate ratio of virtual reality to real world is 78% when typing phrases. Besides, we find that the proposed system can provide a relatively close entry efficiency to that using a pure physical keyboard in the real environment.

**Index Terms:** Human-centered computing—Human computer interaction—Interaction paradigms—Virtual reality; Human-centered computing—Human computer interaction—HCI design and evaluation methods—Usability testing

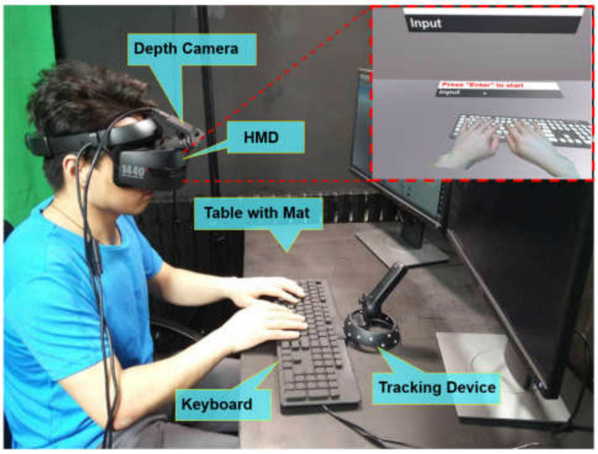


Figure 1: System overview of the proposed mixed reality system. The system is composed of a depth camera, an HMD, a table with a black table mat, a physical keyboard and a tracking device. The dashed red rectangle shows the first-person view of the user in the virtual environment(top left picture which present a virtual keyboard consisted spatial position with physical keyboard and user's segmented hands' image).

## 1 Introduction

More and more people are spending a large amount of time using virtual reality systems for work and entertainment [20, 21], which makes the study on working in a virtual environment (VE) become imperative [17]. In this way, a good input device should be much important for virtual reality systems based on head-mounted displays (HMDs) for both life and entertainment.

An efficient entry method is an essential component for working in a virtual environment. Text entry is an important part in current desktop working environments, and it is also an important communication way in daily life. It is obvious that the physical keyboard is one of the most efficient ways for text entry, and people do lots of these things relying on QWERTY keyboards to a large extent. Though the physical keyboard can be widely used in real world, it becomes much challenging in a HMD-based virtual environment due to the lack of directly seeing the keyboard and the hands.

When people work in a HMD-based virtual environment, they are eager to perceive the surroundings and interact with them [17]. And, the lack of physical feedback for some pure virtual keyboard has limited the immersion of the system and the entry efficiency of users. Some people proposed using the beam from the handle to confirm every entry action, such as HTC Vive, which suffers from the shortcoming of low entry efficiency. Focusing on the problems mentioned above, we have developed a keyboard-based input system called HiKeyb in a style of mixed reality, which integrates the physical keyboard in real world into a virtual environment. The system is shown in Fig. 1. This system improves immersion by putting the real hand image into the virtual environment and provides the physical feedback by using a real keyboard. It does not require users to learn new skills, so that the users can adapt to it quickly. In addition, this system can support interaction of multiple languages exploiting the language module of computer, which makes the HiKeyb can be easily used by different languages user.

To summarize the contributions that we have made in this paper, we highlight the works as follows:

- Propose a mixed reality system called HiKeyb for keyboard-based text entry, illustrating the typical structure of hardware and software, and take measures to improve the robustness of the system. The virtual keyboard's texture could be varied according to the users' preference.

- Propose an approach to segment hands from the background by painting infrared absorption material to the keyboard and the table mat, which makes the environment (except hands) cannot

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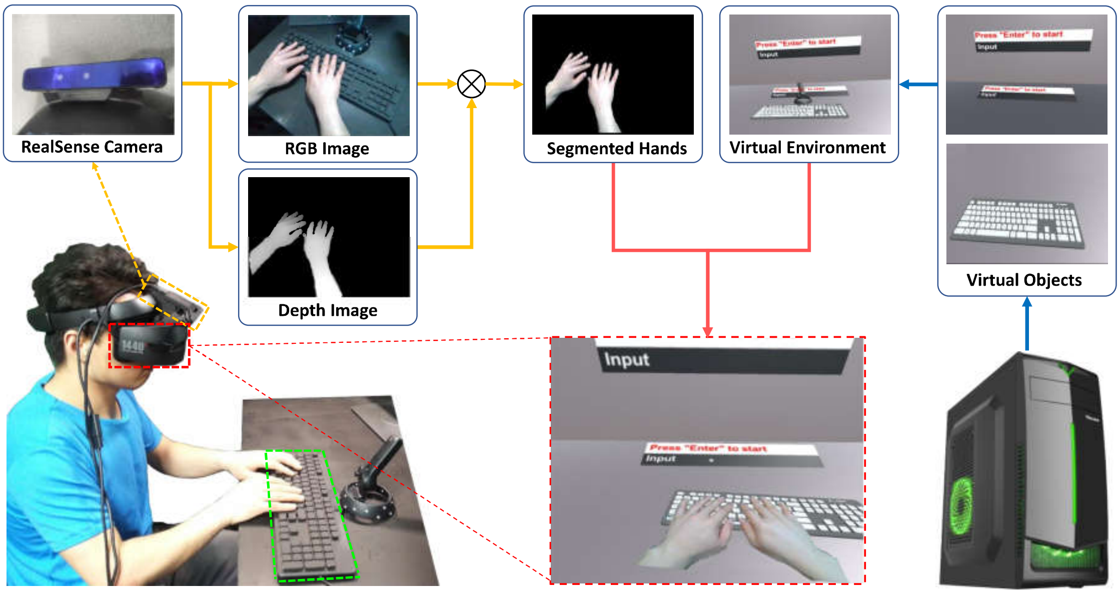


Figure 2: System workflow. When the user is wearing the HMD, the RealSense camera can simultaneously capture the RGB image and the depth image of the real scene in front of the user. Then the depth can serve as a mask to segment the hand area in the RGB image. At the same time, the virtual objects, such as a virtual keyboard corresponding to the real keyboard and some other text boxes, are created by a computer. The position of the virtual keyboard in the virtual environment is determined by tracking a handle which is fixed to the real keyboard. Finally, the segmented hand image and the virtual environment can be fused to a mixed reality scene.

reflect the infrared light that emits from the depth camera.Thus, making the system could use in different light environments.

- Conduct experiments on the system performance in different situations, where the rate ratio of virtual reality to real world is 78% when typing phrases, which is higher than it in the nearest work [5].

The remaining of this paper is organized as follows. Sect. 2 explores some related works in this field. Sect. 3 presents the design of the proposed input system. Sect. 4 introduces the experiments to evaluate the proposed system. Sect. 5 discusses the experimental results and Sect. 6 gives the conclusion.

## 2 Related Work

There were many works to investigate the ways of entry text in the virtual reality. Some studies focused on input devices (*e.g.*, [1, 2, 4, 14, 19, 24]), while some studies used several strategies to improve performance [22, 23]. The influence of hand representation was also investigated (*e.g.*, [5, 6, 9, 12, 13, 17]).

### 2.1 Methods for Text Entry in Virtual Environments

At present, there is not a perfect text input system designed specifically for HMDs. Poupyrev *et al.* [19] proposed a text input system for virtual environments (VEs), which can handle simple entry task for text and number using tablets and pens, but it can only store the contents that users have created without effective conversion to meaningful characters. Fels and Hinton [4] adopted gestures to enter words and phrases, but it required users to remember all gestures in advance. In addition, many kinds of entry methods had been explored by Bowman *et al.* [1], including a voice entry, Pinch keyboard [2], chord keyboard and pen-tablet keyboard, but none of them can satisfy users in term of performance. Voice entry [14] also suffered from discontinuity and low efficiency. ATK system [24] was based on the 3D tracking data from LeapMotion controller, which supported free entry with fingers.But it made users uncomfortable due to the lack of arm support in the air and the physical feedback. ARKB [11] was a virtual keyboard in augmented reality, which used 3D vision to track hands, but still lacked physical feedback.

Walker *et al.* [22] proposed an auxiliary input system called VelociTap for the QWERTY keyboard. Though this system could improve the entry efficiency under the condition that the keyboard was unseen but touchable, it was still much lower than that in the real environment. Then Walker *et al.* [23] modified the system by adding assistance of virtual keyboards. But the layout of this virtual keyboard is much different from a real keyboard and users could not see the hands.

### 2.2 Fusion of Virtual Hand

McGill *et al.* [17] proposed an AV system for HMDs, which segmented the image of hand and keyboard from the green background. They found that even the partial fusion that performs best among three methods was far from that in the real environment.

Grubert *et al.* [5] conducted a study on four different entry styles. The hand-free mode was accompanied with relatively high error rate 15.2%. The 3D hand model led to errors due to the difference from real bodies. In addition, they also compared the typing performance using a physical keyboard and a touch screen in VR [6]. New users could remain an entry rate of 60% using a desktop keyboard and an entry rate of 40% to 45% using multi-touch virtual keyboard.The touch screen performed worse and cannot reach a similar efficiency with desktop keyboard-based text entry.

Knierim *et al.* [9] proposed an apparatus to track the users hands, and visualized them in VR: realistic, abstract, fingertips with no transparency and real hands as well as 50% transparency and no hands. Study demonstrated that inexperienced typists profited from semi-transparent hands, but the apparatus also needs to fix 23 retroreflective markers on each hand and it has high requirements for equipment and the usage environment.



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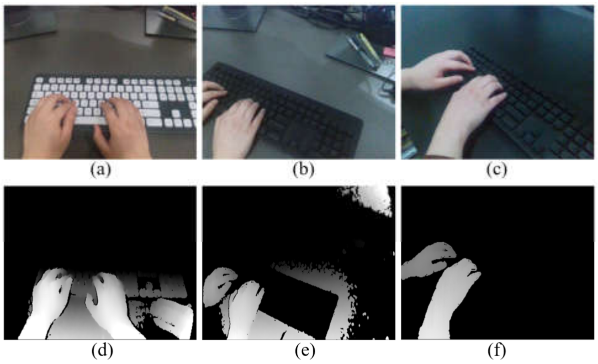


Figure 3: Effects of infrared absorption material. (a) The keyboard and the table are not covered by the infrared absorption material. (b) The keyboard is covered by the infrared absorption material, while the table is not. (c) The keyboard and the table are all covered by the infrared absorption material. (d)(e)(f) are the corresponding depth images with (a)(b)(c) respectively.

Budhiraja *et al.* [3] fused the real objects into a virtual environment, and compared four fusion modes. They found that users obtained the best efficiency when they could see the virtual objects, and the virtual objects had coherent sizes the real objects. This inspired us to let users see their own real hands inside the system.

The appearance of a virtual hand affected the own-body perception [13] which would affect the performance of users in the VEs. The virtual hand illusion (VHI) of realistic hands was stronger than abstract or simple hands. The sense of body ownership was strengthened when the virtual hand was similar to the real hand of the user [18]. This inspired us to use the image of real hands as the virtual hands in the VEs. Lin *et al.* [12] compared the entry performance in different situations, exploring several integrate modes of hands and keyboard in the virtual environment, which indicating that the fusion of hands and keyboard should be much promising.

Therefore, to overcome the mentioned problems above, we propose a QWERTY keyboard-based input method using a mixed reality style, fusing the real hand and keyboard into the virtual environment. This solution can minimize the learning cost of users and guarantee the entry efficiency and user experience to the largest extent.

## 3 System Design

The proposed design can be used for high-efficiency entry in the virtual environment. The design is based on a real keyboard and accurately present a corresponding virtual keyboard in a virtual environment. It is specially developed for HMD-based systems.

The hardware contains a real keyboard, a tracking device for keyboard and a tracking device for hands. The software contains the module for hand segmentation and the module for hand-keyboard fusion.The workflow is shown in Fig. 2.

Based on the proposed design, our system has the following advantages. In our system, the combination of colorful image and depth image can adapt to different lighting environment, so it is more robust compared with other systems [3,5,6]. We only segment the hands and fuse them into a virtual environment, so the virtual keyboard can be custom according to different situations, which makes the virtual keyboard more flexible. For example, we can define the appearance of the virtual keyboard using some beautiful textures, and we can also easily control the graphical rendering to get a good brightness. Considering this, if we together segment the image of the real keyboard into the virtual environment, the resolution will be restricted by the camera parameters as well as the lighting environment.


Figure 4: The system can work in various lighting environments. (a) 14.0 lux. (b) 139.8 lux. (c) 370.7 lux. (d) 574.0 lux.

### 3.1 Hardware

As shown in Fig. 1, the hardware of the system consists of a HMD, a physical keyboard, a depth camera, a tracking device, a desktop computer and a table with a black table mat. The table mat and the keyboard are covered by the absorption material that can absorb the infrared light with the wavelength of 850nm. Since the depth camera can emit the infrared light to the environment, only the hand can reflect this light back to the depth camera. So the configuration of the system is useful to improve the segmentation of hands, that could improve the system efficiency and result. The effects of the infrared absorption material are shown in Fig. 3. The tracking device is fixed on the real keyboard, so the position of the keyboard can be computed by tracking its attached tracking device, which is used to set the virtual keyboard in the virtual environment. All spatial relationships of the mentioned components can also be seen in Fig. 1.

### 3.2 Software

The software is developed using Unity 3D. The virtual keyboard is constructed according to the size of the real keyboard. In our research, the 3D model is obtained from TurboSquid online store. The pose and location of the virtual keyboard in the virtual environment is determined by the real keyboard in the real environment.

To segment the hand from the background, we can use the image from the depth camera. For the reason that the depth camera is fixed to the HMD, it can help to obtain the first-person view of users. As mentioned above, the keyboard and the table mat are all covered by the infrared absorption material, so the hand is the only object that can reflect the infrared light emits from the depth camera. Therefore, in the depth image, the hand is easily to be segmented. Using this data, we can segment the colorful hand from the RGB image by comparing the depth image and the RGB image, and put the segmented hand into the virtual environment.

A high-efficiency for text entry in virtual environment requires a perfect alignment of the hand image, the virtual keyboard and the real keyboard. To reach this goal, the tracking device, the depth camera and the HMD should be integrated into a unified coordinate system. This work should be based on the calibration of different modules and their synchronization in real-time task.

We should calibrate the tracking device, HP Microsoft HMD and the RealSense to determine the spatial relationship among them. The three components should be unified into one coordinate system.

The rate for RealSense to capture depth images and colorful images is 60 fps.The process of these images will lead to latency. The hand image is projected to the virtual environment, which also takes some time. We utilized high-speed camera (MotionBLITZ Cube) to measure the latency of our system, and the rate of the high-speed camera is set to be 1000 fps.The latency between the user's action and the rendering of HMD is obtained as 120 ms.

The proposed system can adapt to different brightness of different office environment because of the infrared absorption material. We tested the system at the illumination of 14.0 lux, 139.8 lux, 370.7 lux and 574.0 lux (see Fig. 4), and it could work well. It indicates that the system can work at any general working environment.



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Figure 5: The experimental configuration for real and virtual environments. (a) One participant is typing in the real environment with the input interface on the computer screen. (b) One participant wearing an HMD is typing in the virtual environment.

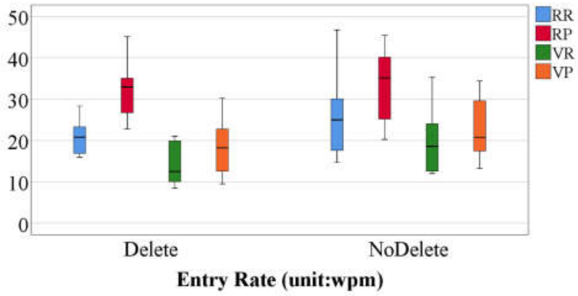


Figure 6: The entry rate in two situations ("Delete" and "NoDelete").

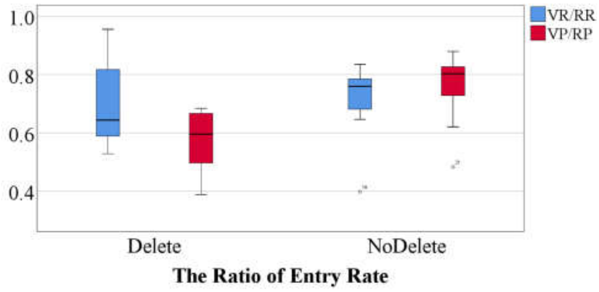


Figure 7: The ratio of entry rate for VR session to RR session and VP session to VR session in two situations.

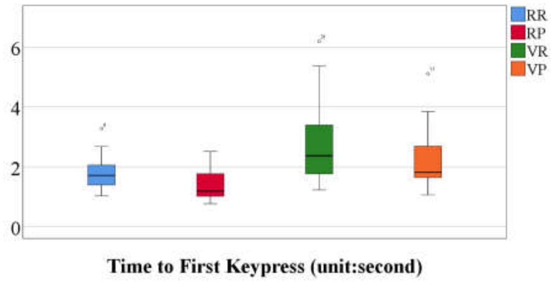


Figure 8: The time to first keypress considering two situations together.

## 4 EXPERIMENTS

The configurations of real and virtual environments are shown in Fig. 5. To verify the effectiveness of the system, we conducted a controlled experiment, including two situations and each situation was composed of four sessions.

Four sessions were created as follows: (1) Real Random (RR). In this session, participants used the physical keyboard to enter random letters appearing on the computer screen in the real environment. (2) Real Phrase (RP). In this session, participants used the physical keyboard to enter the phrases appearing on the computer screen in the real environment. (3) Virtual Random (VR). In this session, participants used the physical keyboard to enter the random letters appearing in the virtual environment in a HMD where they could see the virtual keyboard. (4) Virtual Phrase (VP). In this session, participants used the physical keyboard to enter the phrases appearing in the virtual environment.Before experiments, we exposed every participant to 10 minutes of typing training.

### 4.1 Measurement and Participant

Text entry is the main purpose of keyboard entry. Objective measurements include the users' entry rate and error rate [15], and the time to first keypress [17]. In our system, we used the phrase set recommended by Kristensson, which had similar performance [10, 16] in both familiar and unfamiliar text entry situations. Subjective measurements included the SSQ simulator questionnaire [8], the NASA-TLX questionnaire [7].The SSQ was filled both before and after each session, while the NASA-TLX questionnaires were filled after each session. We recruited 24 participants (11 females, 11 males, mean age 24.2 years, $SD = 2.8$). None took part in previous text entry experiments.

### 4.2 Experimental Result

Participants were tested in a quiet and controlled light illumination of 150 lux office environment. They were divided randomly into two different situations: Delete situation, where they could use the backspace key; and NoDelete situation, where they could not use backspace key. At the end of each session, participants took a rest for 5 minutes and proceeded to the next session until the end of the experiment.The entry rate was obtained by measuring wpm (see Table 1 and Fig. 6). In NoDelete group, paired T-tests indicated there were significant differences. But there was no significant difference between VR and VP sessions. The ratio of VR session to RR session regarding entry rate was 78%, and the ratio of VP session to RP session regarding entry rate was 73%, as shown in

Table 1: Means and standard deviations of the enter rate in different situations.

| Situation | NoDelete | | Delete | |
|---|---|---|---|---|
| | M(wpm) | SD | M(wpm) | SD |
| Real Random | 25.4 | 9.78 | 20.7 | 3.96 |
| Real Phrase | 32.5 | 9.00 | 31.7 | 6.66 |
| Virtual Random | 19.0 | 7.36 | 14.7 | 5.09 |
| Virtual Phrase | 23.1 | 7.31 | 18.6 | 6.70 |

Table 2: Means and standard deviations of the time to first keypress in different situations.

| Situation | NoDelete | | Delete | | ALL | |
|---|---|---|---|---|---|---|
| | M(s) | SD | M(s) | SD | M(s) | SD |
| Real Random | 1.89 | 0.30 | 1.89 | 0.15 | 1.89 | 0.77 |
| Real Phrase | 1.56 | 0.17 | 1.25 | 0.09 | 1.39 | 0.47 |
| Virtual Random | 4.95 | 1.43 | 3.22 | 0.80 | 4.01 | 3.87 |
| Virtual Phrase | 2.58 | 0.46 | 2.39 | 0.34 | 2.48 | 1.35 |



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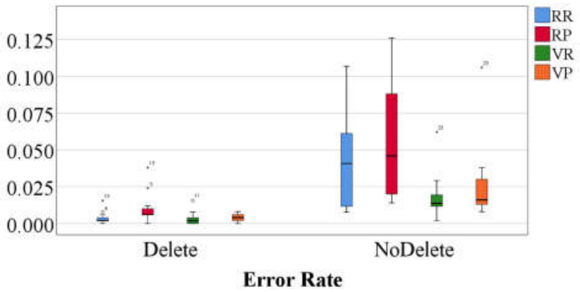


Figure 9: the error rate in two situations.

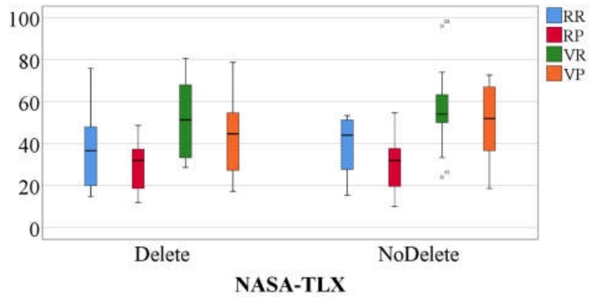


Figure 10: The median scores of NASA-TLX.

the right side of Fig. 7.In Delete group, paired T-tests indicated there were significant differences. The ratio of VR session to RR session regarding entry rate was 70%, and the ratio of VP session to RP session regarding entry rate was 57%, as shown in the left side of Fig. 7.Statistical results indicated that in both situations, the entry rate in the real environment was higher than that in the virtual environment. Moreover, in real or virtual environments, the entry rate of phrases was higher than that of random letters.

The time to first keypress proposed by McGill *et al.* [17] could also be used as an indicator to measure the effectiveness of the system.Since it is not affected by the form of letters,we considered it in two situations together.As shown in Fig. 8, the time to first keypress appear to be the following order: VR >VP>RR >RP.

The accuracy of text entry is determined by the error rate. The statistical results (see Table 3 and Fig. 9) indicated that the error rate of each session in the NoDelete group was higher than in the Delete group, and there was a significant difference ($F_{1,22} = 20.171$, $\eta_p^2 = 0.478, p = 0.000$).

The statistical results (see Table 4 and Fig. 10) indicated that the NASA-TLX value in the virtual environment was higher than that in the real environment. In both situations, the scores in the RR and VR sessions were higher than those in the RP and VP sessions. When evaluating the degree of simulator sickness(see Table 5), we divided all participants into two groups (VE group using this system typing in the HMD and Desktop group typing in the real world).

Table 3: Means and standard deviations of the error rate in different situations.

| Situation | NoDelete | | Delete | |
|---|---|---|---|---|
| | M(%) | SD | M(%) | SD |
| Real Random | 4.29 | 0.011 | 0.35 | 0.001 |
| Real Phrase | 5.62 | 0.013 | 1.02 | 0.003 |
| Virtual Random | 1.80 | 0.001 | 0.33 | 0.001 |
| Virtual Phrase | 2.76 | 0.008 | 0.39 | 0.001 |

Table 4: Means and standard deviations of the NASA-TLX value in different situations.

| Situation | NoDelete | | Delete | |
|---|---|---|---|---|
| | M | SD | M | SD |
| Real Random | 39.0 | 14.3 | 36.7 | 17.4 |
| Real Phrase | 30.0 | 14.7 | 30.0 | 13.0 |
| Virtual Random | 56.2 | 19.3 | 51.7 | 19.6 |
| Virtual Phrase | 50.4 | 17.8 | 44.2 | 18.6 |

## 5 Discussion

We proposed a highly effective mixed-reality entry approach in a virtual environment for HMDs that allowed users in virtual environments to achieve a high entry efficiency as they did in real environments. We verified the typing performance of the user in eight different conditions and compared the entry efficiency of this system with that using a physical keyboard in the real world when users use desktop computers.

The analysis of entry rate, the ratio of entry rate and error rate indicated the system had a good typing performance. Participants as non-native speakers needed to pay some time and attention to the language, which would lead to a slightly lower entry rate compared to English native-speakers. In the virtual environment, the error rate was almost the same as that in the real environment, indicating that the system using the physical keyboard in the virtual environment, to some extent, could achieve the same entry accuracy in the real environment, so users would not feel frustrated due to the high error rate.Meanwhile, that the rate ratio of virtual reality to real world is 78% when typing phrases demonstrates the system could perform better than before works.

As a highly-effective input device, the QWERTY keyboard would be an essential part of livable virtual reality. The experimental results of objective measurements and subjective measurements indicated this system had a good entry performance. So this system could be an important interaction method for HMDs.

At present, the system can be used for entry tasks in a virtual environment considering its low error rate and high entry rate, although the entry rate is slightly lower than that in the real world.The approach of image processing makes it nearly impossible for users to use this system in different light environments due to the specific design against varying illumination.

## 6 Conclusion

In this study, we developed an efficient mixed-reality keyboard input system for the HMD-based virtual environment, which provided an efficient interaction method for future virtual environments, such as office business and entertainment tasks that required a large amount of text entry. The real hands of the user in virtual environment gave users a stronger sense of ownership and agency compared with the 3D hand models, and the integration with the virtual environment improved the user's sense of immersion and comfort. A livable virtual reality system requires many basic properties: adaptation in multiple lighting environments, spatial consistency of the virtual and real keyboard, the comfort and convenience of using the virtual

Table 5: Evaluation of simulator sickness.

| Situation | Desktop | VE |
|---|---|---|
| Before tests | 25.60±5.315 | 30.0±4.900 |
| After tests | 25.13±5.487 | 29.27±7.908 |



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keyboard. In the near future, people could use this system to work and entertain in extended virtual environment without the limitations of the current physical environments.


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## References


[1] D. A. Bowman, C. J. Rhoton, and M. S. Pinho. Text input techniques for immersive virtual environments: An empirical comparison. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 46, pp. 2154–2158. SAGE Publications Sage CA: Los Angeles, CA, 2002.

[2] D. A. Bowman, C. A. Wingrave, J. M. Campbell, and V. Q. Ly. Using pinch gloves for both natural and abstract interaction techniques in virtual environments. *Journal of Allergy & Clinical Immunology*, 126(4):836–844, 2001.

[3] P. Budhiraja, R. Sodhi, B. Jones, K. Karsch, B. Bailey, and D. Forsyth. Where's my drink? enabling peripheral real world interactions while using hmds. *arXiv preprint arXiv:1502.04744*, 2015.

[4] S. S. Fels and G. E. Hinton. Glove-talkii-a neural-network interface which maps gestures to parallel formant speech synthesizer controls. *IEEE transactions on neural networks*, 9(1):205–212, 1998.

[5] J. Grubert, L. Witzani, E. Ofek, M. Pahud, M. Kranz, and P. O. Kristensson. Effects of hand representations for typing in virtual reality. *arXiv preprint arXiv:1802.00613*, 2018.

[6] J. Grubert, L. Witzani, E. Ofek, M. Pahud, M. Kranz, and P. O. Kristensson. Text entry in immersive head-mounted display-based virtual reality using standard keyboards. *arXiv preprint arXiv:1802.00626*, 2018.

[7] S. G. Hart and L. E. Staveland. Development of nasa-tlx (task load index): Results of empirical and theoretical research. In *Advances in psychology*, vol. 52, pp. 139–183. Elsevier, 1988.

[8] R. S. Kennedy, N. E. Lane, K. S. Berbaum, and M. G. Lilienthal. Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. *The international journal of aviation psychology*, 3(3):203–220, 1993.

[9] P. Knierim, V. Schwind, A. M. Feit, F. Nieuwenhuizen, and N. Henze. Physical keyboards in virtual reality: Analysis of typing performance and effects of avatar hands. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, pp. 345:1–345:9. ACM, 2018.

[10] P. O. Kristensson and K. Vertanen. Performance comparisons of phrase sets and presentation styles for text entry evaluations. In *Proceedings of the 2012 ACM International Conference on Intelligent User Interfaces*, pp. 29–32. ACM, 2012.

[11] M. Lee and W. Woo. Arkb: 3d vision-based augmented reality keyboard. In *Proceeding of the International Conference on Artificial Reality and Telexistence*, pp. 54–57, 2003.

[12] J.-W. Lin, P.-H. Han, J.-Y. Lee, Y.-S. Chen, T.-W. Chang, K.-W. Chen, and Y.-P. Hung. Visualizing the keyboard in virtual reality for enhancing immersive experience. In *Proceedings of ACM SIGGRAPH 2017 Posters*, p. 35. ACM, 2017.

[13] L. Lin and S. Jörg. Need a hand?: how appearance affects the virtual hand illusion. In *Proceedings of the ACM Symposium on Applied Perception*, pp. 69–76. ACM, 2016.

[14] J. A. Macas, T. Granollers, and P. Latorre. New trends on humancomputer interaction. *Journal of Small Animal Practice*, 53(2):126131, 2009.

[15] I. S. MacKenzie and R. W. Soukoreff. Text entry for mobile computing: Models and methods, theory and practice. *Human–Computer Interaction*, 17(2-3):147–198, 2002.

[16] I. S. MacKenzie and R. W. Soukoreff. Phrase sets for evaluating text entry techniques. In *Proceedings of CHI'03 Extended Abstracts on Human Factors in Computing Systems*, pp. 754–755. ACM, 2003.

[17] M. McGill, D. Boland, R. Murray-Smith, and S. Brewster. A dose of reality: Overcoming usability challenges in vr head-mounted displays. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, pp. 2143–2152. ACM, 2015.

[18] J. Nordin. Realistic virtual hands: Exploring how appearance affects the sense of embodiment, 2017.

[19] I. Poupyrev, N. Tomokazu, and S. Weghorst. Virtual notepad: handwriting in immersive vr. In *Proceedings of Annual International Symposium on Virtual Reality*, pp. 126–132. IEEE, 1998.

[20] F. Steinicke and G. Bruder. A self-experimentation report about long-term use of fully-immersive technology. In *Proceedings of ACM Symposium on Spatial User Interaction*, pp. 66–69, 2014.

[21] B. H. Thomas. A survey of visual, mixed, and augmented reality gaming. *Computers in Entertainment (CIE)*, 10(1):3, 2012.

[22] J. Walker, S. Kuhl, and K. Vertanen. Decoder-assisted typing using an hmd and a physical keyboard. In *Proceedings of Extended Abstracts of the the ACM Conference on Human Factors in Computing Systems*, vol. 16, 2016.

[23] J. Walker, B. Li, K. Vertanen, and S. Kuhl. Efficient typing on a visually occluded physical keyboard. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, pp. 5457–5461. ACM, 2017.

[24] X. Yi, C. Yu, M. Zhang, S. Gao, K. Sun, and Y. Shi. Atk: Enabling ten-finger freehand typing in air based on 3d hand tracking data. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology*, pp. 539–548. ACM, 2015.




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