Exploring the Impact of Visual Information on Intermittent Typing in Virtual Reality

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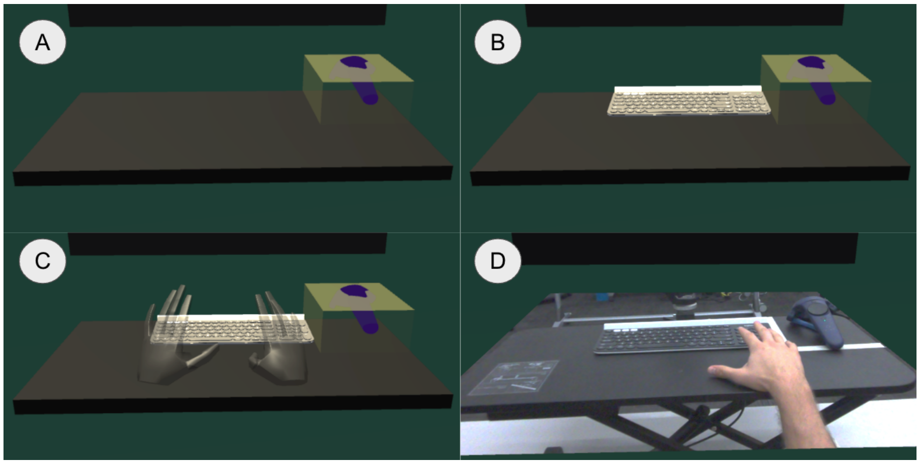

Figure 1: VR view of conditions studied in the experiment. A: NONE - No virtual keyboard or user hand representations. B: KEYBOARD - Virtual keyboard and no user hand representations. C: KEYBOARDHANDS - Virtual keyboard and virtual user hand representations. D: PASS-THROUGH - Video pass-through portal of the physical keyboard and user's physical hand.

Abstract

For touch typists, using a physical keyboard ensures optimal text entry task performance in immersive virtual environments. However, successful typing depends on the user's ability to accurately position their hands on the keyboard after performing other, non-keyboard tasks. Finding the correct hand position depends on sensory feedback, including visual information. We designed and conducted a user study where we investigated the impact of visual representations of the keyboard and users' hands on the time required to place hands on the homing bars of a keyboard after performing other tasks. We found that this keyboard homing time decreased as the fidelity of visual representations of the keyboard and hands increased, with a video pass-through condition providing the best performance. We discuss additional impacts of visual representations of a user's hands and the keyboard on typing performance and user experience in virtual reality.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction devices—Keyboards Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Virtual reality

1 Introduction

As virtual reality (VR) head-worn displays (HWDs) become more commercially available to consumers, designers and developers must consider a broader range of use cases and applications. One area of interest, which has seen a surge in research contributions in recent years, is text entry. Investigators have explored text entry methods and their potential use in such applications as productivity work and immersive analytics within immersive virtual environments (VEs) [8, 9]. In order to support these potential applications, novel text entry modalities such as speech-to-text, controllers, and head motion while wearing an HWD have been used as means to provide symbolic input in VEs [22, 30, 33]. However, these techniques do not match the typing performance of expert typists provided by a more familiar input device: the physical keyboard [7]. In order to achieve the highest text entry performance in VR while using physical keyboards, we need to understand their observed limitations.

The physical keyboard provides great performance across text-entry-heavy applications, such as text editors and instant messaging services, but is not trivial to integrate into VR applications [19]. The sense of presence and embodiment that typifies VR is based on sensorimotor contingencies [28]. In other words, these effects depend on user *movement* in the VE, not only through head rotation, but also turning, crouching, leaning, jumping, and especially walking [29]. However, combining these sorts of movements with a physical keyboard for text entry is problematic, since the keyboard needs to rest on a supporting surface, and it is not practical in most cases for the user to take the keyboard with them as they move through the VE. This has made adopting the physical keyboard in VR difficult since movement and actions with other input devices (e.g., handheld controllers) necessarily cause users to remove their hands from the keyboard. Without the built-in ability for users to see their hands or the keyboard to verify their positioning on top of the keyboard's homing bars (the ridges located on two keys used for left- and right-hand placement on the keyboard), it is not possible for users to perform text-entry tasks as quickly and accurately as in the real

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world [7].

We refer to the activity of locating the keyboard or other device and placing one's hands on a target position (i.e., homing bars of a keyboard) after using another device as **homing** [6]. Successfully completing the homing task depends on sensory information about the location of the hands and the device. While users may be able to remember the general area where the keyboard is located after moving around a VE, this relies on users' individual spatial memory and proprioception. Knowing the general location of the keyboard is not sufficient for homing, as it requires precise finger placement on the target homing position. In the absence of visual information about both the location of the keyboard and the user's hands/fingers, users will have to rely on haptic information to locate the homing bars. However, haptics does not allow users to immediately locate the homing bars; rather, they need to locate the keyboard with their hands, then move their fingers over the keyboard until the homing bars are felt. In other words, the haptic feedback provided by the homing bars only allows users to know when they have *reached* the home position; it does not help them to *find* the home position. Thus, using haptics for keyboard homing is expected to be slow and error-prone.

Of course, visual information is another source of sensory feedback that can aid homing, with techniques such as tracked virtual representations of the keyboard and user's hands, as well as video see-through of the keyboard and user's hands. Prior studies of such visual representations [3, 10, 15, 19] showed that simple virtual feedback could support high levels of typing performance; however, they focused solely on users typing while stationary in front of the keyboard, not accounting for interactions where users move within the VE and use other input devices.

The objective of our work is to understand how visual representations of the keyboard and hands affect homing, as well as the user experience in general while typing in VR intermittently (i.e., typing after movement and use of other devices). We present the findings from an experiment where we compared four visual information conditions that varied the fidelity of representations of the keyboard and user's hands, in order to determine their effects on homing time and the user experience during intermittent typing in VR. We found that as visual fidelity of the keyboard and user's hands increases, up to and including an actual video pass-through of the physical device, keyboard homing time and user experience are significantly improved.

2 Related Work

In the context of VEs being used primarily as visualization tools and for entertainment applications, novel techniques for VR text entry have been developed and investigated. These techniques explore effective ways to input text using HWD gaze- or head-tracking capabilities [17, 23, 32], speech-to-text translations [4, 22], pens and tablets [4, 14], controllers [16, 30, 34], and hand-tracking [24]. Although these techniques propose novel means to enter text, most do not have comparable performance to that of the standard physical keyboard, will require time for users to adopt and use, and do not address all VR use cases [19]. Even if the keyboard is seen as an undesirable peripheral, it is here to stay [5]. As a result, researchers have included physical keyboards in a wide variety of VR applications, highlighting use cases including document editing, chat services, and immersive analytics [8, 9]. Researchers have even explored the capabilities of VR systems to change the input and output characteristics of physical keyboards, finding that updating input and output mappings and adding virtual augmentations to keyboard representations can provide versatility to input for applications [25]. For this reason, several studies have been conducted on keyboard usage in immersive VEs.

2.1 Wearable Keyboards for VR Typing

Few studies have been conducted regarding methods to allow users to carry a physical keyboard with them in a VE, in an effort to enable typing while moving around a VE. Orlosky et al. constructed a system that had users wear a split QWERTY keyboard on the torso of a vest [20]. In an experiment where users typed while sitting, standing, and walking while wearing an HWD, they found that users were able to achieve high word per minute (WPM) entry rates, highlighting the potential of wearable keyboards as an alternative to other devices for mobile text entry tasks. A similar split keyboard solution was proposed by Hutama et al., who mounted a split keyboard to the HWD itself [13]. Their prototype also achieved high text entry rates in typing speed, with users retaining between 70 and 81 percent of their normal keyboard WPM.

Another system that deviated from split QWERTY keyboard experiments was proposed by Pham and Stuerzlinger, who had users wear a hawker's tray to carry a physical keyboard as they performed text entry tasks in VR [21]. This text entry method was found to have comparable typing performance when compared to conventional, seated keyboard usage. However, these studies were noted to have many limitations, with users reporting exhaustion from having to raise their hands to type for long periods of time [13], the unfamiliar keyboard layout impacting typing ability [20], and the system not readily supporting additional input devices such as controllers being transported in the carrying mechanisms [21].

2.2 Keyboard Visualizations in VR

Virtual keyboard visualizations have been studied by researchers for typists in VR using physical keyboards. McGill et al. conducted a series of studies regarding challenges users experience while using VR HWDs, with one study describing performance impairments while typing in VR [19]. The study had users type under four visual feedback conditions: typing without wearing an HWD, typing while wearing an HWD with no visual feedback of the keyboard's position, typing while wearing an HWD with a view of the user's real hands and keyboard, and typing while wearing an HWD with a full view of the real world. Their results indicated that augmenting virtuality with a real keyboard reduced error rates, and they attributed this improvement to users being more capable of orienting themselves to the keyboard with the real keyboard visual feedback. They also found that the incorporation of real-world views in the VE was necessary to preserving text entry rate performance.

However, a later study by Walker et al. introduced a system for HWD users for assisted typing with conditions where the user performed text entry tasks on a physical keyboard which was visually-occluded [31]. Participants in their study were shown a virtual keyboard that highlighted their key presses on the physical keyboard at the bottom of their view/screen. Four conditions were tested, where the participants used a physical monitor and an HWD to perform typing tasks, with and without the virtual keyboard visible. They found no significance in text entry and error rates in conditions where the virtual keyboard was displayed to the user. This showed that fully-virtual feedback could preserve text entry rate performance, but still showed higher error rates by users while using the HWD.

Further investigation regarding virtual representations while using physical keyboards in VR was led by Grubert et al., who conducted a study on the impact of visual feedback in VR on typing performance [11]. Their experiment examined the effect of relocating the virtual representations of the user's hands and the keyboard on typing performance within a VE, such that the keyboard and user's hands were in front of the user's view and not the same as their physical location. The results showed no significant learning impact for users, further cementing the ability of users to transfer their typing skills in VR, and found that the virtual keyboard and hand representations did not affect performance when using the physical keyboard.

While at least some of these studies did examine a form of the homing task (starting each typing task with hands off the keyboard), all of them were limited in their application to intermittent typing. All of these studies had participants type on the physical keyboard while stationary, and none investigated the use of other input devices or mobility within the VE.

2.3 Hand Representations for VR Typing

The performance influences of hand representations in VR on text entry tasks have also attracted the attention of researchers. Grubert et al. performed a study where users had four visualizations of their hands in VR when typing with a physical keyboard: no hands, inverse kinematic virtual hands, virtual fingertips, and video see-through of their real hands [10]. Additional analysis of typing performance and effects of virtual hands was performed by Knierim et al., who conducted a study that experimented with similar conditions, but had additional conditions of abstract hand representations and investigated the effects of transparency on hand models [15]. From these studies, the text entry rates of participants were not significantly impacted by the hand representations in their respective experiments and conditions. Error rates for higher fidelity virtual representations of the user's hands and the keyboard were significantly lower in the studies. However, these studies both required the use of the OptiTrack system to spatially track the user's hands and finger joints, which is not readily available for everyday VR users for VR applications.

Our experiment addresses the limitations of the prior work by investigating the impact of visual representations of the physical keyboard and participant's hands in an immersive VE during intermittent typing. Users move around the VE as part of the experiment, performing tasks using a handheld controller to move them away from the keyboard, in order to measure the homing time taken by each participant per visual condition. Our setup also uses tracking systems that spatially track the user's hands and fingers without requiring many cameras and reflective hand markers, making the results applicable to practical VR systems.

3 Experiment

Our within-subjects experiment evaluated four visual information conditions that varied the display of the keyboard and hands of participants as they performed trials involving both typing and non-typing tasks in each condition. In order to understand the impact of visual information on intermittent typing within immersive VEs, we aimed to answer the following research questions:

RQ1. How do visual representations of the keyboard and hands in VR affect the time taken by users to complete the homing activity? As we argued in Section 1, because proprioceptive and haptic feedback alone are insufficient for homing, and because homing requires precise relative positioning of the hands and the keyboard, we expect that participants will take less time to place their hands on the homing bars of a keyboard as the fidelity of visual representations of the keyboard and hands increases (**H1**).

RQ2. How do visual representations of the keyboard and hands affect typing performance in VR for experienced typists? Once the hands have been placed in the home position on the keyboard, touch typists rely primarily on proprioception and haptic feedback when typing. Thus, we hypothesize that, after homing, experienced typists will have similar typing performance regardless of the fidelity of visual representations of the keyboard and hands (**H2**). Prior VR typing research also supports this hypothesis [11, 31].

RQ3. How do visual representations of the keyboard and hands in VR affect the overall user experience of intermittent typing? Although overall user experience is not always correlated with performance, difficulty in keyboard homing is likely to lead to frustration and feel unnatural. We, therefore, expect participants will have an improved user experience as the fidelity of visual representations of the keyboard and hands in VR increases (**H3**).

3.1 Conditions

In the experiment, four visual information conditions were tested as shown in figure 1: NONE, KEYBOARD, KEYBOARDHANDS, and PASS-THROUGH. These conditions were selected as they have been used in previous text entry studies involving physical keyboard usage in VR [15, 19] and have varying increments of visual information. Additionally, the varying increments of visual information account for the potential hardware capabilities VR users may have, with no additional hardware required for the NONE condition, a tracker to determine keyboard position for the KEYBOARD condition, motion-capture camera to track hands for the KEYBOARDHANDS condition and head-mounted video cameras to view the real keyboard for the PASS-THROUGH condition. For the entirety of the experiment, regardless of the condition under test, participants were able to see a virtual representation of the desk, controller, and controller dock with exact positioning, rotation, and dimensions of the physical equivalents. In the NONE condition, as shown in figure 1A, the participants did not see any visual information regarding the physical position of the keyboard or their hands within the virtual environment. In this condition, the visual representation of the desk would aid participants as they used proprioception to gauge their distance to the desk and position their hands above the desk. However, to find the keyboard and the home position, users would have to rely on haptic feedback from the desk, keyboard, and homing bars. In the KEYBOARD condition, as shown in figure 1B, the participants were able to see a virtual twin of the physical keyboard with the same position, orientation, dimensions, key positions, and visual appearance. With this virtual keyboard representation, participants had reduced dependence on proprioception and haptic feedback of the desk to initially locate the keyboard. Participants could instead use the visual keyboard and knowledge of their hand positions (through proprioception) to place their hands on the keyboard directly. However, this combination of visual and proprioceptive feedback is not likely to be sufficient for the precise placement required for homing, so haptic feedback from the homing bars would be needed to place their fingers on top of the keyboard correctly. In the KEYBOARDHANDS condition, as shown in figure 1C, in addition to the virtual representation of the physical keyboard as in the previous condition, participants could also see tracked, virtual, low-poly representations of their hands within the virtual environment. Individual fingers were tracked on the virtual hands using an Ultraleap camera system built into the HWD. The tracked virtual hands further reduced the need for users to rely on proprioception and haptics for homing since visual information about the relative positions of the fingers and keys was available. However, slight errors in calibration or finger tracking could still require users to verify finger placement through haptic feedback of the homing bars. In the PASS-THROUGH condition, as shown in figure 1D, the participants were able to see live stereoscopic video via front-facing cameras on the HWD through a virtual "portal" with dimensions 0.40m x 0.80m x 0.09m (length x width x height) fixed to the top of the desk, allowing them to naturally view the physical keyboard and their hands when they were in the vicinity of the desk. This condition completely removed reliance on proprioception and haptics by providing complete and accurate visual feedback about the relative positions of fingers and keys.

3.2 Apparatus

Participants wore a Varjo XR-3 HWD for the experiment. The HWD has a 115-degree horizontal and 80-degree vertical field of view. It has a peripheral area resolution of 2880x2720 px per eye and a focus area (27x27 degrees) of 1920x1920 px per eye. The HWD has built-in hand-tracking capabilities, using Ultraleap Gemini (v5). We used this feature to display the virtual hands in the KEYBOARDHANDS condition, as well as in the KEYBOARD condition for initial keyboard position calibration. The HWD also has mixed reality video pass-through via dual 12-megapixel cameras with a 90 Hz refresh rate. This feature was used in the PASS-THROUGH condition.

Four HTC Vive Base Stations were used to track the participant's movement within the virtual environment and to establish a room-scale boundary. The physical desk was tracked by an HTC Vive Tracker (2018) and mapped to its equivalent within the virtual environment. A Logitech Wireless K780 keyboard with dimensions of 380 x 158 mm (width x height) was used for the text entry portions of the experiment. The keyboard had homing bars (i.e., small ridges) on the 'F' and 'J' keys, where the user's index fingers should be placed when in the home position. An HTC Vive Controller was used for controller-based tasks within the experiment, as described in the following section. The desk apparatus and HWD are shown in figure 2.

Figure 2: Physical apparatus with Logitech Wireless K780 keyboard, HTC Vive Controller, HTC Vive Tracker, and Varjo XR-3 HWD.

3.3 Environment

The virtual environment was a simple box-shaped room with dimensions of 5m x 5m x 3m (length x width x height). The desk stood at approximately 1.14m in height and had dimensions of 0.40m x 0.80m x 0.03m. The controller dock was anchored at the top-right corner of the desk with dimensions 0.22m x 0.2m x 0.1m. Visual feedback on a virtual monitor within the experiment's virtual environment informed the participant which task they were required to complete and when they had completed a set of trials for their current condition under test (described further in section 3.4). The virtual monitor had dimensions of 1m x 0.75m (width x height) and was anchored in front of the virtual desk at approximately 1.4m height. One of three virtual cylinders was displayed randomly according to the participant's current task. These cylinders were of size 0.5m x 0.5m x 1m and were each positioned 2m away from the desk. An overhead view of the environment is shown in figure 3.

3.4 Tasks

For each of the four conditions described in section 3.1, participants were required to complete five practice trials and ten test trials. The practice trials were meant to help the participant accustom themselves to the new visual information for the condition under test and to familiarize themselves with trial requirements before performing the timed test trials. A trial consisted of five separate tasks that needed to be completed in sequence.

The first task is referred to as the **keyboard homing** task, where the participant was required to place their hands on the keyboard in the standard home position for touch typing (i.e., with left and right index fingers on top of the 'F' and 'J' homing bars respectively). The participant was then prompted to press 'F', followed by 'J', and then 'space' on the keyboard to complete the keyboard homing task. This task was meant to ensure the participant located the physical

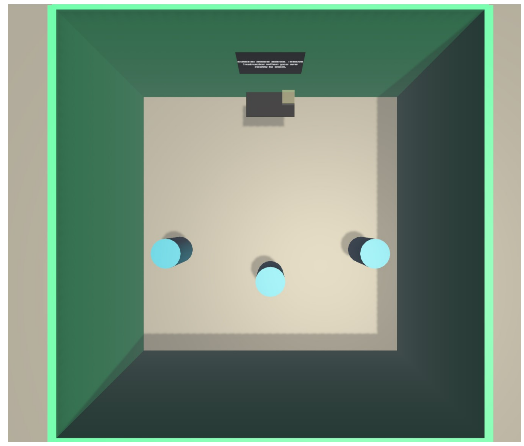

Figure 3: Overhead view of the experiment's virtual environment containing the display, desk with controller dock, and the three cylinders in their respective spawn locations.

position of the keyboard and found the homing bars of the keyboard before starting to type, and it allowed us to precisely measure the keyboard homing time.

Following the keyboard homing task was the **text entry** task, where a word from MacKenzie and Soukoreff's phrase sets [18] was displayed on the virtual screen above the desk, and the participant was asked to type the word. Sixty words from 12 separate phrases were used with an average length of 4.92 characters, of which 49 were unique between phrases selected. With each correct keypress, the corresponding character from the displayed word was removed, until the word was typed completely. Incorrect keypresses did not change the displayed word and did not need to be deleted by the participant. The complete entry of the word ended the text entry task.

Next, in the **controller homing** task, the participant was required to pick up the controller from the controller dock on the top-right corner of the desk. The participant then had to press the menu and trigger buttons simultaneously in order to 'unlock' the controller before the next task would start. This task served to have the participant interact with a different device, such that they removed their hands from the keyboard, and it also allowed us to measure the controller homing time (the time taken to pick up the controller and position the hand appropriately to use its buttons), as a comparison to keyboard homing time.

Next, in the **cylinder touch** task, the participant had to turn around to locate a virtual cylinder behind them. To complete the cylinder touch task, the participant walked with the controller to a cylinder that would spawn in one of three locations (see Figure 3). By touching the top of the cylinder with the controller, the participant removed the cylinder from the environment. This task was meant to have participants turn and walk away from the desk area, such that they no longer were stationed by the keyboard so that they would need to re-home to the keyboard for the next trial.

Finally, the **controller dock** task required the participant to turn around again and walk the controller back to the desk, placing the controller in a highlighted virtual dock at the top-right corner of the desk. The trial ended when the system determined the controller was placed within the virtual dock and the controller was stationary for 0.5s. This task served to terminate the current trial and start the next trial for the participant without having their hands immediately on top of the keyboard to start the homing task.

3.5 Design

The experiment had a within-subjects design, where each participant was required to complete practice and test trials for each of the conditions. We counterbalanced condition order using a Latin square, with the text entry words and cylinder positions for the text entry and cylinder touch tasks remaining in the same order regardless of starting condition. In total, each participant completed 20 practice trials and 40 test trials during the experiment.

The independent variable in the experiment was the visual information condition. Dependent variables were times for task completion within each trial (i.e., keyboard homing time, typing speed, and controller homing time), typing error rate, and subjective ratings of the condition via the User Experience Questionnaire - Short (UEQ-S) [27] and NASA Task Load Index (NASA-TLX) [12]. Times for task completion were measured automatically by the system. The error rate was determined via data logged by the system. UEQ-S and NASA-TLX values were on a seven-point Likert scale, reported for a given condition at the conclusion of its ten test trials.

3.6 Participants

Twenty participants took part in the experiment. Participants were recruited from undergraduate computer science classes and received extra credit for their participation. The ages of participants ranged from 19 to 28 years (M=21.1, SD=1.95), and three participants were female. These participants met the following eligibility criteria from a pre-screening form: they were 18 years of age or older, fluently proficient in the English language, had perfect or corrected vision, and had a minimum typing speed of 30 words per minute (WPM), which participants reported after completing a provided online typing test. Fifteen participants reported typing speeds of more than 50 WPM; three participants reported typing speeds between 40-50 WPM; two participants reported typing speeds between 30-40 WPM. Two participants indicated that they had never used VR, while eight had used VR once or twice, seven had used VR three to ten times, and three had used VR more than ten times. All participants were right-hand dominant. The study was approved, as required, by our local Institutional Review Board.

3.7 Procedure

Each participant completed three phases of the experiment: pre-study, study, and post-study. In the pre-study phase, the participant was given an informed consent document to read and sign, and then filled out a background questionnaire, which recorded information regarding the participant's gender, age, dominant hand, and experience using VR. The participant was then informed of the purpose of the study and introduced to the HWD and the handheld controllers used for the duration of the experiment. The investigator then described the tasks (section 3.4) that the participant would complete during the study session.

In the study phase, the participant put on the HWD and adjusted it to their preference on their head. The participant then completed trials in one of the four conditions, as described in section 3.1, for three modes: tutorial, practice, and test. In the tutorial mode, the investigator informed the participant of the condition under test and encouraged the participant to observe the visual information provided by the condition. The participant indicated verbally when they were comfortable with the condition. Next, the investigator instructed them to calibrate their hand position on the physical keyboard by pressing the 'J' key with their right pointer finger. In conditions where the participant was unable to see their hands (i.e., NONE and KEYBOARD), the investigator would inform them of their pointer finger's location on the keyboard until they located the homing bar atop the 'J' key. After completing this calibration, they were instructed to place their hands at their sides to move on to the practice mode.

In the practice mode, participants completed five trials, as described in section 3.4. The investigator instructed the participant to ask questions regarding task completion requirements as necessary but to otherwise complete the tasks as quickly as possible. When the participant indicated they were ready, the investigator started the tasks in practice mode. After completing the five trials, the participant notified the investigator and was instructed to place their hands at their sides to move on to the test mode.

In the test mode, participants completed ten trials. The investigator instructed the participant to complete the tasks as quickly as possible. When the participant indicated they were ready, the investigator started the tasks for test mode. After completing the ten trials, the participant notified the investigator and was instructed to remove the HWD. The participant then filled out a UEQ-S and NASA-TLX form regarding the condition tested and were given a break. Once they were ready, the participant would repeat the study phase again for the next condition until all conditions were tested.

In the post-study, the participant was interviewed regarding the conditions tested. The interview was audio-recorded and had the participant rank the conditions from their most preferred to their least preferred. They were then asked to provide explanations behind their ranking of each condition. The entire study session took approximately 60 minutes for each participant to complete.

4 Results

We tested our hypotheses with various analyses using the data collected during our study. In order to determine which analyses to perform, we first used a Shapiro-Wilk test for normality. When the result for the Shapiro-Wilk test was $p \leq 0.05$ or was qualitative data gathered from questionnaires and recordings, we conducted a Friedman test followed by a Wilcoxon signed-rank test using Bonferroni corrections for paired significance comparisons. When the result for the Shapiro-Wilk test was $p > 0.05$, we performed a one-way repeated-measures ANOVA (RM-ANOVA) followed by a t-test using Tukey-Kramer HSD corrections for paired significance comparisons. For all significance comparisons, we used an α value of 0.05.

4.1 Homing Time

Figure 4a shows the time taken by participants to complete the keyboard homing task for each condition. The PASS-THROUGH condition took the least amount of time (M=2.10, SD=0.52), followed by KEYBOARDHANDS (M=2.59, SD=0.79), then KEYBOARD (M=3.71, SD=1.35), and finally NONE (M=4.48, SD=1.56). Test statistics via the Friedman test detected a significant effect of condition on keyboard homing time ($\chi^2(3) = 34.380, p < 0.001$). The paired Wilcoxon signed-rank tests revealed that the PASS-THROUGH condition took significantly less time for participants to complete compared to the NONE ($Z = -3.920, p < 0.01$), KEYBOARD ($Z = -3.808, p < 0.01$), and KEYBOARDHANDS ($Z = -3.808, p = 0.018$) conditions. The KEYBOARDHANDS condition also took significantly less time for participants to complete compared to the NONE ($Z = -3.621, p < 0.01$) and KEYBOARD ($Z = -3.136, p = 0.012$) conditions. We did not detect a significant difference between the KEYBOARD and NONE conditions.

Figure 4b shows the time taken by participants to complete the controller homing task for each condition. We combined the NONE and KEYBOARD conditions, as they shared the same visual feedback (i.e., no hand representations) for the controller unlock task. The PASS-THROUGH condition took the least amount of time (M=1.76, SD=0.34), followed by KEYBOARDHANDS (M=1.91, SD=0.51), and finally NONE/KEYBOARD (M=1.92, SD=0.47). An RM-ANOVA did not find a statistically significant effect of condition on controller homing time.

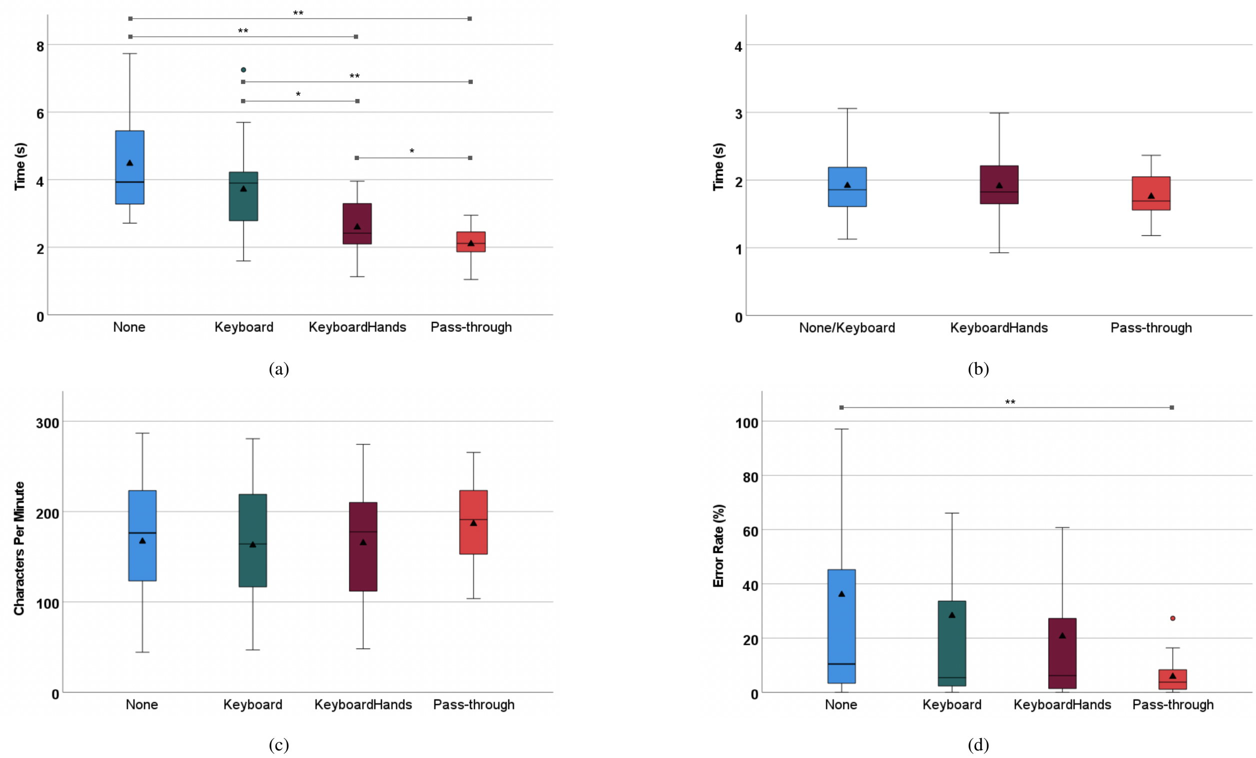

Figure 4: Box plots of homing time and typing metrics. Pairs that are significantly different are marked with * when $p \leq 0.05$ and ** when $p \leq 0.01$. Mean values are marked with a triangle; median is represented by the bar. The box is the interquartile range. The whiskers are the spread of the data (without outliers). (a): Time in seconds to complete the **keyboard homing** task per condition. (b): Time in seconds to complete the **controller homing** task per condition. (c): **text entry rate** in characters per minute per condition. (d): **Error rate** per condition.

4.2 Typing Metrics

We calculated two typing metrics from the data collected during the experiment: typing speed (measured in characters per minute, or CPM) and error rate (ER). For CPM, we altered the WPM formula specified by Arif et al. [1] by removing the 0.2 multiplier (for average word length) and omitting the -1 deduction from the length of the word, as the first keypress which starts the timer for the text entry task takes place in the preceding keyboard homing task. We detail our CPM formula as follows: $CPM = \frac{|T|}{S} * 60$. $|T|$ is the length of the word, S is the time taken in seconds from the first to the last keypress, and 60 is the number of seconds per minute. Figure 4c shows the CPM values by condition. The PASS-THROUGH condition had the highest CPM (M=186.63, SD=46.49), followed by NONE (M=167.04, SD=69.47), then KEYBOARDHANDS (M=165.23, SD=68.33), and finally KEYBOARD (M=162.74, SD=71.26). An RM-ANOVA did not find a statistically significant effect of condition on CPM.

For ER, we used the formula defined by Arif et al. [1]: $ER = \frac{INC}{|T|} * 100\%$. INC is the total number of incorrect characters typed by the participant. The ER percentages by condition are shown in figure 4d. The PASS-THROUGH condition had the lowest ER (M=5.79, SD=6.75), followed by KEYBOARDHANDS (M=20.66, SD=34.51), then KEYBOARD (M=28.25, SD=45.81), and finally NONE (M=36.01, SD=55.93). Test statistics via the Friedman test detected a significant effect of condition ($\chi^2(3) = 11.954, p = 0.008$). The paired Wilcoxon signed-rank tests revealed that the PASS-THROUGH condition had a significantly lower ER percentage compared to the NONE ($Z = -3.379, p < 0.01$) condition. No other significantly different pairs were detected.

4.3 Workload and User Experience

Figure 5 shows a bar chart of the NASA-TLX questionnaire results for each sub-scale per condition. Wilcoxon signed-rank tests were conducted for each sub-scale to test differences. The PASS-THROUGH condition had a significantly lower Mental Demand than the NONE ($Z = -4.174, p < 0.01$) and KEYBOARD ($Z = -3.665, p < 0.01$) conditions. The KEYBOARDHANDS condition also had a significantly lower Mental Demand compared to the NONE ($Z = -2.653, p = 0.0480$) condition. None of the compared pairs showed significance in their Physical and Temporal Demand values. The PASS-THROUGH condition had a significantly greater Performance value than the NONE ($Z = -2.639, p = 0.0498$) and KEYBOARD ($Z = -3.186, p < 0.01$) conditions. The Effort value was significantly lower for the PASS-THROUGH condition compared to the NONE ($Z = -2.984, p = 0.0168$) and KEYBOARD ($Z = -2.992, p = 0.0168$) conditions. Finally, the Frustration value was significantly lower for the PASS-THROUGH compared to the KEYBOARD ($Z = -2.941, p = 0.0198$) condition.

Figure 6 shows a bar chart of the UEQ-S questionnaire results for each sub-scale per condition. Wilcoxon signed-rank tests were conducted for each sub-scale to test differences. The PASS-THROUGH condition had a significantly greater Pragmatic score than the NONE ($Z = 4.726, p < 0.01$) and KEYBOARD ($Z = 4.229, p < 0.01$) conditions. The KEYBOARDHANDS condition also had a significantly greater Pragmatic score compared to the NONE ($Z = -2.809, p = 0.030$) condition. Test statistics revealed no significant differences between condition pairs for their Hedonic scores.

4.4 Preferences

The participants ranked the conditions from first (best) to fourth (worst) according to their experience in completing the tasks, as

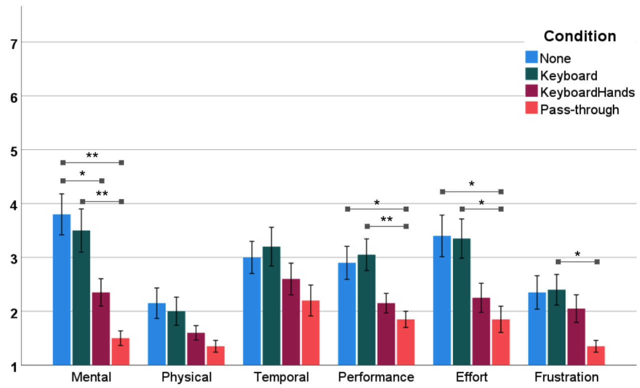

Figure 5: NASA-TLX ratings per condition ($\pm S.E.$).

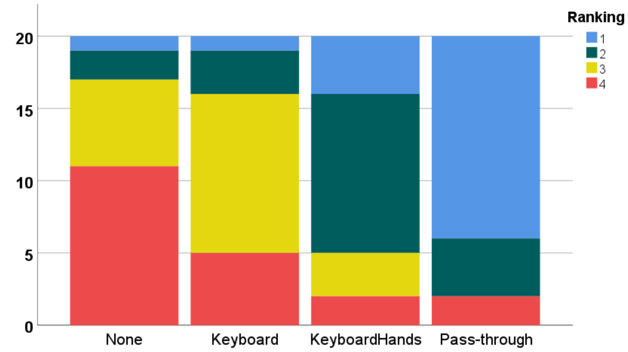

Figure 7: Preference rankings from 1 (best) to 4 (worst).

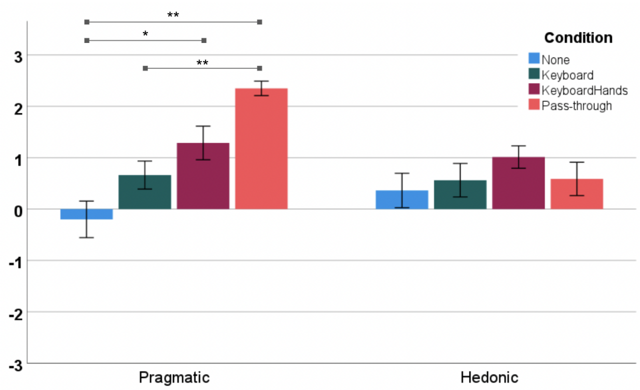

Figure 6: UEQ-S ratings per condition ($\pm S.E.$).

shown in figure 7. The PASS-THROUGH condition was rated first by 14 participants, second by four participants, and fourth by two participants. The KEYBOARDHANDS condition was rated first by four participants, second by 11 participants, third by three participants, and fourth by two participants. The KEYBOARD condition was rated first by one participant, second by three participants, third by 11 participants, and fourth by five participants. The NONE condition was rated first by one participant, second by two participants, third by six participants, and fourth by 11 participants.

5 Discussion

We hypothesized that participants would take significantly less time to place their hands on the homing bars of a keyboard as the fidelity of visual representations of the keyboard and hands in VR increased (**H1**). Our results support **H1**, as all pairs showed significantly lower keyboard homing times for the higher-fidelity visual representations of the keyboard and hands, with the exception of the NONE condition compared to the KEYBOARD condition. Although all users were able to complete the task in all conditions, visual feedback proved crucial in more quickly completing the homing activity. We believe this is due to the visual feedback reducing participant dependence on other sensory modalities. These dependencies were greatest in the NONE condition, where participants had to spend more time finding the keyboard, moving their hands without visual representation, and relying on haptic feedback to determine if they found the homing keys, with P5 describing the absence of visual feedback as feeling like they were *"grabbing at nothing"*. The KEYBOARD condition reduced time spent finding the general location of the keyboard, but still relied heavily on participant proprioception and haptic feedback to confidently determine if their hands were correctly on the homing keys, with P7 stating the lack of hand position visual feedback in KEYBOARD made *"finding the 'F' and 'J' keys difficult"* and P10 explicitly saying it was *"weird to get used to, since no hands made it difficult"*. The KEYBOARDHANDS condition significantly reduced the time spent by the participant to complete the keyboard homing activity, as the addition of hand representations in the VE removed reliance on proprioception and haptics to place their hands properly on top of the keyboard homing bar keys. The real-world view of the participant's hands from the PASS-THROUGH condition further reduced keyboard homing time compared to the KEYBOARDHANDS condition, even though both conditions had hand visualizations. This was attributed by participants to inaccuracies and latency of the virtual hands, with P3 describing the PASS-THROUGH condition as *"no visual glitch between physical and virtual and no delay"* and P4 stating that KEYBOARDHANDS had a *"disconnect due to not being perfect with tracking"*. It could also be partially attributed to insufficient keyboard position calibration, with P1 stating the *"keyboard's physical location did not exactly match the virtual location"* and P12 saying that it was *"hard to calibrate"* the keyboard position.

The combination of visual representations of keyboard and hands was the most important factor in reducing the keyboard homing time. However, this was not the case for the controller homing time, as shown in figure 4b. We attribute this to the controller shape and the simplicity of its button layout compared to the keyboard. Seeing the controller's location (through its virtual representation or the pass-through video) is sufficient to be able to place one's hand on the controller through proprioception. Once the hand is on the controller, the controller's shape naturally guides the hand into the right position when it is picked up. Unlike the keyboard, which has 98 identically shaped and densely packed keys, the controller only has five sparsely distributed, differently shaped buttons on different surfaces. Thus, if the user is holding the controller correctly, it is trivial to find the desired button. The overall effect is that keyboard homing requires a high-quality visual representation of *both* the hands and the keyboard, while a simple visual representation of the controller's location is all that is needed for controller homing.

Our second hypothesis proposed that experienced typists would have similar typing performance regardless of the fidelity of visual representations of the keyboard and hands in VR (**H2**). Our results support **H2**, as no significance in the CPM metric was found, matching similar results in hand representation studies for experienced typists [10, 15], and all but one of the paired comparisons of ER percentages were not found to be significant. Of course, lack of statistical significance is not the same as equivalence, but the contrast between these results and the results for homing time does constitute evidence that visual feedback matters far less for typing than it does for homing. However, there was a significantly higher ER value for the NONE condition compared to the PASS-THROUGH condition. We attribute this increase in ER to participants misplacing their hands while typing a word during the text entry task. P3 explained in detail that *"if it was a long word which I crossed my fingers for any of the letters, it made it even more difficult, since I'd look down to see where some letters were in the middle and I couldn't"*, causing them to mistype until they re-positioned their hands on top of the 'F' and 'J' homing bars. P20 described the advantage of having higher fidelity visual representations when discussing the PASS-THROUGH condition, stating that *"even if I made an offhand slip, I could see the actual letter and actual positioning"* to correct their hand positioning on the keyboard. This finding is similar to the results reported by Grubert et al., where significant differences in ER only existed when using no hand representation [10].

Finally, we hypothesized that participants would have an improved user experience as the fidelity of visual representations of the keyboard and hands in VR increased (**H3**). Combining the results of the participant post-study interview rankings with the UEQ-S and NASA-TLX responses, we believe our results support **H3**, albeit with some interesting exceptions. From our post-study interview with participants, the rankings of conditions reflected the importance of fidelity of the keyboard and hands representations. PASS-THROUGH was ranked first by 70% of the participants, and the median ranks for KEYBOARDHANDS, KEYBOARD, and NONE were 2, 3, and 4 respectively. Reviewing the UEQ-S responses, we found statistical significance between condition pairs in the Pragmatic subscale, with the PASS-THROUGH receiving a higher score than the NONE and KEYBOARD conditions. The KEYBOARDHANDS pragmatic score was significantly higher than the NONE condition. Both PASS-THROUGH and KEYBOARDHANDS had the practical benefit of visual representations of the participant's hands, allowing users to directly visualize the spatial relationships between their fingers and the keys. P9 described this, stating that it was *"easy to see"* their hands in the PASS-THROUGH condition and that although their *"fingers weren't correctly located"* all the time in the KEYBOARDHANDS condition, it *"was good"* to have them, stating that the KEYBOARD and NONE conditions made it such that they *"could not find specific spots"* on the keyboard. The NASA-TLX survey results further support **H3**, as we found statistical significance between condition pairs in the Mental Demand, Performance, Effort, and Frustration sub-scales. The workload was reduced as the fidelity of visual representations of the keyboard and hands increased and was significant for PASS-THROUGH compared to NONE and KEYBOARD conditions, as well as for the KEYBOARDHANDS condition compared to the NONE condition. Like the UEQ-S responses, we credit this to the benefits of hand visualizations, which provide a practical benefit in completing tasks and reducing the overall workload.

Still, not all participants preferred the higher-fidelity conditions. Open comments from participants provided insight as to their reasoning in cases where they chose lower-fidelity conditions as their most preferred conditions. P6 stated they did not like higher-fidelity conditions as it felt like they were *"cheating"* and they *"liked the added challenge"* of not seeing their hands, and P18 described they felt that they were *"able to type better for some reason"* with lower-fidelity conditions. Additionally, the Hedonic sub-scale of the UEQ-S did not show any statistical significance between condition pair scores, indicating that users did not necessarily enjoy the higher-fidelity visual representation conditions more than the lower-fidelity ones. It is interesting to note, however, that the KEYBOARDHANDS condition did have the highest overall Hedonic score, as shown in figure 6. Open comments from participants provided insight as to why the KEYBOARDHANDS condition scored higher, with P6 saying that *"virtual hands were exciting and helped with finding the keyboard and gave confidence for grabbing the controller"*. Participants also described that the higher-fidelity condition of PASS-THROUGH was familiar and not exciting, with P16 referring to the PASS-THROUGH as *"conventional"* and P11 stating the PASS-THROUGH condition was worse comparatively since the *"styles were conflicting"* between the virtual and physical world. We believe this could be further explored in future work, where we would test additional hand representations and their impact on user embodiment and presence.

Overall, we learned that the PASS-THROUGH condition was the best in terms of homing activity performance and user preference. We expected this result, as the PASS-THROUGH condition provided the highest-fidelity representation of the keyboard and user's hand position compared to the other conditions, making it easiest for them to perform the study tasks. However, the KEYBOARDHANDS was more exciting to users, although calibration issues and less-precise fingertip positioning were limitations that kept it from reaching its full potential. Future work should confirm whether improved hand tracking might change the performance and/or preference results for KEYBOARDHANDS. Finally, no difference in homing activity time and user preference were observed between the NONE and KEYBOARD conditions across the measured results. This suggests that users need visual feedback on both hand and keyboard positions for homing in VR; proprioception and haptics are not sufficient.

5.1 Limitations

Our work had several limitations. First, the HWD hand-tracking cameras from Ultraleap are reported to have inaccuracies in virtual fingertip placement on a given target [26]. P9 and P10 noted this, stating that their virtual hands were *"not correctly located, but were good"* and *"sometimes a little off, but helpful"*. A second limitation was that the virtual keyboard location calibration was performed by the user, requiring multiple attempts at times to calibrate successfully. Automating this process could potentially impact the frustration participants reported for the KEYBOARD and KEYBOARDHANDS conditions. Third, the HTC Vive Tracker used to initially position the virtual keyboard and desk has been found to have position inaccuracies in the order of several millimeters [2]. These slight position variances could influence the user's experiences with the KEYBOARD and KEYBOARDHANDS conditions across measurements. Finally, the typing performance measurements were based on a small amount of data, as we only prompted users to type one word at a time. By extending to entire phrases, it is possible we would have found more significant differences in CPM and ER values.

6 Conclusions & Future Work

We have studied the effect of different visual representations of the keyboard and participants' hands on intermittent typing in VR. We found that as the fidelity of visual representations of the keyboard and hands in VR increased, the time taken by participants to place their hands in the home position on the keyboard was reduced significantly. We also found that users preferred the higher-fidelity conditions overall, and they reported improved user experience and reduced workload in these conditions. Our findings underline the importance of good visual feedback for both hands and physical devices when users must often switch between hand-operated devices in VR.

In the future, we envision having more input devices for the user to interact with, such that we could analyze homing time taken across multiple devices. Another consideration would be the relocation of the physical keyboard as the user completes the controller task, such that they would need to find and complete the homing activity with the keyboard in another location within the VE. Finally, we would like to investigate different virtual hand models, including higher polygon, realistic virtual models, and video see-through hands in the VE, to find if there are any changes in user preference and homing task performance.

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