Investigating a Combination of Input Modalities, Canvas Geometries, and Inking Triggers on On-Air Handwriting in Virtual Reality

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Humans communicate by writing, often taking notes that assist thinking. With the growing popularity of collaborative Virtual Reality (VR) applications, it is imperative that we better understand aspects that affect writing in these virtual experiences. On-air writing in VR is a popular writing paradigm due to its simplicity in implementation without any explicit needs for specialized hardware. A host of factors can affect the efficacy of this writing paradigm and in this work, we delved into investigating the same. Along these lines, we investigated the effects of a combination of factors on users' on-air writing performance, aiming to understand the circumstances under which users can both effectively and efficiently write in VR. We were interested in studying the effects of the following factors: 1) input modality: brush vs. near-field raycast vs. pointing gesture, 2) inking trigger method: haptic feedback vs. button based trigger, and 3) canvas geometry: plane vs. hemisphere. To evaluate the writing performance, we conducted an empirical evaluation with thirty participants, requiring them to write the words we indicated under different combinations of these factors. Dependent measures including the writing speed, accuracy rates, perceived workloads, etc. were analyzed. Results revealed that the brush based input modality produced the best results in writing performance, that haptic feedback was not always effective over button based triggering, and that there are trade-offs associated with the different types of canvas geometries used. This work attempts at laying a foundation for future investigations that seek to understand and further improve the on-air writing experience in immersive virtual environments.

CCS Concepts: • **Human-centered computing** → *Displays and images*; **Virtual reality**.

Additional Key Words and Phrases: virtual reality, writing, interfaces, interaction, text entry

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1 Introduction

The evident rapid surge and commercialization of Virtual Reality (VR) devices is making the technology increasingly accessible to users around the world. Commercial Head-Mounted Displays (HMDs) like the Oculus

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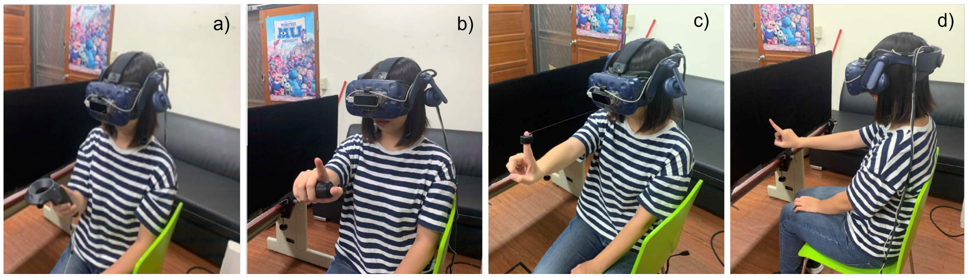


Fig. 1. Writing in VR (a) when using the brush or raycast input modalities (b) by making a pointing gesture while holding down a button to trigger ink. (c) with a non-extendable string used to provide haptic feedback in the gesture-haptic-hemisphere condition. (d) using an acrylic board covered by a black light-absorbing cloth set to provide haptic feedback in the pointing-haptic-plane condition.

Rift, Oculus Quest and the HTC Vive have hence started to see a large increase in demand over the last few years. This growth in the popularity has led to VR applications being integrated into a variety of areas like gaming [13], training [22], therapy [47], education [8], driving simulators [45, 46], etc. Moreover, with modern workplaces transitioning to a more online or virtual setting, VR technology is now being applied to collaborative contexts where users share a virtual space and can work together thus bridging the gap of geographical barriers. Consequently, there has been an increased demand for such collaborative applications like Mozilla Hubs and AltSpaceVR. In such contexts and many others, users are often required to write or input text in the virtual environment, usually facilitated by a virtual keyboard to select keys or buttons sequentially. Along these lines, several keyboard interaction paradigms have been implemented and further evaluated in terms of users' typing performance. As such, text entry is becoming more commonplace in state of the art VR applications.

While virtual keyboard based text entry may be effective and successfully implemented in a variety of VR applications, there may be certain cognitive benefits to handwriting which may not be fully retained in keyboard style typewriting [34]. Memory has been shown to be better for words that have been handwritten than when typed [39]. The meaningful coupling between action and perception during handwriting establishes sensory-motor memory traces that facilitate written language acquisition [28]. Moreover, handwriting offers a more personalized text entry method than the use of standard fonts with a virtual keyboard and may support easier methods to sketch specialized symbols and notations over searching in a virtual keyboard. In VR, handwriting can either be supported using a stylus-tablet paradigm or a completely virtual paradigm where writing is performed on air either using controllers or tracked hand gestures. Holding a pen/stylus and writing on a physical surface provides users with an ergonomic and intuitive experience when it comes to writing and can be considered the de-facto standard as it is one that users are relatively familiar with. It also allows for high precision grip and has been shown to be more accurate for selection and pointing tasks in virtual and augmented reality environments [36]. While such interfaces have been successfully employed for writing in virtual worlds, it presents a more expensive approach due to the need for specialized tablets and pens that support this form of interaction. Moreover, this paradigm can fall prey to latency issues that crop up in integrating these hardware devices with the virtual experience. The latter approach wherein users write on air (without the need for auxiliary hardware) does away with these concerns, providing users with a more fun and engaging experience while also establishing sensory-motor traces that support better written language acquisition [12, 28]. This paradigm of handwriting remains relatively unexplored from a user performance and experience related standpoint. Google's Tilt Brush is one such popular sketching application that currently finds its place as a contemporary immersive 3D sketching and modeling tool in VR [25]. Applications of this sort afford immersive writing and sketching on a

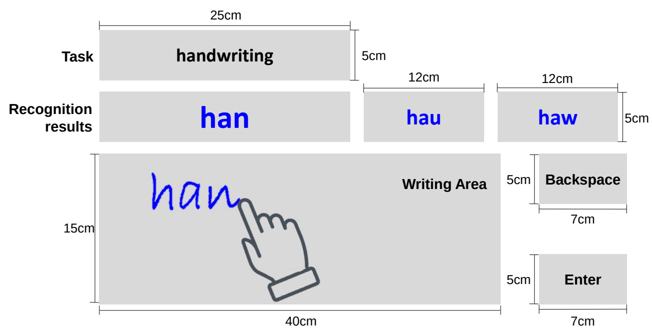


Fig. 2. Schematic representation of input writing system

three dimensional level wherein users are not constricted to write or draw on a virtual canvas, but can instead do so freely in three dimensional space. There also exists other on-air writing paradigms that afford immersive sketching and modeling, constricting the user to perform sketching on a virtual canvas usually presented in, but not restricted to two dimensions. As such, virtual spaces allowing users to collaborate in VR could benefit from affording interaction metaphors that support writing in VR.

When writing is used to support text entry into a system, it is important for the system to be able to recognize the text accurately. Fu et al. proposed the use of a WiFi based air-writing recognition system to recognize human handwriting in VR [14]. The use of a virtual canvas may be better suited for applications that require text entry because system driven text recognition is likely to be more successful when the text being processed is restricted to a canvas. In implementing on-air writing in VR, several factors may affect the effectiveness and efficiency of writing performance like the geometry of the canvas, the availability of haptic feedback on writing, the method used to ink, etc. Given the lack of work in the literature that has explored on-air handwriting in VR, there seems to be merit in pursuing its investigation accounting for such factors that may potentially affect the efficacy of this paradigm.

2 Related Works

2.1 Interfaces in VR

Various user interfaces that allow for interaction in immersive VR have been extensively studied [4]. Researchers have attempted to design seamless (some even invisible) interfaces for users to manipulate virtual objects, change viewpoints, and execute specific tasks in VR [1, 4, 5, 16, 20]. Two dimensional (2D) interfaces like menus with buttons are non-immersive and are many times associated with poor ergonomic design [20, 26] due to inaccuracies in mapping along each degree of freedom. Dung et al. [43] pointed out that users actually perform many 2D tasks in 3D environments. Since people are used to writing on a planar surface in the real world, it might be that a writing interface in VR should be two dimensional as well. However, considering the ergonomics of users' hand reaching motions forming a hemispherical envelope, it may be advantageous to model the interaction canvas as a hemisphere rather than that of a planar surface. Since distances between the user and different regions of a hemispherical interface are identical, the interface may effectively enhance comfort and reduce dizziness associated with 3D interactions in VR, making for a usable means to support textual input in VR.

2.2 Text Entry in VR

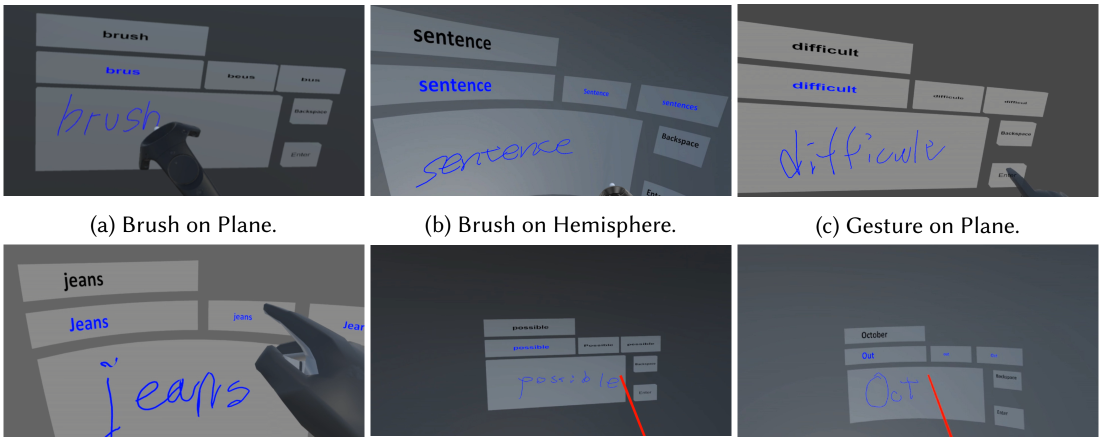
An intuitive technique for text entry in VR is typing on a physical full-sized keyboard. The problem however, is that in IVEs the HMD occludes users from seeing any physical objects thus causing a lack of visual feedback. This in turn has been shown to negatively affect users' typing performance [48]. Furthermore even if a virtual keyboard is provisioned such that it is precisely co-located with the physical keyboard, the resolution of contemporary HMDs like the HTC Vive and Oculus quest are insufficient for users to be able to clearly see the keys, once again making text entry a challenge. Researchers have hence investigated a variety of approaches like blending video of users' hands [35], rendering an inverse kinematic hand model [38], visualizing users' fingertips in VR [17], etc., in attempting to address this issue. Research shows that minimalist fingertip visualization and video inlay approaches significantly reduce text entry error rates but need not increase the speed of users familiar with QWERTY based typing [17]. Other paradigms of text entry involve the the use of gloves [2, 6, 31] which allows for eye-free text entry by touching between hand fingers.

Given that the integration of physical keyboards into VR presents challenges, recent advancements have led to virtual keyboards being used in contemporary VR applications, wherein users select buttons on a virtual QWERTY keyboard. While users type using a virtual keyboard, the provision of live feedback has a crucial impact on the typing performance especially when users don an HMD [32, 48]. In such cases, physical keyboards may not be suitable when standing compared to methods using VR controllers (e.g. pointing or cursor), or no controllers at all (e.g. head pointing [51], FaceTouch [18] or speech [6]). Experiments conducted by Speicher et al. suggests that for text entry, using controllers to point on a virtual keyboard outperforms pad-based cursor controls, be it continuous or discrete [40]. Ray casting using the controller to select buttons allows users type more efficiently [41]. Recent research suggests that different virtual keyboard layouts affect the writing performance [3] and user experience. Recently, Chen et al. [7] described the use of a pressure sensitive touch screen device to input text in immersive VR. While efforts of this sort have shown promise for textual input in VR, handwriting (wherein users input text by explicitly writing out words) may have benefits associated with memory and perception-action coordination that other paradigms do not[28]. This makes it worthwhile to pursue investigations that explore handwriting in VR.

2.3 Handwriting in VR

Although various means for alphanumeric text entry in VR has been extensively reviewed and studied [11], there is very little work that looks into explicit handwriting in VR, let alone in contemporary VR experiences achieved using tracked HMDs. In this line of work, Poupyrev et al. designed and implemented a virtual note taking prototype using a pressure sensitive tablet and sensors [37]. However, tracking issues and high latency coupled with the low-resolution associated with those HMDs made it difficult for users to write effectively. In other work conducted in this area, a proof of concept application was implemented supporting mid air gestures as a means of hand-based writing [42]. However it must be noted that this application did not afford handwriting in the traditional sense where words are explicitly written out in free form. A recent study suggests that text entry in immersive VR is better performed using a virtual keyboard and controllers than when writing using hands [12]. While writing and artistic activities can be successfully supported in VR applications using specialized input devices (stylus+tablet), the accuracy with which users perform such tasks is significantly higher in the real world, highlighting the need for developments that support such fine motor tasks in VR [23]. It stands to reason that the VR community will benefit from explorations that seek to investigate the feasibility of affording free form handwriting interfaces in VR.

While users in the aforementioned studies couldn't write as efficiently as they typed, they found writing with the hands to be more fun and engaging [12]. It seems to follow that studying factors that affect the performance of handwriting in VR is still essential because writing offers a more natural and personalized method of communication. Besides, free form writing also allows users to input symbols, notations and emotions, something they would otherwise have to search for in a virtual keyboard. While the stylus-tablet paradigm of input has been shown to be one that affords high precision and accuracy, its hardware integration, latency and cost related issues make it worthwhile to investigate other means of handwriting in VR. Along these lines, on-air handwriting using readily available commodity hardware (i.e. VR controllers) wherein users write out words



(a) Brush on Plane. (b) Brush on Hemisphere. (c) Gesture on Plane.

(d) Gesture on Hemisphere. (e) Raycast on Plane. (f) Raycast on Hemisphere.

Fig. 3. The virtual world view of the different conditions of the experiment: (a) Brush on Plane, (b) Brush on Hemisphere, (c) Gesture on Plane, (d) Gesture on Hemisphere, (e) Raycast on Plane, and (f) Raycast on Hemisphere.

in 3D space merits investigation seeing as how the literature has remained relatively silent in this area. Such investigations are also relevant given the popularity of VR applications that utilize handwriting as part of the 3D interaction tasks in the VR experience, examples of which include architectural design and annotation [24], and learning to write in a foreign language [50]. We are yet to see a prevalence of work that looks into the factors that support and affect on-air handwriting in VR. With this in mind, we investigated how different input modalities, inking trigger mechanisms, and canvas geometries affect the on-air writing performance and user experience in VR, seeking to contribute to this knowledge base. This work hence sets out to guide VR system designers towards creating more intuitive and comfortable handwriting interfaces in IVEs.

3 System Description

With the overarching goal of studying factors that affect on-air writing in virtual reality, we developed a virtual writing system that supports a variety of interaction mechanisms. By leveraging these metaphors of interaction, we sought to investigate how factors like the geometry of the virtual canvas, the type of ink deployer used and the triggering mechanism affect users' writing performance. In this section, we describe the implementation details and concepts associated with our virtual writing system illustrated in figures 2 and 3.

3.1 Canvas geometry – Hemisphere vs. Plane

The geometry of the canvas pertains to the shape of the virtual canvas that users perform writing on. Although people are used to writing on a planar canvas, research has shown that a curved hemispherical interface may be more user friendly in VR because the interface is implemented along the motion axis [33, 49]. The specifics of the two geometries investigated in this work are detailed below:

3.1.1 Planar Canvas: A planar canvas as the name suggests, involves a geometry that is primitive, taking the form of a two dimensional virtual plane. We provided users with a vertical planar canvas to write in VR. The plane's position and orientation was fixed in the virtual world's coordinate system. Users had to sit on a fixed chair 30 cm away from the center of the planar canvas.

3.1.2 Hemispherical Canvas: In this type of canvas, the surface that is being written on assumes the shape of a section of a hemisphere, making it a curved virtual canvas resembling a curved screen display. The position of the virtual canvas was set up to move with the HMD with its orientation being locked. The radius of the hemisphere canvas was set to 30 cm.

3.2 Input Modality – Pointing Gesture vs. Ray Cast vs. Brush

The input modality pertains to the entity that deploys the ink when writing in VR. Controllers are commonly used to support interaction in VR. However, controllers have a weight associated with them and a shape that may affect their suitability and conduciveness for fine motor interaction in VR. An alternative to support the fine motor action associated with writing in VR is the use of tracked hand gestures. While using one's hand or its associated gestures to deploy ink is not commonplace in the real world, it makes for an interesting investigation seeing as how it frees the user from having to hold a controller to write. Our investigations focused on three different deployer entities, two of which involved the use of an HTC Vive controller, and the other centered around users making a pointing gesture with their hands. The two modalities that featured the controller involved ray casting and a brush based ink deployment approach. A small wrist rotation can create a large stroke in the raycasting approach but a short stroke in the brush modality. Relying on wrist rotation, though labor-saving may demand more precise fine-motor control for writing. In light of this fact, raycast based fine motor interaction has been shown to be challenging [10, 29], despite its usage in a number of applications.

3.2.1 Brush: This modality involves an HTC Vive controller being used as the entity that deploys the ink on to the virtual canvas. The controller is held in the dominant hand and is used as one would a paint brush, resembling Google's Tilt Brush application [25]. Character strokes are co-located with the tip of the controller which is rendered as a capsule.

3.2.2 Ray Cast: The Ray cast modality involves an HTC Vive controller being used as a ray casting entity that deploys the ink onto the virtual canvas. In contrast to the brush input modality, a ray is cast out from the head of the brush. The point at which the ray intersects the canvas is where the ink gets deployed. Users can write on the canvas by manipulating the controller's position and orientation.

3.2.3 Pointing Gesture: This modality involves users making a pointing gesture. The entity that deploys the ink is a virtual hand that is rendered dynamically in real time based on participants' finger motions. We achieved this using a Leap Motion tracking device. With some calibration of the Leap Motion device and the HTC tracker coordinate system, we were able to minimize the offset between the virtual and physical hand location. Through pilots, we determined that tracking the trajectory of the forefinger's tip was best suited for a hand gesture based ink deployment entity, allowing for stable and reliable tracking when users made the gesture of raising only their forefinger (see figure 3(c)).

3.3 Inking Trigger – Button vs. Haptic String

The inking trigger pertains to the trigger event based on which ink is deployed on the canvas. Providing control and feedback during interaction is essential in VR applications [9, 15, 19, 30, 44]. We devised two trigger mechanisms:

3.3.1 Button: In this trigger mechanism, users press and hold down a button to deploy ink. When the button is in its pressed down state, users can write and any movement or stroke of the deployment entity (input modality) is considered to be a segment of handwriting. The button hence affords users the ability to dictate when the ink gets deployed giving them visual feedback whenever they see the inking take place on the canvas. To implement this, we 3D printed an 8-cm tall by 3.2-cm wide plastic cylinder and attached the button and an Adafruit-Feather M0 Wifi module to this cylinder. The Wifi module transmits the button status to the VR system..

3.3.2 Haptic Feedback: In this trigger mechanism, users receive haptic feedback upon which ink is deployed on the virtual canvas. The haptic feedback that we provided was tailored based on the geometries of the canvas described in section 3.1 . We did not provide passive haptic feedback when the brush and raycasting based input modalities were in use. To provide haptic feedback for the planar canvas, we set up a 1-cm thick acrylic board on the desk, as illustrated in figure 1 (c). The board was clamped using three holders to prevent shaking when users touch the board. A virtual board is co-located in VR with the physical acrylic board. When users physically touch the acrylic board, they receive passive haptic feedback upon which the ink is deployed from the deployer. In other words, when the tracked fingertip is on the board, its trajectory is considered to be a segment of the character stroke. Given that the Leap Motion controller is an active tracking device which emits and receives infrared radiation to sense objects, the board was covered with a black light-absorbing cloth to prevent any radiation perturbation reflected from the acrylic board, thus significantly improving the tracking accuracy. To provide haptic feedback for the hemispherical canvas, we adopted Wang et al.'s [49] approach, which constrains the distance between the user's fingertip and the HMD using a thin and non-extendable string. As illustrated in figure 1 (b), one end of the string was attached to the HMD, and the other to the user's fingertip using a velcro strap. Since the distance between the fingertip and the HMD cannot exceed a threshold, an invisible haptic hemisphere can be realized. A virtual hemispherical canvas is co-located with this invisible haptic hemisphere and based on users' fingertip position, ink deployment is triggered when users receive the haptic feedback when stretching the string to its maximum degree, thereby touching the virtual canvas. The fingertip was considered on the canvas if the distance between the fingertip and the canvas is smaller than 0.5 cm. While one can argue that haptic feedback is not exactly a triggering mechanism per se, its manifestation can serve as a trigger by which users are afforded the ability to dictate when inking takes place. In other words, without haptic feedback, ink does not get deployed on the virtual canvas.

3.4 Text Recognition

We operate under the assumption that neat and clear handwriting can be easily recognized by machines. A state-of-the-art handwriting recognition system [27] was used. Whenever users add a stroke in the writing area, the system sends this information (i.e., a stroke or a continuous sequence of strokes) to Google's server using an HTTPWebRequest instance for recognition. The three most likely words are then received by the system within 0.1 seconds and are shown on the top of the panel as illustrated in Fig 2. In VR, participants can thus select the most-likely, second most-likely, or the third most-likely word on the panel. The system was developed to support writing parts of a word in steps such that users could write "univer" and "sity" in two steps to write the word "university".

3.5 Writing Projection

Handwriting in VR is composed of 3D trajectories, which need to be projected on to 2D surfaces before recognition. When users write on a planar canvas with the support of haptic feedback, the projection can easily be achieved because the 3D trajectories are on a vertical plane. However, when users write on a hemispherical surface or without physical support, there is a need to minimize the distortion when projecting these 3D trajectories onto the 2D surface. We individually project each 3D stroke onto a 2D plane, merging the projected strokes by retaining their relative positions, thus minimizing distortions. We apply principal components analysis (PCA) to obtain the projection plane of each stroke. Let c_i^{3D} and c_j^{3D} be the centroids of consecutive strokes i and j, respectively, in 3D, we merge the projected 2D strokes by retaining

$$P_{i,j}\left(\mathbf{c}_i^{3D} - \mathbf{c}_j^{3D}\right) = \mathbf{c}_i^{2D} - \mathbf{c}_j^{2D}, \tag{1}$$

where $P_{i,j} = \frac{1}{2}(P_i + P_j)$, and P_i and P_j are projection functions of strokes i and j, respectively. Each projected stroke is placed according to the position of the previous stroke and the stroke orientation is untouched to prevent the composition distortion of letters.

4 Experiment

4.1 Study Design

In this study, we manipulated the following factors: 1) Input Modality: brush (*Bru*) vs. pointing gesture (*Ges*) vs. near-field raycast (*Ray*), 2) Inking Trigger: button (*But*) vs. haptic feedback (*Phy*), and 3) Canvas Geometry: hemisphere (*Hemi*) vs. plane (*Plan*). Details of these are described in section 3. We employed a 3 x 2 x 2 within-subject design wherein participants wrote under different conditions that featured different levels of the factors manipulated and mentioned above. Out of a total of twelve cell block conditions (3*2*2=12), conditions involving haptic feedback as the ink trigger were not provided for the brush and ray casting input modalities because haptic feedback as a trigger in these conditions typically do not exist. This hence made a total of eight cell block conditions/configurations in our study, the order of which was counterbalanced. The names of the configurations investigated were *ray-button-plane (RayButPlan), ray-button-hemisphere (RayButHemi), brush-button-plane (BruButPlan), brush-button-hemisphere (BruButHemi), gesture-button-plane (GesButPlan), gesture-button-hemisphere (GesButHemi), gesture-haptic-plane (GesPhyPlan),* and *gesture-haptic-hemisphere (GesPhyHemi).* To measure users' writing performance, we used measures such as the number of words written per minute, the time taken to complete the tasks, along with the accuracy of the writing performance. Data on the perceived usability associated with the system was also collected and used in the analyses.

4.2 Research Questions and Hypotheses

We intended to obtain answers to the following questions:

Q1: Which input modality is best suited for on-air writing in VR?
Q2: How does a button based inking trigger mechanism differ from a haptic feedback driven approach?
Q3: How does the canvas geometry affect writing in VR?

For reasons previously discussed, we hypothesize that the brush modality will offer superior performance as compared to the other conditions. For similar reasons of familiarity, we expect users to perform better on the planar as compared to the hemispherical canvas geometry.

4.3 Tasks

An on-air writing task was conducted in the virtual environment wherein participants wrote with different mechanisms based on the cell block condition they were experiencing. The study hence involved users performing the writing task in each of the eight cell block conditions one after another. Each cell block condition was treated as a trial, thus leaving the participant with 8 trials to complete for the successful completion of the experiment. Each trial involved participants writing 33 words (about 200 characters). These 33 words were sourced from a set of the 2000 most commonly used words in English and were used across all the cellblock conditions that a participant experienced. A backspace button was provided to delete the latest stroke. Based on the strokes recognized, the three most likely word suggestions were displayed above the writing panel and could be selected and entered (figure 2). These suggestions would appear in real time based on the Google text recognition API discussed in section 3.4. On average, it took about ten minutes to complete each trial, accruing up to an hour and twenty minutes to complete the writing tasks across all eight cell block conditions. It took participants about one hour and forty five minutes to complete the entire study which additionally included questionnaires and debriefing interviews.

4.4 Participants and Procedure

After conducting an apriori power analysis to determine a sample size using estimates for a repeated measures ANOVA with 8 conditions, 33 words per condition, assuming a small effect size f=0.25, a reasonably medium correlation of 0.50 between measurements, an alpha threshold of 0.05 and power (1-beta) of 0.95, we determined that a sample size of at least 16 participants were required to detect an effect. We managed to recruit a total of 30 (15F,15M) participants for this Institution Review Board (IRB) approved study, which is almost twice the sample size determined by the apriori power analysis. The participant ages ranged from 20 to 29 (M=23.467, SD=2.141). All participants had normal or corrected to 20/20 vision.

Upon arrival to the laboratory, participants were greeted and asked to fill out an informed consent form. After consenting to participate in the study, participants filled out a demographics questionnaire that involved questions on general demographics, VR experience, computer usage per week, etc. There were also questions that asked participants about how often and how competent they were at texting using a writing interface on mobile phones. Following this, participants were briefed about the experiment and asked to report their physical body condition. If any participant felt fatigued or unwell, they were politely encouraged to discontinue the study. Following this exclusion criteria checkpoint, participants proceeded to the VR phase of the study where they began performing the writing task under the eight different conditions.

In each condition/trial, participants first practiced the writing task on a different set of words (6 words) compared to the ones used for analysis. This practice phase allowed for participants to acclimate to that condition for writing. Following this practice phase, they performed the writing task in the respective cellblock condition and upon completion, filled out the NASA TLX questionnaire [21]. Before proceeding to the next condition/trial, it was ensured that participants took a break in an effort to avoid any possible effects of cybersickness or fatigue from carrying over to the next trial. After having finished the task in all eight conditions, participants engaged in a debriefing semi-structured interview that probed into their perceptions of the various conditions.

5 Results

Parametric ANOVA analyses were conducted on the data after carefully verifying that the underlying assumptions were met, i.e., the data in the samples were normally distributed, and error variance between samples were equivalent. We ensured that Box's test of equality of the covariance matrix wasn't significant. Levene's test was conducted to verify homogeneity of variance, and Mauchly's test of sphericity to ensure that the error variance in groups of samples was equivalent. Pairwise post-hoc tests between levels of the between-subjects variables were conducted using Tukey's HSD analysis, and between levels of the within-subjects variables was conducted using Bonferroni's adjusted alpha method. In this section, the terms 'Haptic feedback' and 'Physical' are used interchangeably to refer to the inking trigger based on haptic feedback.

5.1 Speed

5.1.1 Multi-factorial Analysis: The number of words per minute (WPM) was computed across the different cellblock conditions. We first conducted a 3 (input modality) x 2 (inking trigger) x 2 (canvas geometry) unbalanced multi factorial repeated measures univariate ANOVA analysis on speed. Information on multi-factorial quantitative analysis on unbalanced experiment designs that guided our analysis can be found in the following [6, 7, 28]. The ANOVA analysis revealed a significant main effect of input modality, $F(2, 29) = 78.32$, $p < 0.001$, part. $\eta^2 = 0.25$ (figure 4); a significant main effect of inking trigger, $F(1, 29) = 11.82$, $p = 0.001$, part. $\eta^2 = 0.12$ (figure 5); a significant main effect of canvas geometry, $F(1, 29) = 4.82$, $p = 0.029$, part. $\eta^2 = 0.07$ (figure 6). No other main or interaction effects were found.

Post-hoc pairwise comparisons (Bonferroni) revealed that mean WPM was significantly higher in the brush condition (M=10.33, SD=2.0) compared to the pointing gesture condition (M=7.66, SD=2.1) $p < 0.001$ and raycast condition (M=8.21, SD=1.68) $p < 0.001$. Mean WPM in the pointing gesture condition was significantly lower

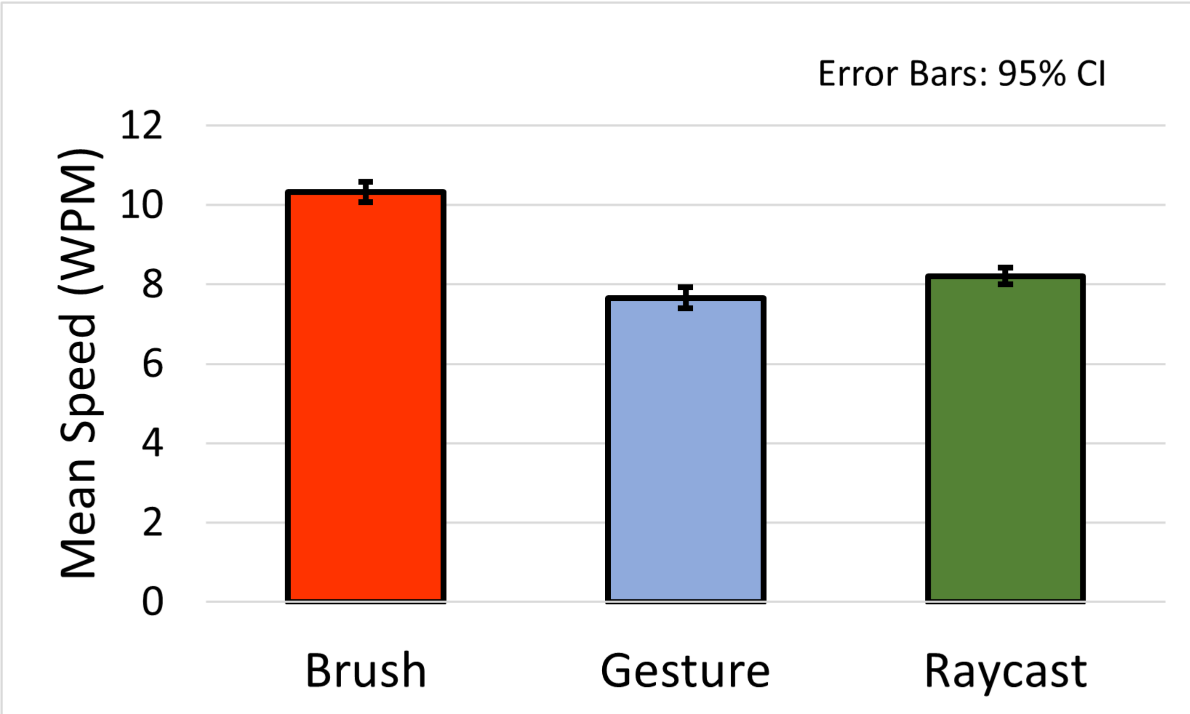


Fig. 4. Graph showing main effect of input modality on the speed of writing.

than the raycast $p = 0.041$ and the brush condition $p < 0.001$. Overall, the mean WPM was highest in the brush condition, lowest in the gesture condition, with the raycast condition in between (figure 4). Post-hoc pairwise comparisons on the inking trigger type (Bonferroni) revealed that the mean WPM was significantly lower in the haptic feedback (M=8.10, SD=2.36) as compared to the button condition (M=8.58, SD=2.21) $p = 0.018$ (figure 5). Post-hoc pairwise comparisons on canvas geometry types (Bonferroni) revealed that the mean WPM was significantly higher in the planar canvas (M=8.67, SD=2.26) as compared to the hemispherical canvas (M=8.26, SD=2.23) $p = 0.022$ (figure 6).

As haptic feedback was only provided for the pointing gesture input modality, we examined this modality more closely by conducting a 2 inking trigger (button vs. haptic feedback) x 2 canvas geometry (plane vs. hemisphere) repeated measures ANOVA analysis in the data from the pointing gesture input modality conditions alone. The ANOVA analysis revealed a significant main effect of inking trigger on speed, F(1, 29) = 10.77, $p = 0.001$, part. η^2 = 0.08. No other main or interaction effects were significant. Post-hoc pairwise comparisons on the inking trigger type using Bonferroni method revealed that mean WPM was significantly higher in the haptic feedback (M=8.10, SD=2.36) conditions as compared to the button conditions (M=7.23, SD=1.69), $p = 0.001$ (figure 9).

5.1.2 Analysis Across All Conditions: We then conducted a one-way within-subjects ANOVA analysis on the 8 conditions in our study's mean WPM data overall, and found the ANOVA analysis to be significant F(7, 203) = 14.94, $p < 0.001$ (figure 7). The brush-button-plane condition had the highest speed, where the WPM was significantly higher than ray-button-plane, ray-button-hemisphere , gesture-button-plane, gesture-button-hemisphere, gesture-haptic-plane, and gesture-haptic-hemisphere conditions ($p < 0.001$). The brush-button-hemisphere condition had the second highest speed, where the WPM in this condition was significantly higher than the ray-button-plane

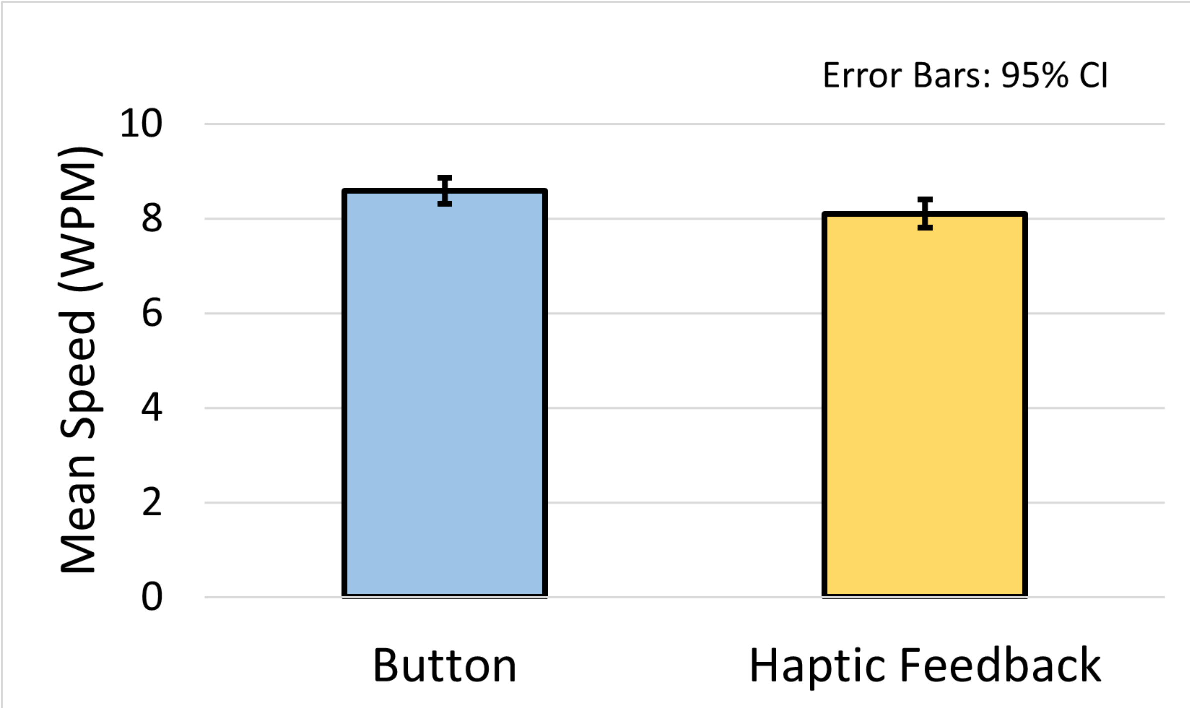


Fig. 5. Graph showing main effect of the inking trigger type on the speed of writing.

($p = 0.015$), ray-button-hemisphere, gesture-button-plane, gesture-button-hemisphere, gesture-haptic-plane, and gesture-haptic-hemisphere conditions ($p < 0.001$). Lastly, the gesture-button-hemisphere condition had the lowest speed overall, being significantly lower than the ray-button-plane $p = 0.046$, brush-button-plane $p < 0.001$, & brush-button-hemisphere $p < 0.001$ conditions.

5.2 Accuracy

5.2.1 Multi-factorial Analysis: The mean accuracy was computed as a percentage for the different cellblock conditions. We conducted a 3 (input modality) x 2 (inking trigger) x 2 (canvas geometry) unbalanced multi factorial repeated measures univariate ANOVA analysis on time in seconds. The ANOVA analysis revealed a significant main effect of input modality , F(2, 29) = 16.42, $p < 0.001$, part. $\eta^2 = 0.12$; a significant main effect of inking trigger, F(1, 29) = 8.08, $p = 0.005$, part. $\eta^2 = 0.076$. No other main or interaction effects were found.

There was a ceiling effect on the accuracy scores overall and the magnitude of effect size was small between conditions. Despite this there were some statistically significant effects between conditions. Post-hoc pairwise comparisons (Bonferroni) revealed that mean accuracy scores in the gesture condition (M=98.43%, SD=2.59) was significantly lower than the raycast (M=99.13%, SD=1.55) $p = 0.006$, and the brush conditions (M=99.50%, SD=0.87) $p < 0.001$. There were no other significant differences between the inking trigger conditions and canvas geometries in terms of accuracy.

As haptic feedback was only provided for the pointing gesture input modality, we again examined this modality more closely by conducting a 2 inking trigger (button vs. haptic feedback) x 2 canvas geometry (plane vs. hemisphere) repeated measures ANOVA analysis in the data from the pointing gesture input type condition only.

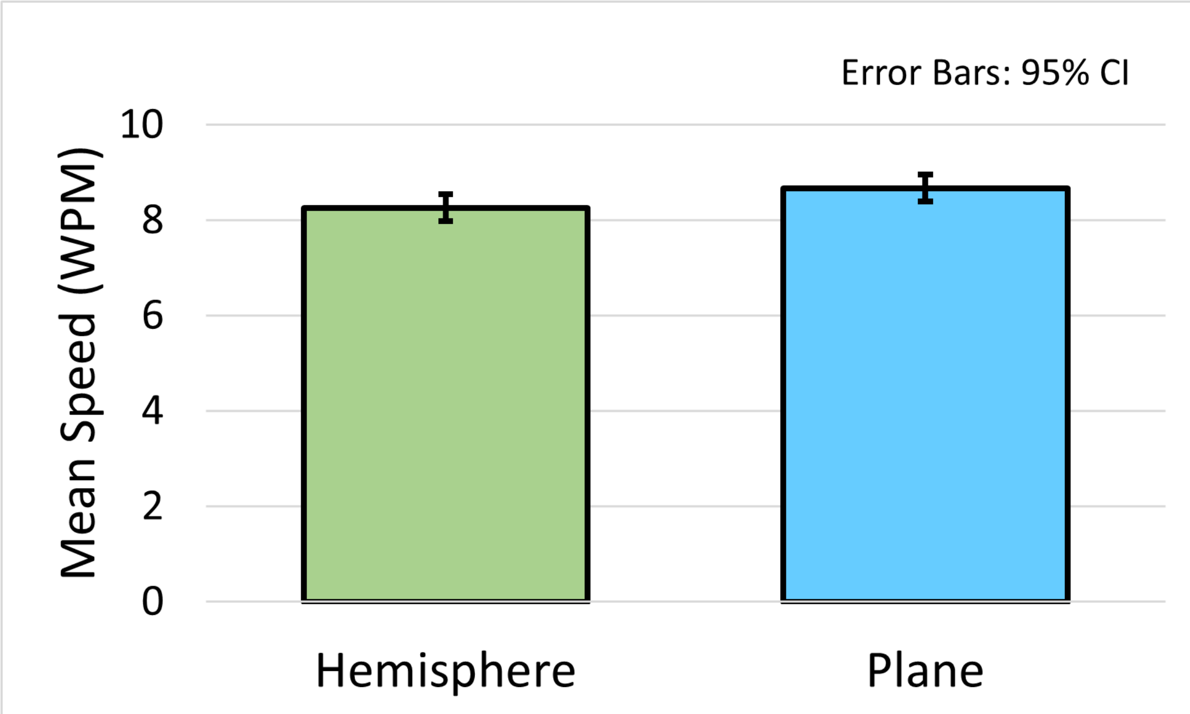


Fig. 6. Graph showing main effect of canvas geometry type on the speed of writing.

The ANOVA analysis revealed a significant main effect of inking trigger, F(1, 29) = 5.013, $p = 0.026$, part. $\eta^2 = 0.045$. No other main or interaction effects were significant. Post-hoc pairwise comparisons on the inking trigger type using Bonferroni method revealed that mean accuracy scores was significantly higher in the haptic feedback (M=98.81%, SD=2.18) conditions as compared to the button conditions (M=98.06%, SD=2.91), $p = 0.026$.

5.2.2 Analysis Across All Conditions: A one-way repeated measures ANOVA analysis on the mean accuracy scores across the different conditions overall, revealed significant differences F(7, 203) = 4.42, $p < 0.001$ (figure 8). Overall, the brush-button-hemisphere condition had the highest accuracy scores and the gesture-button-plane condition had the lowest accuracy scores. Post-hoc pairwise comparisons using the Bonferroni method revealed that the gesture-button-plane condition had significantly lower accuracy scores than the ray-button-plane $p = 0.004$, ray-button-hemisphere $p = 0.027$, brush-button-plane $p < 0.001$, and brush-button-hemisphere $p < 0.001$ conditions.

5.3 NASA TLX:

Users' total workload scores were subjected to a non-parametric Friedman test of difference among repeated measures which rendered a Chi-square value of $X^2(7) = 35.57$ which was significant $p < 0.001$. Post-hoc pairwise comparisons using Wilcoxon signed ranks test with Bonferroni adjusted alpha values based on 8 groups (k related groups) and 28 comparisons (k (k-1)/2) revealed the following significant differences. Overall, the brush-button-hemisphere and brush-button-plane conditions had the lowest overall workload scores, and the gesture-button-hemisphere, gesture-button-plane and gesture-physical-plane conditions had the highest overall workload scores. The brush-button-plane condition (M=32.59, SD=18.05) had significantly lower workload

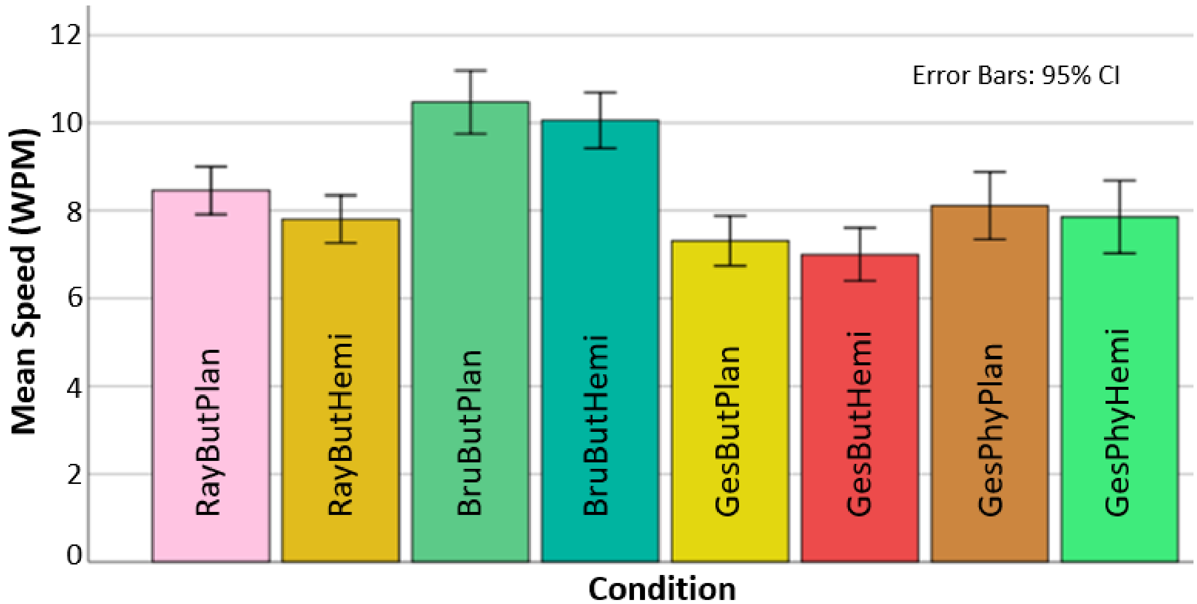


Fig. 7. Mean speed in writing across cellblock conditions.

scores than the gesture-button-hemisphere (M=47.33, SD=22.60) $p = 0.028$, and gesture-physical-plane (M=46.44, SD=20.11) $p = 0.028$ conditions. The brush-button-hemisphere condition (M=32.07, SD=17.70) had significantly lower workload scores than the gesture-button-hemisphere (M=47.33, SD=22.60) $p = 0.005$ and gesture-physical-plane (M=46.44, SD=20.11) $p = 0.024$ conditions. figure 10 depicts these results.

5.4 Interviews

Input Modalities: Users favoured the brush as they felt it was intuitive and easy to learn when compared to the other conditions. Most participants mentioned the relative difficulty associated with the raycasting technique, commenting on the sensitivity, precision, and attention to detail needed in order to write clearly. Many of these participants did however mention that this technique made them feel less dizzy since the canvas was at a comfortable distance and was always in sight, thus not burdening their eyes and neck. Participants in general were clearly not in favor of the pointing gesture, citing fatigue as a reason in addition to tracking inaccuracies and lags. Having to use their hands to both trigger the ink and write simultaneously, was one of the major reasons as to why participants found this technique rather cumbersome.

Inking Trigger: Most users stated that simply holding a button down was an easy way to trigger the ink. They were also receptive and appreciative to the haptic feedback provided by both the acrylic board and the non-extensible string. Some of them were specific in articulating the way they perceived this feedback, going into detail about how it served as a co-requisite of sorts for strokes to appear on canvas. They almost perceived a sense of control such that they knew the inking would begin only when they either, extended their hands far enough to touch the board, or feel the tension in the haptic string. Participants however indicated they had to use it a few times before they got accustomed to using it.

Canvas geometries: Users preferred the planar canvas because they were more familiar with it. They felt that their handwriting was more artistic and personalized when on a planar canvas than a hemisphere. However,

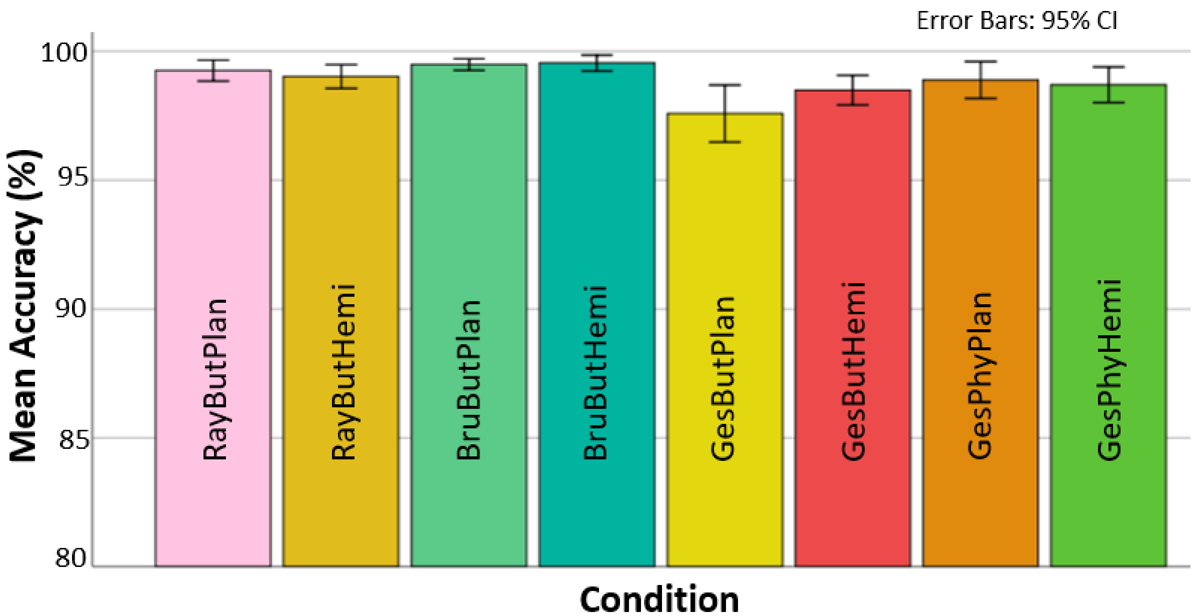


Fig. 8. Mean accuracy scores (%) of writing across the different conditions of our experiment.

participants mentioned that writing on the planar canvas was more pressuring, disorienting, and demanded larger motions than writing on the hemispherical canvas. They took some time to get used to the hemispherical canvas, with many of them even commenting that they were able to see it more clearly especially in areas near the periphery.

6 Discussion

Q1: Which input modality is best suited for on-air writing in VR? While ray casting (controller pointing) was found to be most efficient for selection based text entry in VR [41], objective results from our study were different in that using a brush produced best results in terms of the writing speed (figure 4) and accuracy. However, it must be noted that the aforementioned study focused on selection based textual input which is starkly different from the free form on-air handwriting paradigm implemented in our work. Our results were also buttressed by the comments made by users in the debriefing interviews where they indicated a preference for the brush due to its intuitiveness and low sensitivity to wrist motions. In contrast, the ray casting technique fell prey to sensitivity issues, causing several users to remark about the precision and attention to detail needed to write using this input modality. On the pointing gesture front, users commented that this modality was fatiguing and cumbersome due to the instability in tracking associated with the leap motion controller. This reduced the effectiveness with which users could write because the sensors had to re-calibrate often to accurately track the hands, deterring participants from preferring this modality. Furthermore, analysis of the perceived workload experienced measured using the NASA TLX questionnaire supports comments made by the users about the pointing gesture input modality. Conditions involving the pointing gesture modality were associated with higher workloads than those without. As such, it seems to be the case that the brush based input modality is well suited for on-air writing in VR, supporting our hypothesis developed for the same.

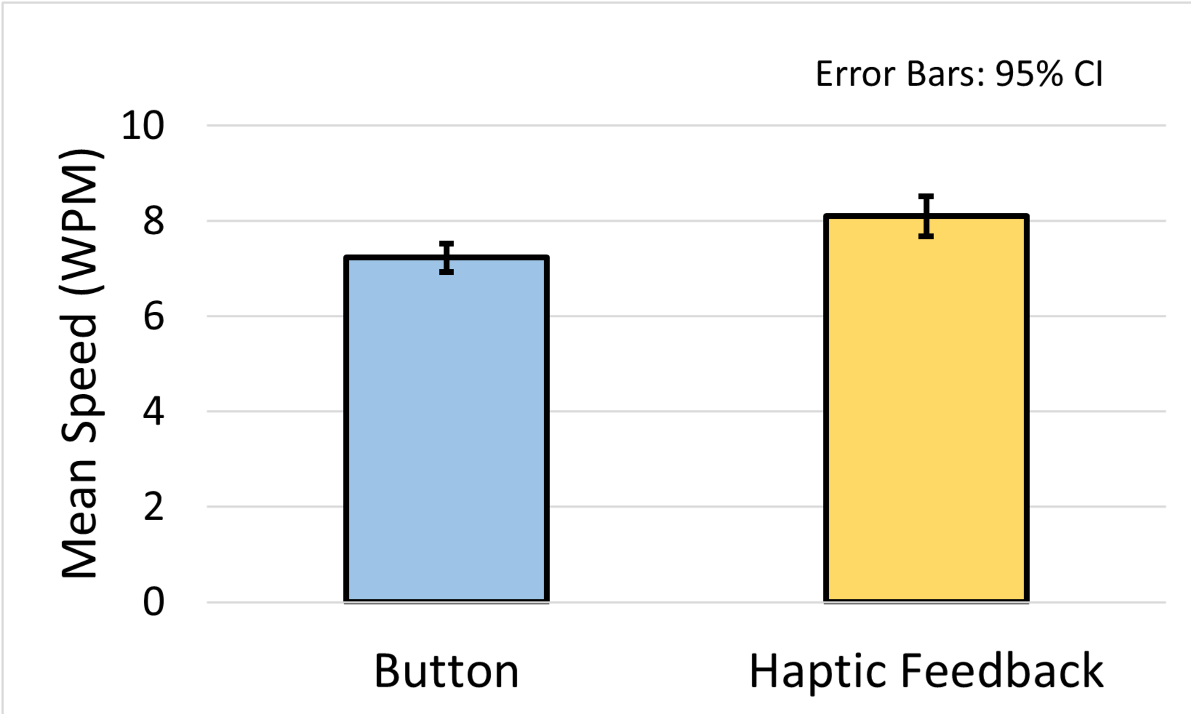


Fig. 9. Graph showing main effect of inking trigger on writing speed for the Pointing Gesture input modality.

Q2: How does a button based inking trigger mechanism differ from a haptic feedback driven approach?
The statistical analysis revealed that the writing speed was significantly slower when haptic feedback was used as an inking trigger as compared to the use of a button to do so. It is important to note that haptic feedback was provided only for conditions that involved the pointing gesture for writing. From the one-way within subjects ANOVA analysis conducted, it appears as though the increased speed associated with the button trigger mechanism could have stemmed from the fact that the brush based input modality afforded higher efficiency and accuracy. This is evident in figure 7 as the brush based button trigger conditions have the highest mean words per minute. We attribute the absence of interaction effects on this front to nature of our cell block conditions being unbalanced. Our results hence seem to suggest that by adopting a good input modality (i.e. brush technique using controller), haptic feedback as an inking trigger may not be necessary to achieve efficient performance of on-air writing in VR. However, more investigations must be conducted to thoroughly investigate the role of inking trigger mechanisms on writing efficacy and efficiency in immersive VR for us to be able to conclusively determine which method is superior.

Q3: How does canvas geometry affect on-air writing in VR?
Data from our study suggests that the geometry of the canvas does affect users' writing performance. These results are not surprising given the fact that almost all participants had no experience with writing on a hemispherical surface. However, this difference in performance was not large. The influence of canvas geometry was smaller than that of the input modality and inking trigger mechanism. It deserves noting that when users were provided with haptic feedback while writing on the plane and the hemisphere, the one-way within subjects ANOVA

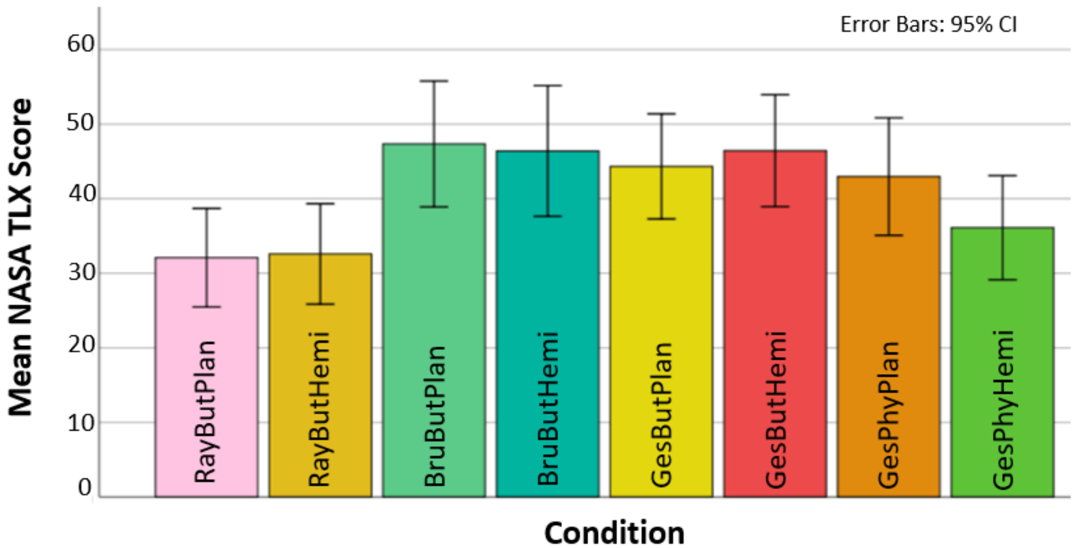


Fig. 10. Average total workload scores in all cellblock conditions

analysis revealed that the mean writing speeds in the pointing gesture-haptic-plane and pointing gesture-haptic-hemisphere conditions were not statistically different. In other words, in the presence of haptic feedback, users performed similarly in writing on the two canvas geometries. Considering the fact that a hemispherical canvas was more visible to participants' eyes, it may be better suited in situations that require a larger use of the entire canvas space. Additionally, the mechanism used to support haptic feedback in realizing a hemispherical canvas is portable and easy to use [49]. Furthermore, users felt that writing on a planar surface was relatively more demanding after a while, suggesting merit in the use of a hemispherical geometry when writing is to be performed for extended periods of time.

Overall, the brush produced the best results in terms of on-air writing in VR. Quantitative analysis and subjective feedback from users implied that stability of the input modality is an important aspect in VR writing. This can be improved by using highly accurate tracking systems that afford users with fine motor control. Its influence was stronger than inking trigger mechanism and canvas geometry because it is difficult to adapt and calibrate to instability. We noticed that participants had a difficulty in triggering the ink using the button when they had to make a pointing gesture. They had to move their forefinger to write while pressing down and releasing the button using their thumb. They commented that this led to tracking and occlusion related issues, making it hard for them to write on the virtual canvas. We hence need to consider the ergonomics and motor control associated with input modalities to ensure that any combination of these modalities with the triggering mechanisms results in effective and efficient handwriting in VR.

7 Limitations

It is important to qualify that our results apply to contexts where users are seated during the experience, opening up further questions about the role of posture and stance in supporting on-air writing in VR. Furthermore, these findings qualify to scenarios that involve an on-air writing interface in users' personal space in which the canvas is presented along the viewing axis with limited width, only requiring subtle head rotation and motion. In this study haptic feedback was not provided for the brush and ray casting input modalities. It hence remains unknown as to what effect this feedback would have on the writing performance when a brush is used, making it important to study the same in future work.

Although our calibration routine was effective in nearly eliminating any mismatch between the virtual and physical pose of the dominant hand, we noted a few limitations. The hand pose tracking required direct line of sight between the leap motion tracker depth cameras and the real hand. Tracking was not truly real-time, and if participants quickly rotated their heads along pitch and yaw axes, there was noticeable latency and jitter between the virtual and physical hand locations. This might be caused by the acquisition delay of the hand during head motion. These limitations may have caused the pointing gesture condition to perform worse than the controller based conditions. It seems to follow that the results obtained in this study apply to gesture based on-air writing supported using popular commodity camera vision based tracking technologies like the leap motion controller which requires line of sight between depth cameras and the real hand. Using high-end gloves or fiducial marker based gestural input devices may offer more accurate and real-time tracking, thus improving the efficacy of gesture based input modalities, an area that requires further investigation.

In this study, the technique used in projecting the three dimensional writing strokes from the hemispherical interface to a flat plane leveraged principal components analysis. This could have potentially caused some distortion that may have affected the recognition performance. Using a conformal mapping technique may have been a more suitable method of mapping these three dimensional writing strokes onto a two dimensional plane, reducing the error in recognition performance. Despite this limitation, we feel that these results are still valid owing to the small amount of surface area associated with the hemispherical canvas. Given that this curved geometry was more in the users' personal space and did not involve curvature subtended by the entirety of a hemisphere, the mapping technique used was still sufficient for projection without much distortion in recognition performance.

8 Conclusion and Future Work

In this work, we examined a combination of different factors that affect the handwriting performance in VR, analyzing writing speeds, accuracy, workload and overall experience associated with these factors. We conducted an empirical evaluation with thirty participants, requiring them to write the words we indicated under different combinations of these factors. Results revealed that the brush based input modality produced the best results in writing performance, that haptic feedback was not always effective over button based triggering, and that there are trade-offs associated with the different types of canvas geometries used. Based on the findings, we discuss some design recommendations and key lessons learned for efficient and effective handwriting in VR.

In future work, we aim to evaluate writing performance on a hand-held canvas as compared to a physically registered passive-haptic canvas with both brush based and pointing gesture based input modalities. We also plan to empirically examine the effects of high fidelity pointing gesture tracked input versus commodity brush based input on writing performance in VR.

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