Shapeshifter: Gesture Typing in Virtual Reality with a Force-based Digital Thimble

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Figure 1: Two users using Shapeshifter to gesture type in virtual reality in four scenarios: (a) on a desk when sitting down, (b) on the lap when sitting down, (c) on the back of the hand when standing up, and (d) on the palm when standing up. Both users are wearing the digital thimble introduced in this paper for gesture detection.

ABSTRACT

Existing text entry techniques for virtual reality are either slow and error-prone, stationary, break immersion, or physically demanding. We present Shapeshifter, a technique that enables text entry in virtual reality by performing gestures and fluctuating contact force on any opaque diffusely reflective surface, including the human body. For this, we developed a digital thimble that users wear in their index finger. The thimble uses an optical sensor to track the finger and a pressure sensor to detect touch and contact force. In a week-long in-the-wild pilot study, Shapeshifter yielded on average 11 wpm on flat surfaces (e.g., a desk) and 9 wpm on the lap when sitting down, and 8 wpm on the palm and back of the hand when standing up in text composition tasks. A simulation study predicted a 27.3 wpm error-free text entry rate for novice users in transcription typing tasks on a desk.

CCS CONCEPTS

• **Human-centered computing** → **Virtual reality**; **Text input**; *Gestural input*.

CHI '22 Extended Abstracts, April 29-May 5, 2022, New Orleans, LA, USA

ACM ISBN 978-1-4503-9156-6/22/04.
https://doi.org/10.1145/3491101.3519679

KEYWORDS

sensors, text entry, fabrication, wearable device, gestures, gesture typing

ACM Reference Format:
Tafadzwa Joseph Dube, Kevin Johnson, and Ahmed Sabbir Arif. 2022. Shapeshifter: Gesture Typing in Virtual Reality with a Force-based Digital Thimble. In *CHI Conference on Human Factors in Computing Systems Extended Abstracts (CHI '22 Extended Abstracts), April 29-May 5, 2022, New Orleans, LA, USA.* ACM, New York, NY, USA, 9 pages. https://doi.org/10.1145/3491101.3519679

1 INTRODUCTION

Virtual reality (VR) is becoming increasingly popular [52], yet its use is mostly limited to applications for entertainment and training simulation due to the absence of an effective text entry technique for the domain [6, 11, 18, 55]. Most existing text entry techniques for virtual reality use extramural devices that are either placed on a table (e.g., physical keyboards [18, 55]) or held with one or both hands (e.g., game controllers [59, 73] and smartphones [9, 34]). Because users cannot see these extramural devices when wearing a head-mounted display (HMD), these techniques usually display their virtual representations in the virtual world and provide continuous graphical and auditory feedback to keep them informed about the current state of the system. These techniques are not always practical for virtual reality since they require a fixed flat surface (i.e., a table), which compromises mobility of users, forcing them to perform only the tasks that can be performed when stationary. Holding extramural devices, on the other hand, restricts their ability to use the hands to perform other tasks. Locating and activating these devices is also difficult when wearing an HMD and can divert users' mind from the task at hand. Techniques that use digital gloves and other wearable devices are conspicuous and uncomfortable [27, 32, 65]. There are also techniques that track the fingers to enable entering text by typing on a virtual keyboard on a flat surface [12, 28, 59]. These techniques, however, require users to look down at the hands for the HMD to track the fingers, which is unnatural. Some techniques also use new keyboard layouts optimized for virtual reality, which are not only difficult to learn and use but also rely heavily on decoders, which makes entering out-of-vocabulary (OOV) words difficult, often impossible.

This paper presents Shapeshifter, a technique to enable freehand gesture typing [37, 74] in the virtual world on any opaque diffusely reflective, including the human body (Fig. 1). It uses a custom digital thimble that users wear in the index finger. The thimble tracks finger position using an optical sensor and touch contact force using a pressure sensor. To enter text with Shapeshifter: users touch a surface with the index finger to see a cursor at the center of a virtual Qwerty, apply and release extra force (like pressing a key) to activate the "positioning mode", position the cursor at the first letter of the intended word by moving the finger, start connecting all letters of the intended word by applying and maintaining extra force (like drawing a gesture with a mouse while pressing down the left key), then release force or lift the finger to complete the gesture and enter the corresponding word. Since Shapeshifter enables gesture typing by varying contact force, users can enter multiple words without ever lifting the finger. Shapeshifter also supports character-level entry (entering one character at a time) for abbreviations and OOV words by applying and releasing extra force on each key. The contribution of this work is thus twofold: the development of a digital thimble that can be used as an independent input and interaction device in virtual reality and the development of a technique that enables users to enter text by drawing gestures with varying contact force.

2 RELATED WORK

Many techniques enable text entry with physical Qwerty keyboards by using external sensors to track the keyboard and the hands, then displaying their virtual representations in the virtual world [5, 18, 24, 33, 35, 44, 45, 49, 55]. Physical keyboards are relatively fast (~39 wpm [18]), but compromise the mobility and immersion of the system. To support mobility, a recent work placed a physical keyboard on a hawker tray with a depth camera in the headset to track the keyboard and the hands [49]. However, this approach is impractical, inconvenient, and likely to cause discomfort and fatigue. Some techniques use virtual Qwerty keyboards for text entry [12, 13, 53, 59], which are much slower than physical keyboards (~12 wpm [12]), likely due to the lack of haptic feedback. To address this, some have used alternative input methods, such as head pointing [39, 40, 59, 73] and eye pointing [51]. These methods are not only slower (10–16 wpm [51, 59]) but also cause high physical strain in prolonged use. A different approach overlays a keyboard layout on the palm, enabling using the index finger of the other hand to type [62]. A similar approach [16] splits Qwerty into two parts to assign each half to one of the hands, and a group of keys to each fingers. To enter text, users pinches the thumb and the finger that holds the intended letter. In an evaluation, this technique reached about 13 wpm but with a high error rate (13%). Some have also used alternative input devices, such as handheld controllers [26, 46, 59], interactive gloves, rings, and straps [27, 63, 65, 69, 70], digital pens [10, 25], and smartphones [4, 19, 23, 34]. These techniques, however, are relatively slow (~6–14 wpm [27, 34, 59]) and highly error prone (15–35% [10, 25, 63]). Gupta et al. [21] used interactive gloves with a wrist worn device to provide users with vibrotactile feedback on each fingertip and the wrist. This approach improved text entry speed substantially (~23 wpm). These techniques, however, encumber the hands and break immersion. A different line of research explore the effects of different virtual hand representations on user performance [17, 36, 57], which is outside the context of this work.

2.1 Gesture Typing in Virtual Reality

Several techniques enable word-level text entry in virtual reality with gesture typing, where users connect the letters of a word on a virtual Qwerty to enter one word at a time [37]. With these techniques, users press a button on the controller, trace the path of a desired word on a floating virtual Qwerty, then release the button to enter the word [9, 71]. There are also some free-hand gesture typing techniques. Gupta et al. [20] developed a digital ring with motion sensors, with which users first rotate the hand to point the cursor to the first letter of the intended word, click a button on the ring to start gesturing, then press the button again to enter the respective word. Jimenez and Schulze [28] attached a Leap Motion controller to the headset to track the fingers. With this technique, users perform the gestures while pinging the finger. Releasing the pinch enters the respective word. The widespread use of smartphones has encouraged gestures typing on smartphones to enter text in virtual reality [9, 23]. Some techniques also enable gesture typing with head movements [73], where users point to the first letter of a word, trace the path of the word with head movements while holding down a controller button, then release the button to enter the respective word. A similar technique [68] replace the controller button with a virtual one, on which users dwell for 400 ms to start gesturing. While some of these techniques can be relatively fast, they require the use of the hands, which limits what users can do in the virtual world, breaks immersion, or causes severe cognitive and physical strain over time. Gesture typing has also been explored in augmented reality [67], which is outside the context of this work. Table 1 presents performance of gesture typing techniques for virtual reality. Dube and Arif [11] provides a comprehensive review of existing text entry techniques for virtual reality.

3 A DIGITAL THIMBLE

We developed a digital thimble to track the index finger in virtual reality. It is made from fabric for comfort and to reduce weight (Fig. 2). It tracks the finger using an FCT 3065-XY Optical Sensor attached to the side using a 3D printed frame. This sensor was collected from a RivenAn Mini 2.4GHz USB Wireless Finger Rings Optical Mouse to reappropriate its circuit board for the thimble

Table 1: Performance of text entry techniques exploiting gesture typing in virtual reality. This table presents the highest reported performance when multiple settings or conditions were explored. Here, OOV represents the support for out-of-vocabulary word entry, and WPM and ER represent the words per minute and error rate performance metrics, respectively. The values marked with τ signify erroneous keystroke error rate [1]. The highlighted row presents performance of the proposed technique.

Technique	Technology	OOV	WPM	ER%	Experimental Task
Freehand [28]	Camera	No	NA	NA	Text transcription
Controller [9]	Controller	Yes	16.4	0.16^{τ}	Text transcription
Controller [71]	Controller	No	21.0	26.0	Text transcription
Smartphone [9]	Touchscreen	Yes	9.6	0.23^{τ}	Text transcription
Smartphone [23]	Touchscreen	Yes	13.15	0.16^{τ}	Text transcription
Hand Rotation [20]	Inertial sensor	Yes	14.8	9.40	Text transcription
Head & Controller[73]	HMD and controller	No	24.7	5.80	Text transcription
Head (circular keyboard) [68]	HMD tracking	No	6.32	5.50	Text transcription
Head [68]	HMD tracking	No	6.32	7.10	Text transcription
Shapeshifter	Digital thimble	Yes	8–11	2–4.6	Text composition
Shapeshifter, Simulated for Novice Users	Digital thimble	Yes	27.3	0	Text Transcription

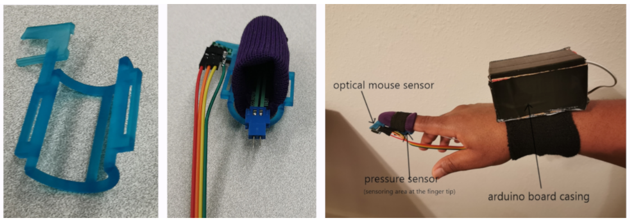

Figure 2: The custom digital thimble. From left: the 3D printed frame to hold the optical sensor, the thimble with the optical sensor on the side and the pressure sensor inside the tip of the thimble, and the complete device with the sensors connected to an Arduino Uno Rev3 microcontroller placed inside a cardboard case worn on the wrist.

(Fig.3). Its 1,200 dpi is also ideal for tracking gestures since it affords users more precision and control. The frame was designed to maintain the recommended 2–2.55 mm distance between the sensor and the fingertip for effective sensing [66]. The wires connecting the optical sensor and the circuit board were also kept as short as possible since longer wires compromise sensing accuracy.

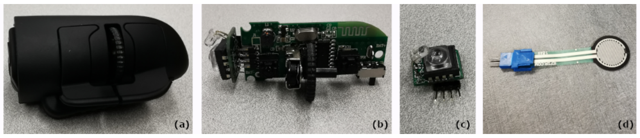

Figure 3: The optical and pressure sensors used in the digital thimble: (a) a RivenAn Mini 2.4GHz USB Wireless Finger Ring Optical Mouse, (b) the mouse without casing, (c) the optical sensor from the mouse, and (d) a Force Sensing Resistors (FSR) 400 series pressure sensor. The images are not to the scale.

The thimble detects touch and contact force using a Force Sensing Resistors (FSR) 400 series pressure sensor. It is attached inside the tip of the thimble, coated with silicone so that it does not irritate the finger. The FSR is connected to a Arduino Uno Rev3 microcontroller placed inside a cardboard case worn on the wrist (Fig. 2). The sensor has a 12.7 mm diameter with a 20 mm^2 sensing area (Fig. 3) and a sensing range between 100 g and 10 kg, which is sufficient for detecting touch. Besides, its circular shape is convenient for measuring force from the fingertip. The resistance of the FSR varies as the force on the sensor changes. When no force is applied, the resistance is slightly larger than 1 MΩ. The harder the sensor is pressed the lower the resistance. Specifically, the FSR and a static resistor form a voltage divider for the analog-to-digital converter of the microcontroller to read a variable voltage and translated to force values. We considered different technologies for tracking the finger, including depth/RGB cameras, magnetism, gyroscope, and infrared sensors (e.g., [30, 48, 56, 60, 72]). But we decided on using an optical sensor due to its availability and affordability. Optical sensors are commonly used in mice as they work on a wide range of surfaces and scenarios [3, 41, 47, 72]. Since the sensor does not rely on a head-mounted display for finger tracking, the thimble can also be used for interaction with other computer systems.

4 SHAPESHIFTER

We designed Shapeshifter, a method for freehand gesture typing in virtual reality using the digital thimble. To use Shapeshifter, users wear the thimble on the index finger and perform gestures on any opaque diffusely reflective surface, including the human body , by varying contact force. To draw a gesture or to perform a thimble-based interaction, users first activate tracking by applying extra contact force. Hence, users can perform other tasks while wearing the thimble without worrying about accidental interactions.

The digital thimble controls a 2D cursor in the virtual world. The cursor has three modes: *inactive*, *active*, and *gesturing*. These modes are visually distinguished by colors grey, red, and green,

(a) (b) (c) (d)

Figure 4: Shapeshifter looks and feels like the default Google Android keyboard. To enter text with Shapeshifter, the user (a) touches a surface (grey cursor), (b) applies extra force to activate the cursor (red cursor), (c) positions the cursor over the first letter of the intended word and applies extra force to start a gesture (green cursor), and (d) completes the gesture maintaining extra force, then reduces force to automatically enter the word associated with the gesture (pick tracing). Shapeshifter enables users to enter multiple words by switching between regular and extra force, without ever lifting the finger. Lifting the finger off the surface deactivates the cursor. The keyboard displays a suggestion bar with the most probable alternative words. The user can replace the output word with a suggested word by applying extra force upon moving the cursor over the suggested word, like pressing a button.

respectively. Touching a surface with the thimble displays the inactive cursor at the center of a virtual keyboard (Fig. 4). To activate the cursor, users increase and decrease contact force once as if they are pressing down and releasing an invisible button. Once activated, moving the finger moves the cursor over the keyboard. To switch to the gesturing mode, users apply and maintain extra force, then gesture type by connecting the letters in the sequence in which they appear in the intended word. Releasing extra force completes a gesture and enters the most probable word associated with the gesture. Expert users, therefore, can enter multiple words by switching between regular and extra force, without ever lifting their fingers. The keyboard provides visual feedback on gesture typing by tracing finger movements in pink. Moving the finger without applying extra force moves the cursor but does not select the items underneath. Users can also enter one character at a time, like entering text with a conventional keyboard, by increasing and deceasing contact force once like pressing a button. This feature is particularly useful when entering out-of-vocabulary (OOV) words.

The digital thimble detects a touch when the contact force is above 10 g, activates the cursor when the contact force increases and decreases between 100 and 400 g, and registers a gesture when the contact force is over 400 g. These values were selected based on a pilot study ($N = 5$, $M = 29$ years) that revealed that usual contact forces are almost always over 10 g, regular touch interactions are usually between 100 and 400 g, and the 400 g threshold is the most reliable to distinguishing between regular and extra force without inducing physical or cognitive stress.

Similar to the default Google Android keyboard [38], Shapeshifter includes a suggestion bar to display the most probable input words (Fig 4). Users can replace an entered word with a suggested word by applying and releasing extra force on the suggestion bar. The suggestion bar can also auto-complete and auto-correct words in character-level text entry. Applying extra force on the Backspace key deletes the last entry, that is, the last word in word-level text entry and the last character in character-level text entry. Table 2 presents the actions required to enter text with Shapeshifter.

We developed a custom keyboard resembling the Google keyboard [38] using Unity3D 2017.14.17 (Fig. 4). It recognizes the gestures drawn over it using a custom algorithm developed based on prior works [37, 61, 73]. It compares the shape and the location of each gesture drawn with gesture templates for 10,000 most common words in the English language [29]. This lexicon is sufficient to cover daily use as the 7,000 most common lemmas make up about 90% of spoken English [29]. The gesture template for a word is programmatically generated as straight lines connecting the center of each key in the sequence in which they form the word. To compare a template to a gesture, both are re-sampled at 50 equidistant points. Prior works found this number to be adequate for comparing patterns [43, 73]. To optimize the comparison, the template set is pruned by only considering the words that start with the two letters closest to the point where the user initiated the gesture. Then, a pairwise comparison of the corresponding points is conducted to determine the similarities between the template and the drawn gesture. Particularly, the algorithm compares the angular difference between the angle formed by each point of the template and the drawn gesture [61]. The average angular difference is then used to approximate the similarity between the two shapes. Given a gesture G and a gesture template T, both are re-sampled at n points. The angular difference $\Delta\theta$ is calculated as follows, where $G\theta_i$ and $T\theta_i$ are angles formed at i^{th} point of the drawn gesture and the template, respectively.

$$\Delta\theta = \sum_{i=1}^{n}(G\theta_i - T\theta_i) \tag{1}$$

To estimate the difference in location between the two gestures, the distance between each corresponding points is computed. The sum of these individual point differences gives the total distance D between the shapes, where G_i and T_i are the vectors of points i of the drawn gesture and the template, respectively. The template yielding the highest similarity and the lowest distance between the shapes is picked as the best match and the respective word is selected as the most probable word.

Table 2: The actions required for word- and character-level text entry with Shapeshifter. OOV refers to out-of-vocabulary words.

Goal	Action	Task	Cursor
Enter a word	Touch any surface (10–100 g)	*Display the cursor in inactive mode*	Grey
	Apply & release force (100–400 g)	*Switch to the active mode*	Red
	Move finger	*Position the cursor over the 1st letter of the word*	Red
	Apply and maintain extra force (>400 g)	*Perform the gesture*	Green
	Release extra force	*Complete gesture and enter the word*	Red/Grey
OOV	Apply & release extra force on a key	Enter the corresponding letter	Green
Pick	Apply & release extra force on a suggestion	Enter the suggested word	Green
Edit	Apply & release extra force on Backspace	Delete the last word or character	Green

$$D = \sum_{i=1}^{n}(G_i - T_i) \tag{2}$$

5 LONG-TERM PILOT STUDY: TEXT COMPOSITION

We conducted a pilot study to evaluate the performance of the proposed technique on composition tasks (i.e., free-from text entry). We were unable to conduct a full-length study since in-person studies are still prohibited in our institution due to the COVID-19 pandemic. The protocol described here was reviewed and approved by the IRB.

5.1 Participants and Apparatus

Two participants, aged 31 and 39 years, volunteered in the pilot study. They were both male and right-handed. None of them wore corrective eye-glasses. They both had some experience with virtual reality (i.e., had used it at least once in the past) but not with the digital thimble. They were aware of gesture typing (i.e., had seen it before) but never used it to enter text on mobile devices.

The study used an Asus ROG GU501GM laptop with 16 gig RAM and Intel Core i7 processor and a Samsung Odyssey mixed reality HMD. The virtual environment displayed only the virtual keyboard and a text input area (Fig. 4).

5.2 Design and Procedure

The study was conducted remotely. We personally delivered the apparatus to each participant and scheduled individual video meetings with them. All forms (including the informed consent form) were completed and signed electronically. Upon completion of the study, we picked up the devices. All devices were disinfected before delivery and after pickup. During the video call, we demonstrated the system to the participants, asked them to practice with it under our guidance, and explained the study procedure. We encouraged them to ask us any questions they might have about the system or the study procedure. We then concluded the call.

In the study, participants used Shapeshifter at home for one week (7 days) to compose free-form text on any desired topic. They composed text three times a day: in the morning, afternoon, and evening in three different settings: on a desk in a seated position, on the lap in a seated position, and on the palm or the back of the hand while standing up (Fig. 5). They could use the settings in any order. In each text entry episode, they were instructed to compose text for about 15 minutes on any desired topic (e.g., plans for the day, summary of the day, vacation plans, views about life, etc.). The system automatically recorded all interactions with the system and the entry speed of each episode using the commonly used words per minute (wpm) performance metric [1]. Upon completion of the study, participants were asked to review the composted passages to identify recognition errors, which we used to calculate the error rate (ER) metric [1]. We also conducted a debrief session to learn about their experience with Shapeshifter.

Figure 5: A user composing text on the thigh in a seated position.

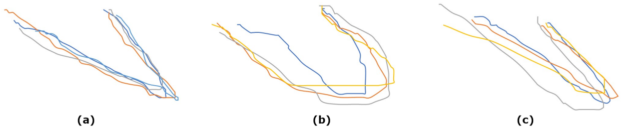

Figure 6: Gestures drawn for the most frequent word in the English language “the" by the participants on: a) the thigh, b) the desk, and c) the palm. Notice that the gestures drawn on the thigh and palm have much sharper corners.

Table 3: Results of the pilot study. Here, Length represents the average number of words in composted paragraphs.

Position	Surface	Length	WPM (Min–Max)	WPM (Mean)	ER (Min–Max)	ER (Mean)
Seated	Desk	58–156	6.3–16.5	11.3 (SD = 2.7)	0.0—6.9	2.0% (SD = 2.1)
Seated	Lap/palm	59–130	5.5–11.6	8.9 (SD = 1.9)	0.4–6.9	2.6% (SD = 1.8)
Standing	Palm/back-of-hand	62–115	5.5–10.0	8.1 (SD = 1.2)	1.1–6.7	4.6% (SD = 2.2)

6 SIMULATION STUDY: TEXT TRANSCRIPTION

We conducted a simulation to estimate how fast novice users can transcribe text with Shapeshifter. After considering several existing models [7, 8, 54], we decided to use the curves, lines, and corners model [8] since it does not overestimate the gesture production time as much as the other models [7, 58]. The model describes gestures as compositions of curves, lines, and corners, but we considered only lines and corners since the effects of direction and corners are negligible in gesture production time [58]. The model describes lines and corners with a power function and a non-linear function, respectively. The production time (T) for a word with N letters is measured as:

$$T = \sum_{i=1}^{N-1} mL_i^n \tag{3}$$

Where, L is the length of the i-th line and m and n are parameters of the model. To find these parameter values, we conducted a study (N = 5, M = 31 years), where novice participants (who did not use Shapeshifter before the study) drew straight lines of lengths 10, 20, 30, 40, and 60 mm at 0, 45, and 90° angles on the virtual keyboard, five times per combination, resulting in $5 \times 5 \times 3 \times 5 = 1,325$ data points. The gestures were drawn on a desk. A regression analysis on the data provided $m = 78.9$ and $n = 0.62$, with a 0.98 coefficient of determination. We then simulated the average transcription time of all 500 phrases in the MacKenzie & Soukoreff set [42] with 0, 1, 3, 5 and 10% error rates. For this, we estimated and added error correction time appropriate for the error rates as users tend to correct almost all errors in transcription tasks [2]. Error correction time for one incorrect word was estimated using the following equation:

$$T = T_p + T_d + T_r \tag{4}$$

Where, T_p is the preparation time (1,200 ms [31]), T_d is the deletion time (one Backspace), and T_r is the time to re-draw the gesture. The average cost of error correction was estimates 2,977 ms per incorrect word. Table 4 presents the results of the simulation.

Table 4: Predicted text entry speed with Shapeshifter in transcription typing tasks.

ER	0%	1%	3%	5%	10%
WPM	27.3	26.2	24.1	21.9	16.4

7 RESULTS AND DISCUSSION

Table 3 presents the results of the pilot study. Shapeshifter yielded on average 11 wpm on flat surfaces (e.g., a desk) and 9 wpm on the lap when sitting down, and 8 wpm on the palm and back of the hand when standing up in text composition tasks. Shapeshifter yielded a relatively lower entry speed reported for some gesture typing methods in the literature. We anticipated this since these techniques were evaluated in transcription typing tasks, where participants had to copy a sequence of presented text. In our study, participants composed text. Unlike transcription typing, people use a variety of cognitive processes when composing text, such as making plans, retrieving ideas from memory, making inferences, and creating and developing concept [14, 22, 64]. Regardless of this, Shapeshifter yielded comparable or higher entry speed than many gesture typing methods for virtual reality (Table 1), which is inspiring. A simulation study predicted a 27.3 wpm error-free text entry rate in transcription typing tasks for novice users, which is faster than the existing gesture typing techniques. However, the simulation assumed an ideal surface, 0% error rate, and no OOV words, thus, the actual entry speed could be slower than predicted. Then again, the model did not consider users selecting words from the suggestion bar or the effects of practice, which could essentially result in a much faster entry speed than predicted.

In the debrief session, both participants praised the digital thimble for being light and comfortable, but complained that the pressure sensor freezes at times and the optical sensor does not work properly when the finger is tilted toward the side of the sensor when it hits the surface. These issues were reported for all surfaces. We believe these issues can be addressed by using a flexible sensor cap that can re-adjusts its orientation when users change their finger orientation. Both participants found gesturing in a seated position the easiest and the most comfortable, regardless of whether using a desk or the lap. However, they found gesturing on the lap more immersive. One participant commented, *"when I was drawing on the lap direct on the skin I felt I was more in the virtual environment "*. This suggests, removal of extra physical devices can improve immersion. Likewise, gesturing on the palm and the back-of-hand whilst standing up was more physical taxing and the least comfortable, especially when entering text for an extended period of time. One participant commented, *"I feel typing on the hand has more fatigue that all the other positions"*. However, between the palm and the back-of-hand, the palm was more comfortable since the posture used to draw on the back-of-hand fatigued the wrist and the arm.

Fig. 6 visualizes the gestures drawn for the word "the" by the participants on various surfaces. One can see that the gestures drawn on the palm and the thigh had much sharper corners compared to the gestures drawn on the desk. The shape comparison algorithm yielded relatively higher match scores for the gestures drawn on the palm (92.5%, SD = 1.8) and the thigh (93.6%, SD = 1.04) than the ones drawn on the table (88.2%, SD = 1.22). This is not surprising since the templates were generated as straight lines with sharp corners. Regardless of the difference in the scores, the algorithm was able to identify all gestures accurately when coupled with the location channel. Relevantly, prior studies showed that users tend to avoids sharp corners to maximize smoothness and reduce the total amount of jerk [15, 50]. The fact that the gestures drawn on the desk had rounder corners supports this. The gestures drawn on the palm and the thigh had sharper corners, presumably, due to the roughness of the surfaces. Hence, the effectiveness of the algorithm could be further improved by collecting samples from different surfaces and developing a model that can predict and compensate for the surface where gestures are drawn.

Participants found entering out-of-vocabulary words relatively difficult since navigating the finger to each letter took more time. Navigating the cursor to the Backspace key was also time-consuming. Both participants found the visual feedback of the cursor helpful in identifying different levels of pressure.

8 CONCLUSION

We presented Shapeshifter, a text entry technique for gesture typing using a digital thimble in virtual reality. The digital thimble consists of an optical sensor to track the finger and a pressure sensor to detect touch and contact force. In a week-long in-the-wild pilot study, Shapeshifter yielded on average 11 wpm on flat surfaces and 9 wpm on the lap when sitting down, and 8 wpm on the palm and back of the hand when standing up with novice users in text composition tasks. A simulation study predicted a 27.3 wpm error-free text entry rate for novice users in transcription typing tasks on a desk. A post-pilot debrief session revealed that uneven surfaces made gesture typing with the thimble difficult and performing gestures when standing up caused more physically strain than when sitting down. In the future, we will refine the digital thimble to make it more robust for uneven surfaces. We will also explore the possibility of using it for interaction with virtual interfaces.

REFERENCES

[1] Ahmed Sabbir Arif and Wolfgang Stuerzlinger. 2009. Analysis of Text Entry Performance Metrics. In *2009 IEEE Toronto International Conference Science and Technology for Humanity (TIC-STH)*. IEEE, Washington, DC, USA, 100–105. https://doi.org/10.1109/TIC-STH.2009.5444533

[2] Ahmed Sabbir Arif and Wolfgang Stuerzlinger. 2010. Predicting the Cost of Error Correction in Character-Based Text Entry Technologies. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '10)*. ACM, New York, NY, USA, 5–14. https://doi.org/10.1145/1753326.1753329 event-place: Atlanta, Georgia, USA.

[3] Patrick Baudisch, Mike Sinclair, and Andrew Wilson. 2006. Soap: A Pointing Device That Works in Mid-Air. In *Proceedings of the 19th Annual ACM Symposium on User Interface Software and Technology - UIST '06*. ACM Press, Montreux, Switzerland, 43. https://doi.org/10.1145/1166253.1166261

[4] Sabah Boustila, Thomas Guégan, Kazuki Takashima, and Yoshifumi Kitamura. 2019. Text Typing in VR Using Smartphones Touchscreen and HMD. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, Osaka,Japan, 860–861. https://doi.org/10.1109/VR.2019.8798238

[5] Sidney Bovet, Aidan Kehoe, Katie Crowley, Noirin Curran, Mario Gutierrez, Mathieu Meisser, Damien O Sullivan, and Thomas Rouvinez. 2018. Using Traditional Keyboards in VR: SteamVR Developer Kit and Pilot Game User Study. In *2018 IEEE Games, Entertainment, Media Conference (GEM)*. IEEE, Galway, Ireland, 1–9. https://doi.org/10.1109/GEM.2018.8516449

[6] Doug A Bowman. 2020. Embracing Physical Keyboards for Virtual Reality. *IEEE Annals of the History of Computing* 53, 09 (Sept. 2020), 9–10. https://doi.org/10.1109/MC.2020.3004605

[7] Ulrich Burgbacher and Klaus Hinrichs. 2015. Modeling Human Performance of Stroke-Based Text Entry. In *Proceedings of the 17th International Conference on Human-Computer Interaction with Mobile Devices and Services (MobileHCI '15)*. Association for Computing Machinery, Copenhagen, Denmark, 137–143. https://doi.org/10.1145/2785830.2785858

[8] Xiang Cao and Shumin Zhai. 2007. Modeling Human Performance of Pen Stroke Gestures. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '07)*. Association for Computing Machinery, San Jose, California, USA, 1495–1504. https://doi.org/10.1145/1240624.1240850

[9] Sibo Chen, Junce Wang, Santiago Guerra, Neha Mittal, and Soravis Prakkamakul. 2019. Exploring Word-Gesture Text Entry Techniques in Virtual Reality. In *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems (CHI EA '19)*. Association for Computing Machinery, Glasgow, Scotland Uk, 1–6. https://doi.org/10.1145/3290607.3312762

[10] Seyed Amir Ahmad Didehkhorshid, Siju Philip, Elaheh Samimi, and Robert J. Teather. 2020. Text Input in Virtual Reality Using a Tracked Drawing Tablet. In *HCI International 2020 – Late Breaking Papers: Virtual and Augmented Reality (Lecture Notes in Computer Science)*. Springer International Publishing, Cham, Switzerland, 314–329. https://doi.org/10.1007/978-3-030-59990-4_24

[11] Tafadzwa Joseph Dube and Ahmed Sabbir Arif. 2019. Text Entry in Virtual Reality: A Comprehensive Review of the Literature. In *Human-Computer Interaction. Recognition and Interaction Technologies (Lecture Notes in Computer Science)*, Masaaki Kurosu (Ed.). Springer International Publishing, Cham, 419–437. https://doi.org/10.1007/978-3-030-22643-5_33

[12] Tafadzwa Joseph Dube and Ahmed Sabbir Arif. 2020. Impact of Key Shape and Dimension on Text Entry in Virtual Reality. In *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems Extended Abstracts (CHI '20)*. Association for Computing Machinery, Honolulu, HI, USA, 1–10. https://doi.org/10.1145/3334480.3382882

[13] John Dudley, Hrvoje Benko, Daniel Wigdor, and Per Ola Kristensson. 2019. Performance Envelopes of Virtual Keyboard Text Input Strategies in Virtual Reality. In *2019 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. IEEE, Beijing, China, 289–300. https://doi.org/10.1109/ISMAR.2019.00027

[14] Cynthia Ann Edwards. 2005. *The Writing Processes of College Students With and Without Learning Disabilities: A Protocol Analysis.* Ph.D. Dissertation. University of Maryland, College Park. https://drum.lib.umd.edu/handle/1903/3104 Accepted: 2006-02-04T06:54:29Z.

[15] Sascha E Engelbrecht. 2001. Minimum Principles in Motor Control. *Journal of Mathematical Psychology* 45, 3 (June 2001), 497–542. https://doi.org/10.1006/jmps.2000.1295

[16] Jacqui Fashimpaur, Kenrick Kin, and Matt Longest. 2020. PinchType: Text Entry for Virtual and Augmented Reality Using Comfortable Thumb to Fingertip Pinches. In *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems*. ACM, Honolulu HI USA, 1–7. https://doi.org/10.1145/3334480.3382888

[17] J. Grubert, L. Witzani, E. Ofek, M. Pahud, M. Kranz, and P. O. Kristensson. 2018. Effects of Hand Representations for Typing in Virtual Reality. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, Reutlingen, Germany, 151–158. https://doi.org/10.1109/VR.2018.8446250

[18] Jens Grubert, Lukas Witzani, Eyal Ofek, Michel Pahud, Matthias Kranz, and Per Ola Kristensson. 2018. Text Entry in Immersive Head-Mounted Display-Based Virtual Reality Using Standard Keyboards. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, Reutlingen, Germany, 159–166. https://doi.org/10.1109/VR.2018.8446059

[19] Jan Gugenheimer, David Dobbelstein, Christian Winkler, Gabriel Haas, and Enrico Rukzio. 2016. FaceTouch: Enabling Touch Interaction in Display Fixed UIs for Mobile Virtual Reality. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology (UIST '16)*. Association for Computing Machinery, Tokyo, Japan, 49–60. https://doi.org/10.1145/2984511.2984576

[20] Aakar Gupta, Cheng Ji, Hui-Shyong Yeo, Aaron Quigley, and Daniel Vogel. 2019. RotoSwype: Word-Gesture Typing Using a Ring. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (CHI '19)*. Association for Computing Machinery, Glasgow, Scotland Uk, 1–12. https://doi.org/10.1145/3290605.3300244

[21] A. Gupta, M. Samad, K. Kin, P. O. Kristensson, and H. Benko. 2020. Investigating Remote Tactile Feedback for Mid-Air Text-Entry in Virtual Reality. In *2020 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. IEEE, Recife/Porto de Galinhas, Brazil, 350–360. https://doi.org/10.1109/ISMAR50242.2020.00062

[22] J. Haves. 1980. Identifying the Organization of Writing Processes. In *Cognitive Processes in Writing* (1st ed.), Lee W. Gregg and Erwin R. Steinberg (Eds.). Lawrence Erlbaum Assosiates.

[23] Jay Henderson, Jessy Ceha, and Edward Lank. 2020. STAT: Subtle Typing Around the Thigh for Head-Mounted Displays. In *22nd International Conference on Human-Computer Interaction with Mobile Devices and Services (MobileHCI '20)*. Association for Computing Machinery, New York, NY, USA, 1–11. https://doi.org/10.1145/3379503.3403549

[24] Adrian H. Hoppe, Leonard Otto, Florian van de Camp, Rainer Stiefelhagen, and Gabriel Unmüßig. 2018. qVRty: Virtual Keyboard with a Haptic, Real-World Representation. In *HCI International 2018 – Posters' Extended Abstracts (Communications in Computer and Information Science)*, Constantine Stephanidis (Ed.). Springer International Publishing, Cham, 266–272. https://doi.org/10.1007/978-3-319-92279-9_36

[25] Bret Jackson, Logan B Caraco, and Zahara M Spilka. 2020. Arc-Type and Tilt-Type: Pen-Based Immersive Text Input for Room-Scale VR. In *Symposium on Spatial User Interaction*. ACM, Virtual Event Canada, 1–10. https://doi.org/10.1145/3385959.3418454

[26] Haiyan Jiang and Dongdong Weng. 2020. HiPad: Text Entry for Head-Mounted Displays Using Circular Touchpad. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, Atlanta, GA, USA, 692–703. https://doi.org/10.1109/VR46266.2020.1581236395562

[27] Haiyan Jiang, Dongdong Weng, Zhenliang Zhang, and Feng Chen. 2019. HiFinger: One-Handed Text Entry Technique for Virtual Environments Based on Touches between Fingers. *Sensors (Basel, Switzerland)* 19, 14 (July 2019), 3063. https://doi.org/10.3390/s19143063

[28] Janis G. Jimenez and Jürgen P. Schulze. 2018. Continuous-Motion Text Input in Virtual Reality. *Electronic Imaging* 2018, 3 (Jan. 2018), 450–1–450–6. https://doi.org/10.2352/ISSN.2470-1173.2018.03.ERVR-450

[29] Josh Kaufman. 2020. First20hours/Google-10000-English. https://github.com/first20hours/google-10000-english.

[30] Wolf Kienzle and Ken Hinckley. 2014. LightRing: Always-Available 2D Input on Any Surface. In *Proceedings of the 27th Annual ACM Symposium on User Interface Software and Technology (UIST '14)*. Association for Computing Machinery, New York, NY, USA, 157–160. https://doi.org/10.1145/2642918.2647376

[31] David Kieras. 1993. Using the Keystroke-Level Model to Estimate Execution Times. *Technical Report, University of Michigan* 555 (1993), 11.

[32] Junhyeok Kim, William Delamare, and Pourang Irani. 2018. ThumbText: Text Entry for Wearable Devices Using a Miniature Ring. In *Proceedings of the 44th Graphics Interface Conference* (Toronto, Canada) *(GI '18)*. Canadian Human-Computer Communications Society, Waterloo, CAN, 18–25. https://doi.org/10.20380/GI2018.04

[33] Sooyoung Kim and Gerard Jounghyun Kim. 2004. Using Keyboards with Head Mounted Displays. In *Proceedings of the 2004 ACM SIGGRAPH International Conference on Virtual Reality Continuum and Its Applications in Industry (VRCAI '04)*. Association for Computing Machinery, Singapore, 336–343. https://doi.org/10.1145/1044588.1044662

[34] Youngwon R. Kim and Gerard J. Kim. 2017. HoVR-Type: Smartphone as a Typing Interface in VR Using Hovering. In *2017 IEEE International Conference on Consumer Electronics (ICCE)*. IEEE, Las Vegas, NV, USA, 200–203. https://doi.org/10.1109/ICCE.2017.7889285

[35] Pascal Knierim, Thomas Kosch, Johannes Groschopp, and Albrecht Schmidt. 2020. Opportunities and Challenges of Text Input in Portable Virtual Reality. In *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems (CHI EA '20)*. Association for Computing Machinery, Honolulu, HI, USA, 1–8. https://doi.org/10.1145/3334480.3382920

[36] Pascal Knierim, Valentin Schwind, Anna Maria Feit, Florian Nieuwenhuizen, and Niels Henze. 2018. Physical Keyboards in Virtual Reality: Analysis of Typing Performance and Effects of Avatar Hands. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–9. https://doi.org/10.1145/3173574.3173919

[37] Per-Ola Kristensson and Shumin Zhai. 2004. SHARK2: A Large Vocabulary Shorthand Writing System for Pen-Based Computers. In *Proceedings of the 17th Annual ACM Symposium on User Interface Software and Technology (UIST '04)*. Association for Computing Machinery, Santa Fe, NM, USA, 43–52. https://doi.org/10.1145/1029632.1029640

[38] Reena Lee. 2016. Gboard, Now Available for Android. https://blog.google/products/search/gboard-now-on-android/

[39] Xueshi Lu, Difeng Yu, Hai-Ning Liang, Xiyu Feng, and Wenge Xu. 2019. DepthText: Leveraging Head Movements towards the Depth Dimension for Hands-Free Text Entry in Mobile Virtual Reality Systems. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, Osaka, Japan, Japan, 1060–1061. https://doi.org/10.1109/VR.2019.8797901

[40] X. Lu, D. Yu, H.-N. Liang, W. Xu, Y. Chen, X. Li, and K. Hasan. 2020. Exploration of Hands-Free Text Entry Techniques For Virtual Reality. In *2020 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. IEEE, Recife/Porto de Galinhas, Brazil, 344–349. https://doi.org/10.1109/ISMAR50242.2020.00061

[41] Kent Lyons. 2020. Wearable Magnetic Field Sensing for Finger Tracking. In *Proceedings of the 2020 International Symposium on Wearable Computers (ISWC '20)*. Association for Computing Machinery, New York, NY, USA, 63–67. https://doi.org/10.1145/3410531.3414304

[42] I. Scott MacKenzie and R. William Soukoreff. 2003. Phrase Sets for Evaluating Text Entry Techniques. In *CHI '03 Extended Abstracts on Human Factors in Computing Systems (CHI EA '03)*. Association for Computing Machinery, Ft. Lauderdale, Florida, USA, 754–755. https://doi.org/10.1145/765891.765971

[43] Anders Markussen, Mikkel Rønne Jakobsen, and Kasper Hornbæk. 2014. Vulture: A Mid-Air Word-Gesture Keyboard. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '14)*. Association for Computing Machinery, Toronto, Ontario, Canada, 1073–1082. https://doi.org/10.1145/2556288.2556964

[44] Mark McGill, Daniel Boland, Roderick Murray-Smith, and Stephen Brewster. 2015. A Dose of Reality: Overcoming Usability Challenges in VR Head-Mounted Displays. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*. Association for Computing Machinery, Seoul, Republic of Korea, 2143–2152. https://doi.org/10.1145/2702123.2702382

[45] Tim Menzner, Alexander Otte, Travis Gesslein, Jens Grubert, Philipp Gagel, and Daniel Schneider. 2019. A Capacitive-Sensing Physical Keyboard for VR Text Entry. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, Osaka, Japan, Japan, 1080–1081. https://doi.org/10.1109/VR.2019.8797754

[46] Anh Nguyen, Samuel Bittman, and Markus Zank. 2020. Text Input Methods in Virtual Reality Using Radial Layouts. In *26th ACM Symposium on Virtual Reality Software and Technology (VRST '20)*. Association for Computing Machinery, New York, NY, USA, 1–3. https://doi.org/10.1145/3385956.3422114

[47] Tao Ni and Patrick Baudisch. 2009. Disappearing Mobile Devices. In *Proceedings of the 22nd Annual ACM Symposium on User Interface Software and Technology - UIST '09*. ACM Press, Victoria, BC, Canada, 101. https://doi.org/10.1145/1622176.1622197

[48] Keunwoo Park, Daehwa Kim, Seongkook Heo, and Geehyuk Lee. 2020. MagTouch: Robust Finger Identification for a Smartwatch Using a Magnet Ring and a Built-in Magnetometer. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (CHI '20)*. Association for Computing Machinery, Honolulu, HI, USA, 1–13. https://doi.org/10.1145/3313831.3376234

[49] Duc-Minh Pham and Wolfgang Stuerzlinger. 2019. HawKEY: Efficient and Versatile Text Entry for Virtual Reality. In *25th ACM Symposium on Virtual Reality Software and Technology (VRST '19)*. Association for Computing Machinery, Parramatta, NSW, Australia, 1–11. https://doi.org/10.1145/3359996.3364265

[50] Philip Quinn and Shumin Zhai. 2018. Modeling Gesture-Typing Movements. *Human–Computer Interaction* 33, 3 (May 2018), 234–280. https://doi.org/10.1080/07370024.2016.1215922

[51] Vijay Rajanna and John Paulin Hansen. 2018. Gaze Typing in Virtual Reality: Impact of Keyboard Design, Selection Method, and Motion. In *Proceedings of the 2018 ACM Symposium on Eye Tracking Research & Applications (ETRA '18)*. Association for Computing Machinery, Warsaw, Poland, 1–10. https://doi.org/10.1145/3204493.3204541

[52] Grand View Research. 2017. *Virtual Reality Market Size, Industry Growth Analysis Report, 2025*. Technical Report GVR-1-68038-831-2. Grand View Research. 125 pages.

[53] Mark Richardson, Matt Durasoff, and Robert Wang. 2020. Decoding Surface Touch Typing from Hand-Tracking. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology (UIST '20)*. Association for Computing Machinery, New York, NY, USA, 686–696. https://doi.org/10.1145/3379337.3415816

[54] Jochen Rick. 2010. Performance Optimizations of Virtual Keyboards for Stroke-Based Text Entry on a Touch-Based Tabletop. In *Proceedings of the 23nd Annual ACM Symposium on User Interface Software and Technology (UIST '10)*. Association for Computing Machinery, New York, New York, USA, 77–86. https://doi.org/10.1145/1866029.1866043

[55] Daniel Schneider, Alexander Otte, Travis Gesslein, Philipp Gagel, Bastian Kuth, Mohamad Shahm Damlakhi, Oliver Dietz, Eyal Ofek, Michel Pahud, Per Ola Kristensson, Jörg Müller, and Jens Grubert. 2019. ReconViguRation: Reconfiguring Physical Keyboards in Virtual Reality. *IEEE Transactions on Visualization and Computer Graphics* 25, 11 (Nov. 2019), 3190–3201. https://doi.org/10.1109/TVCG.2019.2932239

[56] Maximilian Schrapel, Florian Herzog, Steffen Ryll, and Michael Rohs. 2020. Watch My Painting: The Back of the Hand as a Drawing Space for Smartwatches. In *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems (CHI EA '20)*. Association for Computing Machinery, Honolulu, HI, USA, 1–10. https://doi.org/10.1145/3334480.3383040

[57] Valentin Schwind, Pascal Knierim, Cagri Tasci, Patrick Franczak, Nico Haas, and Niels Henze. 2017. "These Are Not My Hands!": Effect of Gender on the Perception of Avatar Hands in Virtual Reality. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, 1577–1582.

[58] Brian A. Smith, Xiaojun Bi, and Shumin Zhai. 2015. Optimizing Touchscreen Keyboards for Gesture Typing. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*. Association for Computing Machinery, Seoul, Republic of Korea, 3365–3374. https://doi.org/10.1145/2702123.2702357

[59] Marco Speicher, Anna Maria Feit, Pascal Ziegler, and Antonio Krüger. 2018. Selection-Based Text Entry in Virtual Reality. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems - CHI '18*. ACM Press, Montreal QC, Canada, 1–13. https://doi.org/10.1145/3173574.3174221

[60] Srinath Sridhar, Franziska Mueller, Antti Oulasvirta, and Christian Theobalt. 2015. Fast and Robust Hand Tracking Using Detection-Guided Optimization. In *2015 IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*. 3213–3221. https://doi.org/10.1109/CVPR.2015.7298941 ISSN: 1063-6919, 1063-6919.

[61] Dylan Vester. 2015. Mouse Gesture and Shape Recognition with .NET. http://dylanvester.com/2015/10/mouse-gesture-and-shape-recognition-with-dotnet.

[62] Cheng-Yao Wang, Wei-Chen Chu, Po-Tsung Chiu, Min-Chieh Hsiu, Yih-Harn Chiang, and Mike Y. Chen. 2015. PalmType: Using Palms as Keyboards for Smart Glasses. In *Proceedings of the 17th International Conference on Human-Computer Interaction with Mobile Devices and Services (MobileHCI '15)*. Association for Computing Machinery, New York, NY, USA, 153–160. https://doi.org/10.1145/2785830.2785886

[63] Eric Whitmire, Mohit Jain, Divye Jain, Greg Nelson, Ravi Karkar, Shwetak Patel, and Mayank Goel. 2017. DigiTouch: Reconfigurable Thumb-to-Finger Input and Text Entry on Head-Mounted Displays. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 1, 3 (Sept. 2017), 113:1–113:21. https://doi.org/10.1145/3130978

[64] Stephen P. Witte and Roger D. Cherry. 1986. Writing Processes and Written Products in Composition Research. In *Studying Writing: Linguistic Approaches* (1 ed.). Vol. 1. Sage Publications, Beverly Hills, CA, USA, 112–153.

[65] Chien-Min Wu, Chih-Wen Hsu, Tzu-Kuei Lee, and Shana Smith. 2017. A Virtual Reality Keyboard with Realistic Haptic Feedback in a Fully Immersive Virtual Environment. *Virtual Reality* 21, 1 (March 2017), 19–29. https://doi.org/10.1007/s10055-016-0296-6

[66] Wang Xin and Katsunori Shida. 2008. Optical Mouse Sensor for Detecting Height Variation and Translation of a Surface. In *2008 IEEE International Conference on Industrial Technology*. IEEE, Chengdu, China, 1–6. https://doi.org/10.1109/ICIT.2008.4608448

[67] Wenge Xu, Hai-Ning Liang, Anqi He, and Zifan Wang. 2019. Pointing and Selection Methods for Text Entry in Augmented Reality Head Mounted Displays. In *2019 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. Beijing, China, IEEE, 279–288. https://doi.org/10.1109/ISMAR.2019.00026

[68] Wenge Xu, Hai-Ning Liang, Yuxuan Zhao, Tianyu Zhang, Difeng Yu, and Diego Monteiro. 2019. RingText: Dwell-Free and Hands-Free Text Entry for Mobile Head-Mounted Displays Using Head Motions. *IEEE Transactions on Visualization and Computer Graphics* 25, 5 (May 2019), 1991–2001. https://doi.org/10.1109/TVCG.2019.2898736

[69] Zheer Xu, Weihao Chen, Dongyang Zhao, Jiehui Luo, Te-Yen Wu, Jun Gong, Sicheng Yin, Jialun Zhai, and Xing-Dong Yang. 2020. BiTipText: Bimanual Eyes-Free Text Entry on a Fingertip Keyboard. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3313831.3376306

[70] Zheer Xu, Pui Chung Wong, Jun Gong, Te-Yen Wu, Aditya Shekhar Nittala, Xiaojun Bi, Jürgen Steimle, Hongbo Fu, Kening Zhu, and Xing-Dong Yang. 2019. TipText: Eyes-Free Text Entry on a Fingertip Keyboard. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology (UIST '19)*. Association for Computing Machinery, New York, NY, USA, 883–899. https://doi.org/10.1145/3332165.3347865

[71] Naoki Yanagihara, Buntarou Shizuki, and Shin Takahashi. 2019. Text Entry Method for Immersive Virtual Environments Using Curved Keyboard. In *25th ACM Symposium on Virtual Reality Software and Technology (VRST '19)*. Association for Computing Machinery, Parramatta, NSW, Australia, 1–2. https://doi.org/10.1145/3359996.3365026

[72] Xing-Dong Yang, Tovi Grossman, Daniel Wigdor, and George Fitzmaurice. 2012. Magic Finger: Always-Available Input through Finger Instrumentation. In *Proceedings of the 25th Annual ACM Symposium on User Interface Software and Technology (UIST '12)*. Association for Computing Machinery, New York, NY, USA, 147–156. https://doi.org/10.1145/2380116.2380137

[73] Chun Yu, Yizheng Gu, Zhican Yang, Xin Yi, Hengliang Luo, and Yuanchun Shi. 2017. Tap, Dwell or Gesture? Exploring Head-Based Text Entry Techniques for HMDs. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17)*. Association for Computing Machinery, Denver, Colorado, USA, 4479–4488. https://doi.org/10.1145/3025453.3025964

[74] Shumin Zhai and Per Ola Kristensson. 2012. The Word-Gesture Keyboard: Reimagining Keyboard Interaction. *Commun. ACM* 55, 9 (Sept. 2012), 91–101. https://doi.org/10.1145/2330667.2330689