Get a Grip: Evaluating Grip Gestures for VR Input using a Lightweight Pen

Nianlong Li[1,2] **Teng Han**[1,3∗] **Feng Tian**[1,3] **Jin Huang**[1,3] **Minghui Sun**[4]
Pourang Irani[5] **Jason Alexander**[6]

[1]State Key Laboratory of Computer Science and Beijing Key Lab of Human-Computer Interaction, Institute of Software, Chinese Academy of Sciences, Beijing, China
[2]School of Computer Science and Technology, University of Chinese Academy of Sciences, Beijing, China
[3]School of Artificial Intelligence, University of Chinese Academy of Sciences, Beijing, China
[4]Department of Computer Science, Jilin University, Changchun, China
[5]Department of Computer Science, University of Manitoba, Winnipeg, MB, Canada
[6]School of Computing and Communications, Lancaster University, Lancaster, UK
linianlong16@mails.ucas.ac.cn, {hanteng, tianfeng, huangjin}@iscas.ac.cn, smh@jlu.edu.cn,
pourang.Irani@cs.umanitoba.ca, j.alexander@lancaster.ac.uk

ABSTRACT

The use of Virtual Reality (VR) in applications such as data analysis, artistic creation, and clinical settings requires high precision input. However, the current design of handheld controllers, where wrist rotation is the primary input approach, does not exploit the human fingers' capability for dexterous movements for high precision pointing and selection. To address this issue, we investigated the characteristics and potential of using a pen as a VR input device. We conducted two studies. The first examined which pen grip allowed the largest range of motion—we found a tripod grip at the rear end of the shaft met this criterion. The second study investigated target selection via 'poking' and ray-casting, where we found the pen grip outperformed the traditional wrist-based input in both cases. Finally, we demonstrate potential applications enabled by VR pen input and grip postures.

Author Keywords

Virtual Reality; pen input; finger and wrist dexterity; grip postures; handheld controller; spatial target selection.

CCS Concepts

•**Human-centered computing** → **Virtual reality; User studies;**

INTRODUCTION

Virtual Reality (VR) is emerging as the next generation computing platform for diverse domains including entertainment, education, training, research, clinical practice, and productivity [15]. While the visual quality and immersive capabilities of current consumer VR devices have reached a steady state for presenting impressive graphics, the corresponding input technologies have seen much greater variety in terms of form-factors and user interactions, which remain under active exploration [19, 30, 42, 62]. While researchers have proposed many input modalities, including bare hand gestures [67], gaze [13] and speech [21], application developers heavily rely on handheld controllers as the primary means for 3D spatial [18] and consumer level VR input. This is evident by the large number of multi-button and multi-function controllers with devices such as the HTC Vive [61] and Oculus Rift [54].

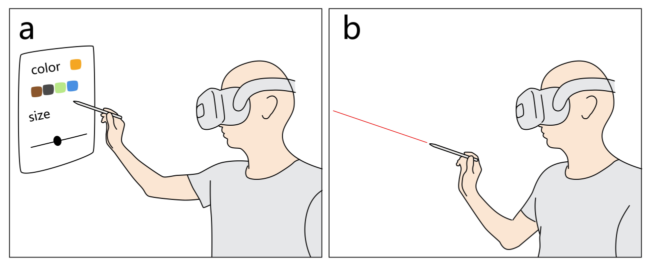

Figure 1. A user grips a pen controller to perform (a) poke gestures, and (b) tilt gestures.

For the majority of current VR controllers, users grasp them in a manner to primarily exploit "wrist rotations" [52]. For many applications, including gaming and menu interactions, wrist-based movements are adequately efficient [27] (Figure 7b). However, such grips often require that all fingers maintain a force to hold the device, inevitably restricting movements and input ranges that could normally be achieved if users' fingers were unconstrained [52]. As VR use proliferates new domains, such as immersive analytics [47], artistic endeavors [4] and clinical simulations [25], refined and precise input operations will be required, needing new grip styles.

We draw attention to the potential of pen-style controllers and grips that can exploit our fingers' rich dexterity for VR input (Figure 1). We advocate the recent commercial VR/MR pen controllers (e.g., VR Ink [23], Holo Stylus [34], Massless Pen [46]), and explore the use of relaxed grip postures to better involve the fingers' movement in a skillful and coordinated manner for precise operations. Pen input has a long tradition

∗Corresponding author

CHI '20, April 25–30, 2020, Honolulu, HI, USA.

ACM ISBN 978-1-4503-6708-0/20/04 ...$15.00.
http://dx.doi.org/10.1145/3313831.3376698

in interaction literature, from exploring the many sensors embedded on pens for tilt [59], roll [6], pressure [53], and multi DOF input [29, 32, 66]. Pen devices also support a rich set of explorations into multi-modal interactions [7, 33, 51], input for ambient displays [9], and show higher accuracy in dynamic user interface [36, 37]. Nonetheless, VR pen controllers are a relatively new introduction and face several challenges such as the lack of physical anchor surfaces. Aside from its potential as a high precision input device, we possess limited knowledge as to what extent pen controllers can benefit VR target pointing, selecting, gesturing and mode switching.

To this end, we explore how pen grips exploit our fingers' dexterous ability in mid-air. In a systematic approach, we first explore five suitable pen grip postures, including the common tripod grip, for enabling tilt-based operations in mid-air in Study 1. We find that the tripod grip at the rear end of the shaft performed better than the other grip postures. It led to significantly larger moving distances and tilt angles in most directions. We next explore the efficiency of target selection in VR, and in Study 2 we execute a ISO 9241-9 reciprocal selection test [39]. In this study, we compared performance of the pen grip (tripod grip at the rear end of the shaft) with that of a *Palm Grip* (such as the one used with the HTC controller). With two stages of the study, participants selected near-field targets with poking gestures, and distant targets using ray-casting and tilting gestures, respectively. The results showed that the pen grip posture improved the target selection time with both gestures, and was less error-prone with poking gestures.

Based on the previous studies and understandings, we demonstrate potential applications with pen input and the grip postures. We show that it is easy to switch between the *Pen Grip* and *Palm Grip* postures, enabling interaction opportunities that can exploit the benefits of both. We propose the design of pen based gestural widgets for performing short and rapid input bursts, such as tilting and poking. Lastly, we illustrate that using the pen controller helps in removing the eye-hand visibility mismatch problem.

This paper makes the following contributions: (i) empirical evidence shows the potential of using a pen to afford more precise and dexterous operations in VR; (ii) studies that identified a suitable grip posture for a pen when trying to achieve the largest comfortable range of motion; (iii) studies that evaluated the pen grip posture's performance in target selections; (iv) demo applications that showed potential applications enabled by VR pen input and grip postures.

RELATED WORK

We take inspiration from the ongoing research exploring VR input techniques, and from the recent introduction of pens in VR. In this section, we first look at related work on VR input techniques, and then we examine previous research work exploring pen based interactions. We end with a brief presentation of prior ergonomic studies on pen grip postures.

VR Input Devices and Techniques

Input devices play an important role in the creation of successful VR experiences. Traditional desktop input devices like the mouse, joystick, and keyboard are not compatible with fully immersive virtual environments due to the lack of physical surfaces [15]. Researchers have proposed a variety of input methodologies that specifically suit virtual environments. Notable examples include wearable devices [40], vision based tracking devices [49], and handheld controllers [57].

In recent years, wearable input devices have gained popularity both in the research community and commercially. They provide high quality tracking capabilities while enabling natural use of the hand. For instance, data gloves facilitate hand motion tracking, gesture recognition, and haptic feedback [40]. As gloves are often bulky, ongoing research efforts have explored lightweight sensing [45] and haptic rendering mechanisms [31] for data gloves. Similarly, supporting direct hand manipulation in VR via bare hand tracking (e.g., Leap Motion [49]), has drawn significant interest, albeit with a lack of haptic feedback. Alternative input modalities include eye gaze [13] and speech [21]. Though promising, these approaches still require further development for fluid spatial 3D input [15].

Mainstream VR manufacturers commonly use handheld controllers as their primary input device. Early controller prototypes focused on the game-play, not necessarily representing the hands' essential functions [56]. Current handheld controllers [54, 61] typically include haptic and touch-sensitive controls, allowing users to launch continuous and discrete commands or movements in the virtual environment [15]. These controllers deploy different forms of hand grip in an attempt to retain ergonomic capabilities that mimic humans' physical and manual dexterity and agility [10]. In essence, controllers exploit humans' inherent abilities developed for manipulating physical tools [8, 18]. This has motivated a rich set of VR controller designs that capture fine hand and finger motions and provide realistic haptic sensations [42, 57]. Recently released commercial controllers [38] demonstrate the capabilities of capturing both static and dynamic hand postures, as well as grip force, which enrich interactions in VR.

This paper further expands this design space by investigating the input characteristics of a pen-like controller and its grip postures.

3D Selection Techniques

Beyond hardware innovations, novel interaction techniques can increase the efficiency of target selection and manipulation in VR. Grasping metaphors emulate natural (real world) object grasping and manipulating actions with the hand [41]. Virtual hand representations are often used, and directly mapped to a user's physical hand motions [48]. However, this limits its reachability, where objects out of a user's physical reach are not selectable in the virtual world. Non-linear mapping methods can be used to resolve out-of-reach concerns. For instance, Chae et al. [11] recently proposed a method to shrink the virtual space to select distant objects.

Ray-casting is widely used and explored for distant pointing—a virtual ray is 'casted' from a point of origin along a given direction [41]. Ray-casting allows the user to select objects beyond their area of reach and requires little physical movement [3]. Research into ray-casting covers various aspects including how the ray is controlled, the ray shape, and the method to disambiguate among small, crowded, and occluded targets [30]. Other techniques such as using a touch surface [5], and designing physical proxies [12] also facilitate 3D selections.

In our work, we use 'poking' gestures for near target selection and ray-casting for distant target selection, and explore the distinctions imposed by different pen grips on these tasks.

Pen Based Interaction Techniques

Pen-based input has a long tradition in interactive systems, as it enables precise input on digital device, mimicking our handwriting in physical environments. Cockburn et al. investigated the stylus' performance in tapping and dragging on touchscreen, and compared it with the finger and mouse [16]. Their results revealed that pen input is accurate even with small targets in pointing tasks, and also facilitates dragging tasks. This was followed by many works seeking to understand pen input characteristics on tablets and phones [1, 14].

Pen input exploits our wrist and fingers' dexterous motions which can be leveraged for multi degree-of-freedom input [29]. Pressure Widgets [53] and HoverWidget [28] explored the use of continuous pressure sensing and hover sensing to operate onscreen widgets. Closer to our work, Tian et al. [59, 60] explored pen tilting gestures for cursor and menu design. Bi et al. [6] used pen rolling based interaction techniques. Xin et al. [66] carried out a more systematic investigation on how pressure, tilt and azimuth information could be leveraged to enhance pen input. The pen was also found to be useful in designing multi-modal input on touchscreens [7, 32, 33, 51].

Recently, Wu et al. [65] and Wacker et al. [62] demonstrated pen-based object selection and manipulation techniques in Augmented Reality. Our work takes an empirical, study driven approach to design and understand the use of pen and grip postures in VR.

Ergonomic Study of Grip Postures

A pen's input capabilities can be enhanced to a large extent by sensing the user's grip posture. For instance, Song et al. [55] implemented a multi-touch pen that supported the detection of various grips to enable implicit input mode switching. Grip postures are also widely studied in both the interaction and ergonomic literature [27]. Rahman et al. [52] investigated the dexterity of wrist-based input when a mobile phone was gripped in the hand. This included a framework that measured ergonomic factors like axial range-of-motion and discretization of tilt angles. Eardley et al. [22] examined how mobile devices' form-factor affected users' grip postures and hand movements. There is significant literature seeking to better understand how pen grip postures affect children's learning [44], handwriting performance [35], and stability [64].

Inspired by these prior results, we first study how different pen grip postures affect ergonomic capabilities such as the range of motion and comfort level.

STUDY 1: EFFECT OF PEN GRIP POSTURES ON WRIST AND FINGER MOTION

The overarching aim of this study was to examine the effect of pen grip style on the possible range of wrist and finger motion. Participants performed a tilt motion in eight cardinal directions while holding a pen in five common grips.

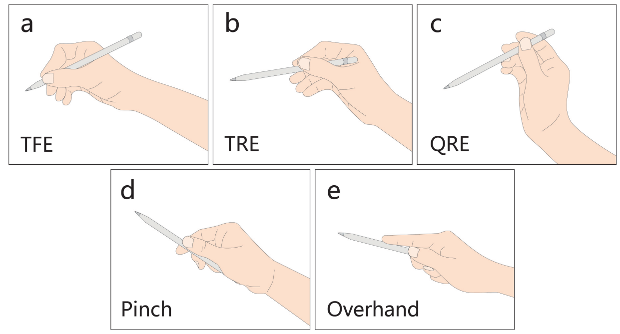

Figure 2. Candidate grip postures: (a) tripod at front end, (b) tripod at rear end, (c) quadropod at rear end, (d) pinch, and (e) overhand.

Candidate Grip Postures

We assessed a total of five grip postures based on prior work [20, 33, 55, 64], as well as those commonly used in art [63]. We excluded postures that add firm constraints to the finger/wrist movements. Figure 2 illustrates the five grip postures that were investigated in this study, their descriptions follow:

Tripod at Front End (TFE): This is the most common grip posture for precise writing and drawing on a surface (Figure 2a). It is considered the most popular and useful grip to support precise mid-air drawing and sketching [64] and often adopted in commercial VR pens. Tripod grip, with fingers positioned at the front of the shaft (TFE), facilitates writing. It is however unclear how such a grip impacts operations such as menu selection and target acquisition in VR, that often come with the requirement for agile motions of larger range. In mid-air, there is limited support for users to rest their hands.

Tripod at Rear End (TRE): This represents an alternate tripod grip where users hold the pen shaft at the rear end (Figure 2b). Wu et al. [64] observed many users held pens in this way during surface pointing and clicking tasks. Compared to TFE, gripping a pen at the rear encourages its use as a lever (with the tip feeling 'weightier').

Quadropod at Rear End (QRE): A quadropod grip is similar to the tripod grip, except that two fingers (i.e., index finger and middle finger) are used to control the pen together with the thumb (Figure 2c). The ring finger is used to rest the pen. QRE is often seen from holding a writing brush in Chinese calligraphy, where it is easy to twist the pen shaft while keeping the pen stable.

Pinch: In this grip, users perform a pinch action, holding the pen between their thumb and fingers, as if they have picked it up from a table (Figure 2d). With Pinch, the pen can be positioned parallel to the writing surface. In the context of paper writing or drawing, this helps to loosen the user's wrist and to move the pen by hovering it over the paper.

Overhand: Overhand is the posture used to hold a pen to allow the tip's use for line drawing and shading on paper in a more versatile way (Figure 2e). The hand is relaxed with fingers

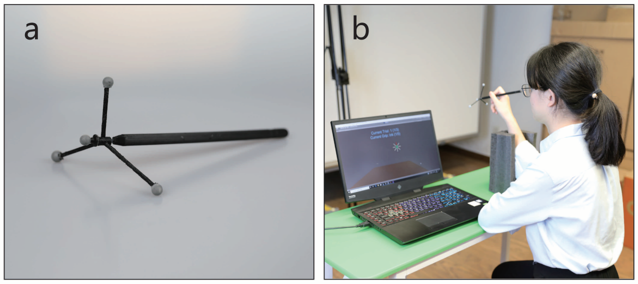

Figure 3. (a) The 3D printed pen was used in the studies; (b) A user took participant in Study 1.

and thumb lightly holding the pen. It creates several ways to control the pen, such as rolling forward or backward, sliding and even flipping.

Hardware Configuration

In this study we do not consider factors such as the pen's weight, length, or radius as there exist sufficient evidence showing how these factors affect one's grip capabilities[26]. We do not attempt to design the best pen form-factor as we instead focus on studying how pen grip affects motion. Considering that current commercially available VR pens are commonly bulky in size, we examined the design of over 10 commercial digital pens for mobile phones and pads, and decided to use the Apple Pencil [50] as the design reference. The Apple Pencil is of a compact size, lightweight and reasonable length. This offers many grip possibilities ergonomically, thus fits our study purpose.

A pen proxy, similar in size to the Apple Pencil [50] was 3D printed, as shown in Figure 3a. It measures 178 mm in length, and has a radius of 9 mm. Four additional stickers with reflective markers were attached to the pen for tracking purposes. Altogether it weights 11 g. The pen was tracked with an OptiTrack V120: Trio[1], which was driven by a Windows 10 laptop. This allows us to retrieve the spatial position and orientation of the pen at 120 fps.

Participants

Twelve (12) participants (5 female, avg. age = 24.6) were recruited from a local university for the study. All were right-handed. Each participant was rewarded with $USD20 for their participation. We first described the purpose of the study and instructed each participant to familiarise themselves with the five grip postures. They practiced moving their wrist with the pen. They were seated and placed their elbow on a table (Figure 3b). A sponge mat was used to restrain their arm to eliminate any potential effects of inadvertent arm movements.

Tasks and Procedure

The study procedure was composed of three blocks. In each block, participants were prompted to tilt the pen with a particular grip posture in eight cardinal directions sequentially (i.e., north, west, south, east, northwest, northeast, southwest and southeast) as far as they can without reaching discomfort. Before switching to the next grip posture, participants held the

[1] https://optitrack.com/products/v120-trio/

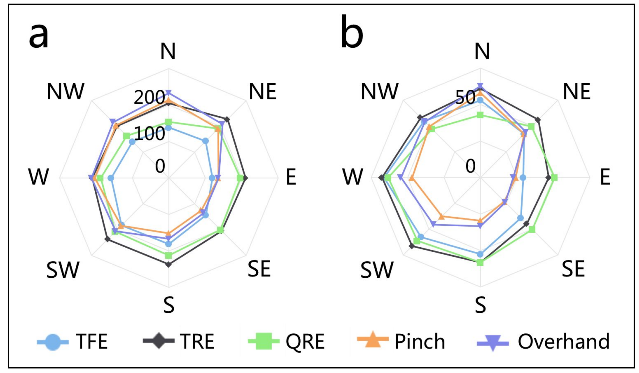

Figure 4. The results of Study 1: (a) Pen tip travelled distance (mm); (b) Pen shaft tilted angle (°).

pen in a natural position and pressed the *Ctrl* button to initialize the coordinates of the reference center. Once ready, a trial started when the participants pressed the *Spacebar* key and the target direction was prompted on screen. After performing the tilt motion, participants returned their posture to the home position, and pressed the *Spacebar* key. This ended the current trial and started the next one. Each direction was repeated three times and the same procedure was repeated for each grip posture. The order of the grip gestures used in each block was randomized. During the study, the participants were free to use their fingers and wrist to tilt the pen (i.e., no restrictions were imposed on how they should use their fingers and wrist), and were allowed to rest between trials. The tracker captured the pen tip's spatial position and the pen's orientation information at every frame during a trial (120 fps). In total, the system captured 3 blocks $\times$ 5 postures $\times$ 8 directions $\times$ 3 repetitions = 360 data logs for each participant. The participants were asked to complete a NASA-TLX form to rate workload factors from 1 to 7. The study lasted on average 40 mins per participant.

Results

As the tilt actions are centred around the wrist and not on a gripping point on the pen, the resulting tilt motion is the joint effects of pen tip translation and pen shaft rotation for each grip posture and for each direction. These two values were calculated by averaging the euclidean distance travelled by the pen tip, and the angle tilted by the pen shaft (i.e., the angle between two vectors standing for the initial and maximally tilted orientations of the shaft). Data were normally distributed according to a Shapiro-Wilks test at the 5% level. Results were analyzed using a repeated measures ANOVA and are illustrated in Figure 4.

Distance Pen-Trip Travelled

Overall there was a significant main effect of *Grip Posture* on the pen tip's moving distance ($F_{4,44} = 23.557, p < 0.001$). Pairwise comparisons using the Bonferroni adjustment yielded the moving distance with *TRE* grip ($\mu = 216.79mm, \sigma = 8.55mm$) was significantly larger than all others (all $p < 0.05$), and the moving distance of the *TFE* grip ($\mu = 151.06mm, \sigma = 5.00mm$) was significantly shorter than all others (all $p < 0.05$). There were no significant differences among *Pinch*

($\mu = 176.44mm, \sigma = 9.95mm$), *QRE* ($\mu = 188.92mm, \sigma = 8.90mm$), and *Overhand* ($\mu = 189.31mm, \sigma = 9.59mm$).

Across postures, the moving distance in the *Southwest* direction was the largest ($\mu = 204.10mm, \sigma = 11.76mm$), and the shortest distance was in the *East* direction ($\mu = 159.80mm, \sigma = 9.44mm$) (both $p < 0.05$). This is in line with expectations, as all of our participants were right-handed, with their actions appearing to be more flexible when tilting the wrist and fingers inwards rather than outwards. However, significant effects were not found on every pair of the directions, and there was an interactive effect between *Grip Postures* and *Directions* ($F_{28,308} = 15.21, p < 0.001$). The moving distance of *TRE* and *QRE* postures were significantly larger than others in the *East*, *Southeast* and *South* direction (all $p < 0.05$, except for the pair of *QRE* and *Pinch* in the *East* direction where $p = 0.078$). In both *North* and *Northwest* directions, *Overhand* had the largest moving distance, but was not significantly different to *TRE* in *North* ($p = 0.056$), and to *TRE*, and *Pinch* in *Northwest* (all $p > 0.05$). Besides, in the two directions, *TFE* and *QRE* postures led to significantly shorter distance than others (all $p < 0.05$, except for the pair of *QRE* and *Pinch* in *Northwest* where $p = 0.064$).

Tilt Angle

There was a significant main effect of *Grip Posture* on the tilt angle ($F_{4,44} = 26.19, p < 0.001$). Pairwise comparisons using the Bonferroni adjustment yielded a tilt angle with *TRE* ($\mu = 57.33°, \sigma = 3.42°$) was significantly larger than other postures (all $p < 0.05$), except for *QRE* ($\mu = 52.89°, \sigma = 3.93°$) ($p = 0.65$). The *Pinch* posture ($\mu = 38.87°, \sigma = 2.70°$) led to a significantly smaller tilt angle than other postures (all $p < 0.05$), except for *Overhand* ($\mu = 42.59°, \sigma = 2.95°$) ($p = 0.237$).

Across postures, *Direction* also had a significant main effect on the tilt angle ($F_{7,77} = 21.10, p < 0.001$). The tilt angle in the *West* direction ($\mu = 59.67°, \sigma = 5.51°$) was significantly larger than that of *East*, *Southeast*, and *Southeast* directions (all $p < 0.05$). The *East* direction let to the smallest tilt angle ($\mu = 34.72°, \sigma = 2.67°$), which was significantly smaller than other directions (all $p < 0.05$) except for the *Southeast* direction ($p = 0.73$).

Similar to the moving distance, there was also an interactive effect between *Postures* and *Directions*($F_{28,308} = 13.03, p < 0.001$). In the *East* direction, the *TRE* and *QRE* postures led to significantly larger tilt angle (all $p < 0.05$). In the *Southeast*, *South*, and *Southwest* direction, the tilt angle of *Pinch* and *Overhand* postures were significantly smaller than all other postures (all $p < 0.05$). No significant effect was found among the five postures in the *North* and *Northwest* direction except for the pair of *TRE* and *QRE* ($p = 0.01; p = 0.015$).

Subjective Workload

Study results were analyzed using a Friedman test with Wilcoxon signed rank tests for pair-wise comparisons. Overall, average NASA-TLX ratings for all grip postures were less than 3.5 (with 1 indicating the posture was very easy and 7 being very hard to learn) except for *QRE* ($\mu = 4.127$). This suggests that most of the participants could use these postures

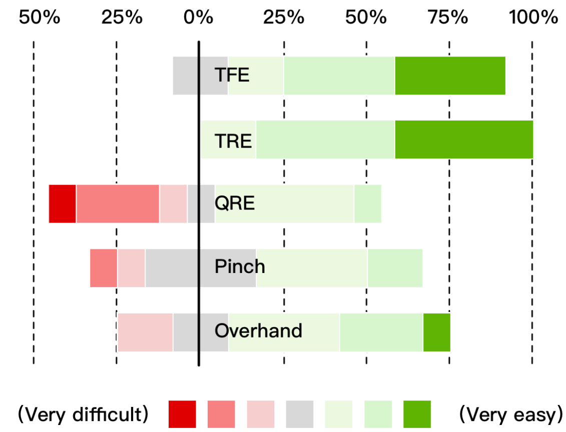

Figure 5. Participant responses to the workload of different grip postures. Graphs are centered around the neutral response, with the proportion of positive and negative responses on the right and left side, respectively.

well except for *QRE* (Figure 5). Some participants said that they had no experience in writing with Chinese brush. The Friedman test yielded a significant difference in *Grip Posture* ($\chi^2(4, N = 12) = 23.54, p < 0.001$). The *TRE* posture was rated as significantly easier ($\mu = 1.87$) to use than others (all $p < 0.05$) except for *TFE* ($\mu = 2.08$)($p = 0.747$).

Discussion

This study focused on identifying the effect of different pen grips on achieving the largest comfortable range of motion. It allowed us to examine the extent to which, the joint motions of wrist and finger movements contribute to the tilting actions. Different grip postures added various constraints to not only to the fingers' extension, but also to the wrists. Amongst the five grip postures, *Pinch* and *Overhand* were found to produce smaller range of motions compared to the others.

Overall, *TRE* performed better than the other grip postures. It led to larger moving distances and tilt angles in most directions. This is understandable, as compared to *TFE*, gripping the pen at the rear end places the fulcrum further from the pen tip, allowing a larger radius of movement by the pen tip. Furthermore, a relatively more loaded force can be sensed by hands. Moreover, the *TFE* grip often rests the pen on the thumb cleft, that restricts the tilt range of the pen. Participants also confirmed that *TRE* felt more comfortable and relaxed.

QRE also grips the pen at the rear end, and similar to *TRE*, it shows advantages in moving distances and tilt angles in *East*, *Southeast*, and *South*. However, *TRE* significantly outperformed *QRE* in the *North* and *Northwest* directions. Compared to *TRE*, *QRE* grips the pen more strenuously and the two fingers (i.e., index and middle) used to control the pen restrict its upward tilt movement (i.e., *North*).

The effects of *Direction* matched our expectations, where the fingers became more engaged while tilting the pen upwards (*North*) and downwards (*South*). As confirmed by the par-

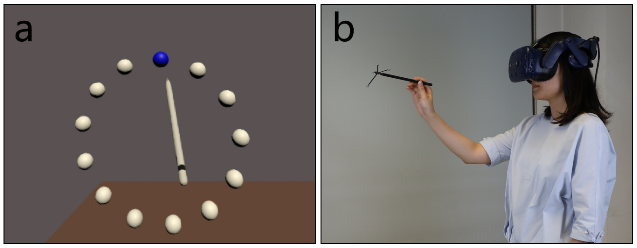

Figure 6. (a) The user interface for selection with the poke; (b) A participant uses the *Pen Grip* and selects with the poke in Study 2.

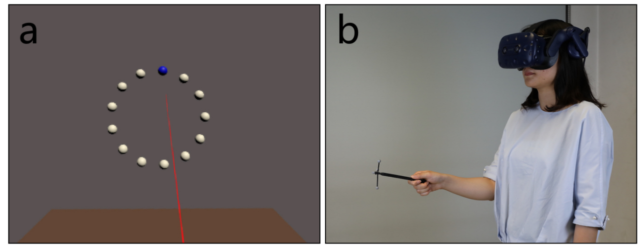

Figure 7. (a) The user interface for selection with tilt; (b) A participant uses the *Palm Grip* and selects with tilt in Study 2.

ticipants, it was especially difficult to tilt the pen in the *East* direction due to wrist ulnar/radial deviation. In this case, the tilting action is primarily performed by the wrist regardless of which grip posture was used. While this type of motion can be avoided in the design of interactions, when a larger range of tilt in the *East* or *West* direction is required, it may be achieved by rotating the wrist 90 ° to perform a wrist pronation/suppination movement. Furthermore, we analyzed and compared the consistency of the raw tilt trajectories for each of the grip postures and each direction, which was defined as how similar the repetitive tilt motion of the same condition was to each other, but found that no grip posture showed an obvious advantage.

These results and analysis suggest that *TRE* is the better suited posture for largest wrist motion reach. It allows the fingers to also contribute to the overall motion and can facilitate a larger input range for pen based VR interfaces. However, it is unclear how this grip posture would benefit typical VR interface tasks such as target selection. We examine this in Study 2.

STUDY 2: PERFORMANCE IN VR TARGET SELECTION

Pen input enables precise drawing and writing [23] in VR, however its performance in general interface tasks such as target selection has yet to be evaluated. In the previous study we found that griping the pen at the rear end of the shaft can better facilitate the fingers' dexterous motions. Based on these findings, this study aims to understand how efficient pen input is for VR target selection, in comparison with the typical *Palm Grip* used in current commercial controllers. For this study we use *Pen Grip* to refer to the TRE posture, and distinguish it from *Palm Grip*. These two grip postures are illustrated in Figure 6b and Figure 7b.

To guide our study design, we analyzed existing interface metaphors and gestures for menu and object selection tasks in commercial VR devices (e.g., HTC Vive [61] and Oculus Rift [54]). Two typical gestures were identified: *poke* and *tilt*:

Poke: Poke gestures are used to select items on menus that are physically reachable. The action is similar to touching a screen, however, users do not perceive any haptic feedback. It is intuitive and normally requires no trigger mechanism.

Tilt: In contrast to *Poke*, *Tilt* gestures are often used alongside ray-casting for distant pointing. This is especially common in VR interactions, where menus are floated in space beyond a user's zone of physical reach. A trigger mechanism is needed to confirm the user's selection, e.g., button or dwell.

Experimental Tasks and Conditions

This study adopted the design of the ISO 9241-9 reciprocal selection test [39], where 13 balls of various sizes are placed around circles of various radii, and participants select each of the balls in a random order with a given input device or technique. There were two sessions in the study: in the first session, the *Poke* gesture was used; and in the second the *Tilt* gesture was used for selection. This is because the comparison of pointing based on tilting and poking is not of interest to us in this paper. In both sessions, we asked the participants to select the balls with *Pen Grip* and *Palm Grip*, and compared their performance for selecting targets.

Beyond the *Grip Posture (Pen Grip, Palm Grip)*, the *Target Width and Target Distance* were set following Teather et al. [58], where in the *Poke* condition, the target widths (i.e., diameter of the target ball) were set to (0.018, 0.03), and the target distance were set to (0.14, 0.30, 0.38). In the *Tilt* condition, the target widths were set to (0.054, 0.09), and the target distance were set to (0.42, 0.90, 1.14), all with the units of meters. This resulted in Fitts' IDs of (2.50, 3.13, 3.46, 3.77, 4.14, 4.47) in both conditions.

The order of the *Pen Grip* and the *Palm Grip* was counterbalanced, while each pair of *Target Size* and *Circle Radius* was repeated 5 times, and appeared in random order. In a similar manner to Teather et al. [58], a trial was counted when the participant completed the selection of all 13 targets around the circle, thus in each session, there were 2 (grip postures) $\times$ 2 (target size) $\times$ 3 (circle radius) $\times$ 5 (repetitions) = 60 trials, that included 60 (trials) $\times$ 13 (targets) = 780 poke or tilt selections.

Apparatus and Procedure

This study used the same tracking device and pen prototype as used in Study 1. A different group of 16 right-handed participants (7 female, avg. age = 23.63) were recruited from the same university. In the same manner as Study 1, each of the participants were rewarded with $20 for their participation. They were introduced to the idea and the study setup, and were asked to stand in front of a table while wearing an HTC Vive Headset (Figure 6b and 7b) that ran the experimental (Unity) application. They were provided sufficient time to get familiar with the tasks and techniques before the formal study started.

A trial is initialized by displaying 13 target balls at the current condition, and with a target ball highlighted in red. Once the ball is successfully selected, the ball turns blue for 1 second and the next target ball is highlighted in red. The trial starts when the participants make the first selection, and ends when the last target gets selected. The appearances of the target was randomized. Note the time for selecting the first target did not count for the trial time.

After each session, the participants were asked to complete a NASA-TLX form for each of the grip postures. The study lasted an average of 1 hour per participant.

Poke Gestures

The virtual targets were displayed in the VR headset, at a fixed depth of 0.2m, with their heights adjusted based on the participants' hand positions, making it comfortable for users to perform poke gestures. Specifically, the height value was determined by averaging the current participant's hand position when naturally holding the pen with *Pen Grip* and *Palm Grip* when not moving towards to the target. The poking action is identified by the pen entering the 3D target volume and then exiting it. To avoid the participant slide over the target (instead of poking it), they were asked to lift the pen at least 5 cm after a selection. The pen tip entering and exiting a pre-defined invisible plane (5 cm from the target center) without touching the target was recorded as an error. Meanwhile, the targets must be 'poked' from the side that faced the participants in order to be selected. If the participants missed to select a target, she/he had to continue to select the next one. An error was counted and the missed target appeared in the last. Thus for each trial, we recorded the conditions, trial time and errors. The participants were allowed to take rest between trials, but not during a trial.

Tilt Gestures

In the second session, the *Tilt* gesture was used. The experiment setup was the same as the first session, except that the targets were displayed 2m away, and the participants made the selection with ray-casting. Once the ray is moved within the target, the target turned to green, and the participants held it (i.e., dwell) for 500 milliseconds to confirm the selection. Note that dwell was simply a design artifact of our study, not necessarily an optimal design choice. Selection can be made with other methods, e.g., button, force press, finger tap, depending on the tasks and applications. Also in this session, the participants had to make successful selections before moving to the next targets, thus there was no error data.

Results

Data were normally distributed according to a Shapiro-Wilks test at the 5% level. We analyzed the results using repeated measures ANOVA and post-hoc comparisons with Bonferroni adjustment.

Selection Time

For the selection tasks based on *Poke* gesture, a within-subject ANOVA analysis on average selection time showed a significant effect for *Postures* ($F_{1,15} = 58.06, p < 0.001$), *Target Width* ($F_{1,15} = 138.93, p < 0.001$), and *Target Distance* ($F_{2,30} = 64.79, p < 0.001$). Post-hoc tests revealed that the *Pen Grip* ($\mu = 1023ms, \sigma = 31.22ms$) was significantly faster than the *Palm Grip* ($\mu = 1257ms, \sigma = 46.82ms$) ($p < 0.001$). Based on our observations, with *Pen Grip*, the participants were more likely to move their forearm, and co-ordinated

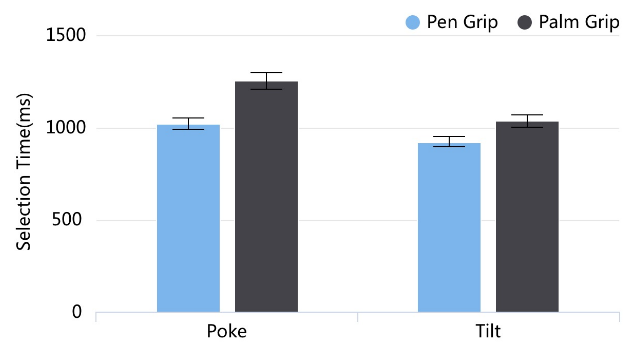

Figure 8. Mean selection time for poke and tilt.

their wrist and finger tilting actions when approaching the targets. Participants' actions appeared agile and dexterous. In contrast, poking with the *Palm Grip* involved more arm and forearm extensions, and less wrist motions. Additionally, the post-hoc tests on other factors can be anticipated: selection time significantly increased with increasing target width and target distance (all $p < 0.001$). No other significant interaction effects were found (all $p > 0.05$).

For the selection task based on *Tilt* gesture, the 500ms dwell time was removed, as in this study, our primary goal was to measure target acquisition times, not target plus selection. There was a significant effect for *Postures* ($F_{1,15} = 31.30, p < 0.001$), *Target Width* ($F_{1,15} = 170.90, p < 0.001$), and *Target Distance* ($F_{2,30} = 313.39, p < 0.001$) on average selection time. Post-hoc tests revealed that the *Pen Grip* ($\mu = 926.014ms, \sigma = 28.00ms$) was significantly faster than the *Palm Grip* ($\mu = 1039.20ms, \sigma = 31.86ms$) ($p < 0.001$). The participants were able to leverage both finger and wrist tilting motions to point the ray to the targets when using *Pen Grip*, whereas with the *Palm Grip* they controlled the ray with wrist rotations. Similar to the previous session, significant interactive effects existed for $Postures \times Width$ ($p < 0.001$). No other significant interaction effects were found.

Error Rates

The error rates of the poke gesture were calculated and all three variables *Postures*, *Width*, and *Distance* had significant main effects of error rates (all $p < 0.001$). However, no significant interactive effect was found between them. The error rates of *Pen Grip* ($\mu = 0.096, \sigma = 0.012$) was significantly lower than *Palm Grip* ($\mu = 0.133, \sigma = 0.012$) ($p < 0.001$). In the *Tilt* condition, the participants had to successfully select each target before proceeding to the next. As such, there was no error data. The same protocol was used in prior evaluations [17].

Fitts' Law Test

Trial times across the grip postures and selection techniques were further analyzed to see whether they can be modelled with Fitts' law [24]. Pairing the target widths and distances yielded the same group of five IDs for both sessions. Figure 9 revealed a strong correlation between the trial time and ID for *Tilt* gestures, with both R^2 values above 0.88. We noticed that the two lines intersects at very low IDs, and with increasing IDs, *Pen Grip* selection is more efficient than *Palm Grip*.

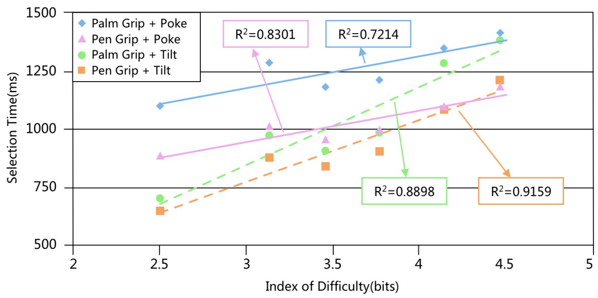

Figure 9. Fitts' law models for the poke (solid line) and tilt (dash line) tasks.

On the other hand, we did not see a strong correlation with *Poke* gestures, especially with *Palm Grip* ($R^2 = 0.7214$). This might because the pen might overshoot the targets as there was no physical surface that provides haptic feedback when using the *Poke* gesture. Nonetheless, *Pen Grip* was uniformly faster than *Palm Grip*.

Subjective Workload

Study results were analyzed using a Friedman test with Wilcoxon signed rank tests for pair-wise comparisons. Overall, average NASA-TLX ratings for all grip postures were less than 3.5 (with 1 indicating the posture was very easy and 7 being very hard to learn). This suggested that most of the participants agreed that the grip postures were easy to use for poke and tilt (Figure 10). There was no significant between the two gestures in poke ($\chi^2(1, N = 16) = 70.50, p = 0.255$) and tilt ($\chi^2(1, N = 16) = 50.50, p = 0.899$). Though *Pen Grip* was faster in acquiring the target, it did raise the fatigue issue as indicated from the followings responses:

"The Pen Grip is more tiring than Palm Grip in poking, especially for a long time, but it allows you to select target faster. " [S5]

"I can't feel the difference between Pen Grip and Palm Grip in tilting, but shoulder soreness occurs when using Pen Grip for a period of time." [S14]

Discussion

The results showed that using the *Pen Grip* improved target selection time with both poke and tilt gestures, and was less error-prone with poke gestures. This indicates that the *Pen Grip* is an efficient candidate for selection in VR interfaces.

Exploiting the fingers' dexterous motions helps to accelerate the process of adjusting the pen tip towards the target, while the user's wrist flexion motion can then quickly 'jab' it. Holding the pen with the *Pen Grip* benefits from less arm movement, where in the *Tilt* session, users were able to tilt the pen only by moving their fingers, especially when the target distance was small. While in the *Poke* session, users did not necessarily engage their upper arm motions to make the selection.

Another factor that may have contributed to this performance improvement, is that with *Pen Grip*, the pen is held higher than that with *Palm Grip*, meaning the pen is closer to the eye-line. This makes it easier for users to aim the pen. On the other

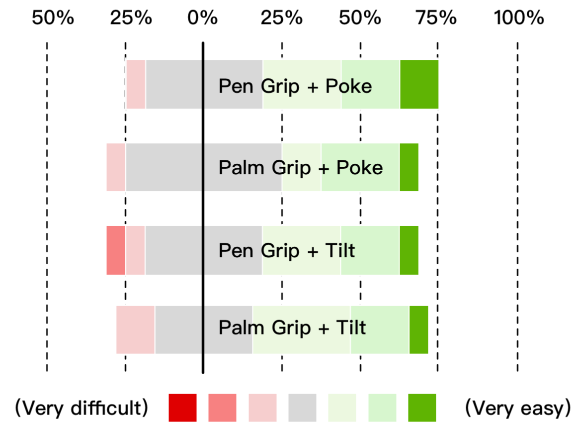

Figure 10. Participant responses to the workload of poke and tilt. Graphs are centered around the neutral response, with the proportion of positive and negative responses on the right and left side, respectively.

hand, this might also introduce a shortcoming: when the pen is held higher, the appearance of the virtual pen in the dominant view angle might add obstructions, while this is not the case for holding the pen at a lower position, where the virtual pen only appears in the user's peripheral vision. However, this needs further investigation to fully understand this effect.

The two grip postures also resulted in different comfort zones of operation. We did not include this factor in the study, but it is clear that with *Pen Grip*, a user can easily point a pen to the front and downwards, while with *Palm Grip*, pointing a pen to the front and upwards will be easier. Additionally, the fatigue caused by different grips is also worth deeper exploration. The participants reported that the *Pen Grip* felt relaxed at the beginning as they could just leverage finger motions to control the pen. However, fatigue was gradually perceived when the forearm were raised and held for a certain time, and participants took more breaks during the test. In comparison, the participants did not report similar issues with *Palm Grip*. This indicated that the *Pen Grip* was not suitable for performing long-duration tasks.

INTERACTION TECHNIQUES AND APPLICATIONS

This section presents three scenarios enabled by VR pen input and grip postures.

Switching Grips

Although the *Pen Grip* is shown to be more capable for quick and precise selection, the *Palm Grip* has the advantage of familiarization and is less tiring. Inspired by this, we looked at how to combine the two to bring a better user experience when using the pen. Key to this, is switching between gripping postures. It can be easily done, for example, by flipping the pen. This enables new interaction opportunities like input mode switching. For instance, in an interior design application, one can select furniture with the *Palm Grip*, and switch to the *Pen Grip* to invoke a menu and perform operations like picking a color from a palette, or adjusting values on a scale by dragging a slider (Figure 11). There are many approaches to

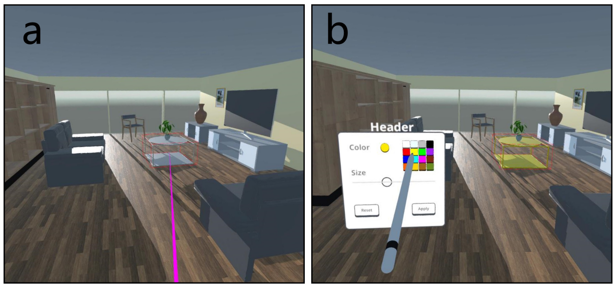

Figure 11. (a) A participant first selected a furniture using *Palm Grip*, (b) then changed its color using *Pen Grip*.

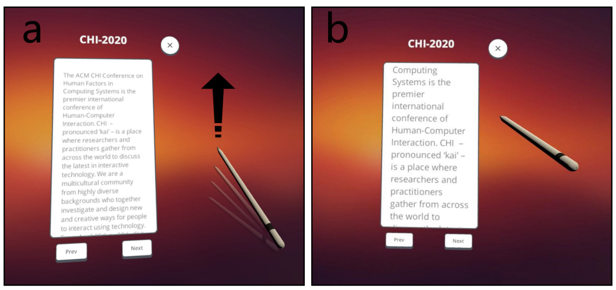

Figure 12. (a) A participant used tilt gesture to scroll the web page, (b) and double poked to zoom in or zoom out.

support grip switching actions, such as using capacitive touch sensors on the pen's surface or an internal motion sensor.

Pen-based Gestural Widgets

The user's ability to exert dexterous and large-range finger motions while gripping the pen at its rear end, allows us to design a set of unique pen based gestures in mid-air that are otherwise hard to do with other postures. With the grip, one can easily perform short and rapid input bursts, such as tilting and poking. These gestures can be captured and recognized either via the external motion tracker, or in a self-contained way (e.g., accelerometer). In this demo scenario (Figure 12), we show that the gestures can be utilized as interface widgets, which trigger scrolling or zooming operations on a web view with tilting and poking the pen respectively. A double tilt makes the page scroll automatically, while a double poke calls a stop. In 3D painting and visual data analysis scenarios, it is more convenient to manipulate 3D models. Gestural widgets as such can help improve the interface efficiency without relying on menus.

Avoiding the Eye-Hand Visibility Mismatch

When using virtual pointing techniques to select targets in VR, the user may suffer from eye-hand visibility mismatch [3]. For example, it is difficult for users to manipulate complex molecular substructures or select the human skeleton in medical treatment [2]. More specifically, in the scenario shown in Figure 13a, the user can select an object which is hidden by another object he can't see with the *Palm Grip*, leading to misinterpretation. Moreover, in Figure 13b, the larger object is stacked below the target object. While a user can see the target

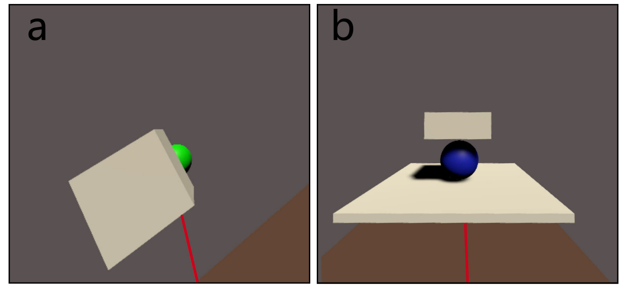

Figure 13. (a) A participant can select an invisible object; (b) A participant can see but cannot select the target.

object, the larger object can easily block the pointing ray if the user holds the controller with the *Palm Grip*. This may cause selection errors and cause user frustration. In contrast, the *Pen Grip* avoids this problem and keeps a high consistency between the visibility of the eyes and that of the hands. As shown in Study 2, the posture also helps users when aiming the pen at targets where precise selection is needed.

DISCUSSION AND FUTURE WORK

The concept of using a pen shaped controller in VR is not new. However, little was previously known on its performance in the fundamental interaction tasks of pointing and selection. Our first study identified the grip posture best suited for a pen when trying to achieve the largest comfortable range of motion. Different from the typical tripod grip that holds the pen at its front end, we found that using the tripod gesture at the rear end resulted in a larger range of motion while maintaining a good level of comfort. With the second study, we confirmed its efficiency in pointing tasks when used for performing tilt and poke gestures. The results indicated there is a good potential to use the pen for VR operations in the future, provided we instruct users on the proper grip. One way of doing so is in the pen design itself, suggest where and how the user should grip.

Nonetheless, our paper has several limitations, some of which are worth exploration in future research. Besides tilt and poke gestures, the pen's use has been explored in many other ways. Bi et al. [6] investigated the properties of rolling a pen and its design space on a touch surface. This rolling gesture is also a viable input method in VR. One challenge of performing pen rolling gestures in air, is to identify suitable grip gestures that keep a good balance of range of motion (i.e., angle of rotation) and stabilization. The Quadropod grip posture could be a good candidate but requires further evaluation.

In the second study, dwell was used to confirm a selection with tilt gestures and ray-casting. Dwell is considered an experimental artifact, not necessarily an optimal choice to trigger a selection. Designers could also add a physical button to the pen, close to the user's thumb or index finger when they hold the pen. This could be a more practical solution, but raises a new challenge that as the fingers are primarily used in gripping and wielding the pen in the *Pen Grip* posture, it is unclear how switching the fingers' roles frequently would affect performance in pointing tasks. The *Palm Grip* could be better in this case, as it relies on wrist rotations, leaving thumb and index finger for other operations. This indicates that a joint use of both grip postures could be more practical, as shown in the demo application. Another challenge is the location of physical button, one cannot easily look directly at the physical pen to see where the button is. Some existing methods may be able to solve this problem by using motion sensors for detecting taps without buttons [32, 43].

Similar to most controllers, haptic feedback is critical for creating successful use experiences of the pen. This brings new opportunities as well as challenges for future work. Adding vibrotactile feedback to the pen device is feasible with a high frequency linear actuator, which can be leveraged to render a rich set of haptic profiles with proper mapping to interface interactions.

In our studies, we used a compact-sized 3D printed pen, that was similar to a regular pen, which users are accustomed to. The results may vary if a bulkier or heavier pen was used. However, despite the technical challenges, developers should aim for VR pen's of this smaller form factor; larger, heavier form factors may play a critical (potentially negative) role in the user's experience. Meanwhile, other form-factor design options should be considered and evaluated in future work.

CONCLUSION

The current design of handheld controllers, such as those used with the HTC Vive and Oculus Rift, primarily exploit wrist rotation gestures for input. These miss the opportunity to fully utilize the fingers' capability for dexterous movements for high precision pointing and selection in VR. In this paper, we look into the potential of a pen-style controller and grip that can exploit our fingers' rich dexterity for VR input. With two studies, we found that the tripod grip at the rear end is an optimal grip posture for a pen when trying to achieve the largest comfortable range of motion. This improved the target selection time with either poke or tilt gestures, and was less error-prone with poke gestures. Finally, we discussed interaction design and application opportunities with pen input in VR.

ACKNOWLEDGMENTS

We thank Luyao Shen for help with figure drawing and video editing, Zongqi Zhang for help with conducting the experiments, Sinong Zhan for help with the software implementation, the members of IEL ISCAS, and the reviewers for their constructive feedback. This work was supported by the National Key R&D Program of China (Grant No. 2016YFB1001402), the National Natural Science Foundation of China (Grant No. 61802379, 61872164) and Youth Innovation Promotion Association CAS.

REFERENCES

[1] Michelle Annett, Fraser Anderson, Walter F. Bischof, and Anoop Gupta. 2014. The Pen is Mightier: Understanding Stylus Behaviour While Inking on Tablets. In *Proceedings of Graphics Interface 2014 (GI '14)*. Canadian Information Processing Society, Toronto, Ont., Canada, Canada, 193–200. http://dl.acm.org.uml.idm.oclc.org/citation.cfm?id=2619648.2619680

[2] Ferran Argelaguet and Carlos Andujar. 2009. Efficient 3D pointing selection in cluttered virtual environments. *IEEE Computer Graphics and Applications* 29, 6 (2009), 34–43.

[3] Ferran Argelaguet and Carlos Andujar. 2013. A survey of 3D object selection techniques for virtual environments. *Computers & Graphics* 37, 3 (2013), 121–136.

[4] Rahul Arora, Rubaiat Habib Kazi, Fraser Anderson, Tovi Grossman, Karan Singh, and George Fitzmaurice. 2017. Experimental Evaluation of Sketching on Surfaces in VR. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17)*. ACM, New York, NY, USA, 5643–5654. DOI: http://dx.doi.org/10.1145/3025453.3025474

[5] Hrvoje Benko and Steven Feiner. 2007. Balloon selection: A multi-finger technique for accurate low-fatigue 3d selection. In *2007 IEEE Symposium on 3D User Interfaces*. IEEE.

[6] Xiaojun Bi, Tomer Moscovich, Gonzalo Ramos, Ravin Balakrishnan, and Ken Hinckley. 2008. An Exploration of Pen Rolling for Pen-based Interaction. In *Proceedings of the 21st Annual ACM Symposium on User Interface Software and Technology (UIST '08)*. ACM, New York, NY, USA, 191–200. DOI: http://dx.doi.org/10.1145/1449715.1449745

[7] Drini Cami, Fabrice Matulic, Richard G. Calland, Brian Vogel, and Daniel Vogel. 2018. Unimanual Pen+Touch Input Using Variations of Precision Grip Postures. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology (UIST '18)*. ACM, New York, NY, USA, 825–837. DOI: http://dx.doi.org/10.1145/3242587.3242652

[8] Xiang Cao and Ravin Balakrishnan. 2003. VisionWand: Interaction Techniques for Large Displays Using a Passive Wand Tracked in 3D. In *Proceedings of the 16th Annual ACM Symposium on User Interface Software and Technology (UIST '03)*. ACM, New York, NY, USA, 173–182. DOI: http://dx.doi.org/10.1145/964696.964716

[9] Xiang Cao and Ravin Balakrishnan. 2006. Interacting with Dynamically Defined Information Spaces Using a Handheld Projector and a Pen. In *Proceedings of the 19th Annual ACM Symposium on User Interface Software and Technology (UIST '06)*. ACM, New York, NY, USA, 225–234. DOI: http://dx.doi.org/10.1145/1166253.1166289

[10] Eli Carmeli, Hagar Patish, and Raymond Coleman. 2003. The aging hand. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences* 58, 2 (2003), M146–M152.

[11] Han Joo Chae, Jeong-in Hwang, and Jinwook Seo. 2018. Wall-based Space Manipulation Technique for Efficient Placement of Distant Objects in Augmented Reality. In *Proceedings of the 31st Annual ACM Symposium on*

User Interface Software and Technology (UIST '18). ACM, New York, NY, USA, 45–52. DOI: http://dx.doi.org/10.1145/3242587.3242631

[12] Lung-Pan Cheng, Eyal Ofek, Christian Holz, Hrvoje Benko, and Andrew D. Wilson. 2017. Sparse Haptic Proxy: Touch Feedback in Virtual Environments Using a General Passive Prop. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17)*. ACM, New York, NY, USA, 3718–3728. DOI:http://dx.doi.org/10.1145/3025453.3025753

[13] Mungyeong Choe, Yeongcheol Choi, Jaehyun Park, and Hyun K Kim. 2019. Comparison of Gaze Cursor Input Methods for Virtual Reality Devices. *International Journal of Human–Computer Interaction* 35, 7 (2019), 620–629.

[14] Kyung-mi Chung and Dong-Hee Shin. 2015. Effect of Elastic Touchscreen and Input Devices with Different Softness on User Task Performance and Subjective Satisfaction. *Int. J. Hum.-Comput. Stud.* 83, C (Nov. 2015), 12–26. DOI: http://dx.doi.org/10.1016/j.ijhcs.2015.06.003

[15] Pietro Cipresso, Irene Alice Chicchi Giglioli, Mariano Alcañiz Raya, and Giuseppe Riva. 2018. The past, present, and future of virtual and augmented reality research: a network and cluster analysis of the literature. *Frontiers in Psychology* 9 (2018), 2086.

[16] Andy Cockburn, David Ahlström, and Carl Gutwin. 2012. Understanding Performance in Touch Selections: Tap, Drag and Radial Pointing Drag with Finger, Stylus and Mouse. *Int. J. Hum.-Comput. Stud.* 70, 3 (March 2012), 218–233. DOI: http://dx.doi.org/10.1016/j.ijhcs.2011.11.002

[17] Andy Cockburn and Carl Gutwin. 2009. A predictive model of human performance with scrolling and hierarchical lists. *Human–Computer Interaction* 24, 3 (2009), 273–314.

[18] David M Cook and Derani N Dissanayake. 2019. Virtual Reality and Older Hands: Dexterity and accessibility in hand-held VR Control. *Virtual Reality* (2019).

[19] Nathan Cournia, John D. Smith, and Andrew T. Duchowski. 2003. Gaze- vs. Hand-based Pointing in Virtual Environments. In *CHI '03 Extended Abstracts on Human Factors in Computing Systems (CHI EA '03)*. ACM, New York, NY, USA, 772–773. DOI: http://dx.doi.org/10.1145/765891.765982

[20] Julie L Dennis and Yvonne Swinth. 2001. Pencil grasp and children's handwriting legibility during different-length writing tasks. *American Journal of Occupational Therapy* 55, 2 (2001), 175–183.

[21] Denis V Dorozhkin and Judy M Vance. 2008. Implementing speech recognition in virtual reality. In *ASME 2002 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. American Society of Mechanical Engineers Digital Collection, 61–65.

[22] Rachel Eardley, Anne Roudaut, Steve Gill, and Stephen J. Thompson. 2017. Understanding Grip Shifts: How Form Factors Impact Hand Movements on Mobile Phones. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17)*. ACM, New York, NY, USA, 4680–4691. DOI: http://dx.doi.org/10.1145/3025453.3025835

[23] Logitech VR Ink Pilot Edition. 2019. (2019). Retrieved July 31, 2019 from https://www.logitech.com/en-us/promo/vr-ink.html.

[24] Paul M Fitts. 1954. The information capacity of the human motor system in controlling the amplitude of movement. *Journal of experimental psychology* 47, 6 (1954), 381.

[25] Bernie Garrett, Tarnia Taverner, Diane Gromala, Gordon Tao, Elliott Cordingley, and Crystal Sun. 2018. Virtual reality clinical research: promises and challenges. *JMIR serious games* 6, 4 (2018), e10839.

[26] Ravindra S Goonetilleke, Errol R Hoffmann, and Ameersing Luximon. 2009. Effects of pen design on drawing and writing performance. *Applied ergonomics* 40, 2 (2009), 292–301.

[27] Etienne Grandjean and Harold Oldroyd. 1980. *Fitting the task to the man: an ergonomic approach*. Vol. 387. Taylor & Francis London.

[28] Tovi Grossman, Ken Hinckley, Patrick Baudisch, Maneesh Agrawala, and Ravin Balakrishnan. 2006. Hover Widgets: Using the Tracking State to Extend the Capabilities of Pen-operated Devices. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '06)*. ACM, New York, NY, USA, 861–870. DOI: http://dx.doi.org/10.1145/1124772.1124898

[29] Khalad Hasan, Xing-Dong Yang, Andrea Bunt, and Pourang Irani. 2012. A-coord Input: Coordinating Auxiliary Input Streams for Augmenting Contextual Pen-based Interactions. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '12)*. ACM, New York, NY, USA, 805–814. DOI: http://dx.doi.org/10.1145/2207676.2208519

[30] Juan David Hincapié-Ramos, Kasim Ozacar, Pourang P. Irani, and Yoshifumi Kitamura. 2015. GyroWand: IMU-based Raycasting for Augmented Reality Head-Mounted Displays. In *Proceedings of the 3rd ACM Symposium on Spatial User Interaction (SUI '15)*. ACM, New York, NY, USA, 89–98. DOI: http://dx.doi.org/10.1145/2788940.2788947

[31] Ronan Hinchet, Velko Vechev, Herbert Shea, and Otmar Hilliges. 2018. DextrES: Wearable Haptic Feedback for Grasping in VR via a Thin Form-Factor Electrostatic Brake. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology (UIST '18)*. ACM, New York, NY, USA, 901–912. DOI: http://dx.doi.org/10.1145/3242587.3242657

[32] Ken Hinckley, Michel Pahud, Hrvoje Benko, Pourang Irani, François Guimbretière, Marcel Gavriliu, Xiang 'Anthony' Chen, Fabrice Matulic, William Buxton, and Andrew Wilson. 2014. Sensing Techniques for Tablet+Stylus Interaction. In *Proceedings of the 27th Annual ACM Symposium on User Interface Software and Technology (UIST '14)*. ACM, New York, NY, USA, 605–614. DOI: http://dx.doi.org/10.1145/2642918.2647379

[33] Ken Hinckley, Koji Yatani, Michel Pahud, Nicole Coddington, Jenny Rodenhouse, Andy Wilson, Hrvoje Benko, and Bill Buxton. 2010. Pen + Touch = New Tools. In *Proceedings of the 23Nd Annual ACM Symposium on User Interface Software and Technology (UIST '10)*. ACM, New York, NY, USA, 27–36. DOI: http://dx.doi.org/10.1145/1866029.1866036

[34] Holo-Stylus. 2019. (2019). Retrieved July 31, 2019 from https://www.holo-stylus.com.

[35] Hsiao-Man Hsu, Yu-Chen Lin, Wei-Jr Lin, Chien-Ju Lin, Yen-Li Chao, and Li-Chieh Kuo. 2013. Quantification of handwriting performance: Development of a force acquisition pen for measuring hand-grip and pen tip forces. *Measurement* 46, 1 (2013), 506–513.

[36] Jin Huang, Feng Tian, Xiangmin Fan, Xiaolong Luke Zhang, and Shumin Zhai. 2018. Understanding the uncertainty in 1D unidirectional moving target selection. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. ACM, 237.

[37] Jin Huang, Feng Tian, Nianlong Li, and Xiangmin Fan. 2019. Modeling the Uncertainty in 2D Moving Target Selection. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*. ACM, 1031–1043.

[38] imore.com. 2019. Valve Knuckles controllers: Everything you need to know! (2019). Retrieved July 31, 2019 from https://www.imore.com/valve-knuckles-controllers-everything-you-need-know.

[39] ISO 9241-9 2000. *Ergonomic Requirements for Office Work with Visual Display Terminals (VDTs) – Part 9: Requirements for Non-keyboard Input Devices*. Standard. International Organization for Standardization, Geneva, CH.

[40] Ji-Hwan Kim, Nguyen Duc Thang, and Tae-Seong Kim. 2009. 3-D hand motion tracking and gesture recognition using a data glove. In *2009 IEEE International Symposium on Industrial Electronics*. 1013–1018. DOI: http://dx.doi.org/10.1109/ISIE.2009.5221998

[41] Joseph J LaViola Jr, Ernst Kruijff, Ryan P McMahan, Doug Bowman, and Ivan P Poupyrev. 2017. *3D user interfaces: theory and practice*. Addison-Wesley Professional.

[42] Jaeyeon Lee, Mike Sinclair, Mar Gonzalez-Franco, Eyal Ofek, and Christian Holz. 2019. TORC: A Virtual Reality Controller for In-Hand High-Dexterity Finger Interaction. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (CHI '19)*. ACM, New York, NY, USA, Article 71, 13 pages. DOI: http://dx.doi.org/10.1145/3290605.3300301

[43] Frank Chun Yat Li, Richard T Guy, Koji Yatani, and Khai N Truong. 2011. The 1line keyboard: a QWERTY layout in a single line. In *Proceedings of the 24th annual ACM symposium on User interface software and technology*. ACM, 461–470.

[44] Qiushi Lin, Jianfei Luo, Zhongcheng Wu, Fei Shen, and Zengwu Sun. 2015. Characterization of fine motor development: Dynamic analysis of childrenâĂŹs drawing movements. *Human movement science* 40 (2015), 163–175.

[45] Eric Markvicka, Guanyun Wang, Yi-Chin Lee, Gierad Laput, Carmel Majidi, and Lining Yao. 2019. ElectroDermis: Fully Untethered, Stretchable, and Highly-Customizable Electronic Bandages. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (CHI '19)*. ACM, New York, NY, USA, Article 632, 10 pages. DOI: http://dx.doi.org/10.1145/3290605.3300862

[46] Massless. 2019. (2019). Retrieved July 31, 2019 from https://massless.io.

[47] Patrick Millais, Simon L. Jones, and Ryan Kelly. 2018. Exploring Data in Virtual Reality: Comparisons with 2D Data Visualizations. In *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems (CHI EA '18)*. ACM, New York, NY, USA, Article LBW007, 6 pages. DOI: http://dx.doi.org/10.1145/3170427.3188537

[48] Alec G Moore, John G Hatch, Stephen Kuehl, and Ryan P McMahan. 2018. VOTE: A ray-casting study of vote-oriented technique enhancements. *International Journal of Human-Computer Studies* 120 (2018), 36–48.

[49] Leap Motion. 2019. (2019). Retrieved July 31, 2019 from https://www.leapmotion.com/.

[50] Apple Pencil. 2019. (2019). Retrieved July 31, 2019 from https://www.apple.com/apple-pencil/.

[51] Ken Pfeuffer, Jason Alexander, Ming Ki Chong, Yanxia Zhang, and Hans Gellersen. 2015. Gaze-Shifting: Direct-Indirect Input with Pen and Touch Modulated by Gaze. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology (UIST '15)*. ACM, New York, NY, USA, 373–383. DOI: http://dx.doi.org/10.1145/2807442.2807460

[52] Mahfuz Rahman, Sean Gustafson, Pourang Irani, and Sriram Subramanian. 2009. Tilt Techniques: Investigating the Dexterity of Wrist-based Input. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '09)*. ACM, New York, NY, USA, 1943–1952. DOI: http://dx.doi.org/10.1145/1518701.1518997

[53] Gonzalo Ramos, Matthew Boulos, and Ravin Balakrishnan. 2004. Pressure Widgets. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '04)*. ACM, New York, NY, USA, 487–494. DOI: http://dx.doi.org/10.1145/985692.985754

[54] Oculus Rift. 2019. (2019). Retrieved July 31, 2019 from https://www.oculus.com/?locale=en_US.

[55] Hyunyoung Song, Hrvoje Benko, Francois Guimbretiere, Shahram Izadi, Xiang Cao, and Ken Hinckley. 2011. Grips and Gestures on a Multi-touch Pen. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '11)*. ACM, New York, NY, USA, 1323–1332. DOI: http://dx.doi.org/10.1145/1978942.1979138

[56] Source.com. 2019. VR controllers: the good, the bad, and the ugly. (2019). Retrieved July 31, 2019 from https://vrsource.com/vr-controllers-6794/.

[57] Evan Strasnick, Christian Holz, Eyal Ofek, Mike Sinclair, and Hrvoje Benko. 2018. Haptic Links: Bimanual Haptics for Virtual Reality Using Variable Stiffness Actuation. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. ACM, New York, NY, USA, Article 644, 12 pages. DOI:http://dx.doi.org/10.1145/3173574.3174218

[58] Robert J Teather and Wolfgang Stuerzlinger. 2013. Pointing at 3d target projections with one-eyed and stereo cursors. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, 159–168.

[59] Feng Tian, Xiang Ao, Hongan Wang, Vidya Setlur, and Guozhong Dai. 2007. The Tilt Cursor: Enhancing Stimulus-response Compatibility by Providing 3D Orientation Cue of Pen. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '07)*. ACM, New York, NY, USA, 303–306. DOI: http://dx.doi.org/10.1145/1240624.1240675

[60] Feng Tian, Lishuang Xu, Hongan Wang, Xiaolong Zhang, Yuanyuan Liu, Vidya Setlur, and Guozhong Dai. 2008. Tilt Menu: Using the 3D Orientation Information of Pen Devices to Extend the Selection Capability of Pen-based User Interfaces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '08)*. ACM, New York, NY, USA, 1371–1380. DOI: http://dx.doi.org/10.1145/1357054.1357269

[61] HTC VIVE. 2019. (2019). Retrieved July 31, 2019 from https://www.vive.com/us/.

[62] Philipp Wacker, Oliver Nowak, Simon Voelker, and Jan Borchers. 2019. ARPen: Mid-Air Object Manipulation Techniques for a Bimanual AR System with Pen & Smartphone. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (CHI '19)*. ACM, New York, NY, USA, Article 619, 12 pages. DOI:http://dx.doi.org/10.1145/3290605.3300849

[63] WaterColorPainting.com. 2019. 6 KEY WAYS TO HOLD A WATERCOLOR BRUSH. (2019). Retrieved July 31, 2019 from https://watercolorpainting.com/brush-exercise/.

[64] Fong-Gong Wu and Shuyi Luo. 2006. Design and evaluation approach for increasing stability and performance of touch pens in screen handwriting tasks. *Applied Ergonomics* 37, 3 (2006), 319–327.

[65] Po-Chen Wu, Robert Wang, Kenrick Kin, Christopher Twigg, Shangchen Han, Ming-Hsuan Yang, and Shao-Yi Chien. 2017. DodecaPen: Accurate 6DoF Tracking of a Passive Stylus. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology (UIST '17)*. ACM, New York, NY, USA, 365–374. DOI: http://dx.doi.org/10.1145/3126594.3126664

[66] Yizhong Xin, Xiaojun Bi, and Xiangshi Ren. 2012. Natural Use Profiles for the Pen: An Empirical Exploration of Pressure, Tilt, and Azimuth. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '12)*. ACM, New York, NY, USA, 801–804. DOI: http://dx.doi.org/10.1145/2207676.2208518

[67] Yukang Yan, Chun Yu, Xiaojuan Ma, Xin Yi, Ke Sun, and Yuanchun Shi. 2018. VirtualGrasp: Leveraging Experience of Interacting with Physical Objects to Facilitate Digital Object Retrieval. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. ACM, New York, NY, USA, Article 78, 13 pages. DOI: http://dx.doi.org/10.1145/3173574.3173652