Examining the Fine Motor Control Ability of Linear Hand Movement in Virtual Reality

Xin Yi*
Tsinghua University
Zhongguancun Laboratory

Xueyang Wang†
Tsinghua University

Jiaqi Li‡
Tsinghua University

Hewu Li§
Tsinghua University
Zhongguancun Laboratory

Abstract

Linear hand movement in mid-air is one of the most fundamental interactions in virtual reality (e.g., when dragging/scaling/manipulating objects and drawing shapes). However, the lack of tactile feedback makes it difficult to precisely control the direction and amplitude of hand movement. In this paper, we conducted three user studies to progressively examine users' ability of fine motor control in 3D linear hand movement tasks. In Study 1, we examined participants' behavioural patterns when drawing straight lines in various directions and lengths, using both the hand and the controller. Results showed that the exhibited stroke length tended to be longer than perceived, regardless of the interaction tool. While displaying the trajectory could help reduce directional and length errors. In Study 2, we further tested the effect of different visual references and found that, compared with an empty room or cluttered scenarios, providing only a virtual table yielded higher input precision and user preference. In Study 3, we repeated Study 2 in real dragging and scaling tasks and verified the generalizability of the findings in terms of input error. Our core finding is that the user's hand moves significantly longer than the task length due to the underestimation of stroke length, yet the error of the Z-axis movement is smaller than that of the X-axis and the Y-axis, and a simple virtual desktop can effectively reduce errors.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Virtual reality Human-centered computing—Human computer interaction (HCI)—HCI design and evaluation methods—User models

1 Introduction

As one of the most fundamental interactions in virtual reality, linear hand movement is widely used for dragging, scaling, and 3D object manipulation. It is also common in target acquisition tasks [1], as it maximizes the efficiency of hand movement. Compared with hand movements on 2D desktops or touchscreens, mid-air hand movements in VR have greater spatial freedom. Moreover, the lack of physical support and tactile feedback makes it difficult to precisely control the direction and amplitude of hand movement [41]. The proliferation of hand movement-based interaction in VR (e.g., 3D modeling [23, 65], sketching [8, 21, 61], and out-of-view target acquisition [25, 66, 67]) has put forward requirements for finer control of hand movements. Therefore, understanding the user's ability to fine motor control in linear 3D hand movements is crucial for a wide variety of VR applications.

Researchers have noted that fine control of mid-air hand movement relies on both proprioception and visual perception [14, 46]. Existing work has found that human proprioception [67] and visual perception are biased in virtual environments: people consistently underestimate distances in virtual environments [51] and perceive an object's size to be smaller than the actual [56]. However, little research has been done on the effect of this perceptual bias on the performance of their 3D input in VR. Alternatively, several works have attempted to generalize the classical Fitts' law [22] into 3D space to predict human performance in pointing tasks [10, 60]. However, the results cannot be applied directly to linear movement tasks that also require the straightness of the movement.

In this research, we conducted three user studies with a total of 60 participants to examine users' fine motor control ability of linear hand movement in virtual reality. Three consecutive studies explored the three most influential factors in VR applications, including interaction tools (using controllers or hands), visual references (indoor and outdoor environments with different levels of clutter), and interaction tasks (drawing lines, dragging, and scaling objects). In addition, the human factors of hand movement direction and distance have also been studied in depth.

In Study 1, we asked participants to draw straight lines with specified directions and lengths, which was the simplest linear hand movement task in VR. We compared different drawing tools (hand vs. controller) and stroke visibility (visible vs. invisible). The results showed that user-drawn trails were significantly longer than task length in the X-axis (left-to-right) and the Y-axis (up-to-down), but only slightly longer when drawing in the Z-axis (back-to-front). And compared with using a controller, drawing by hand produces a larger deviation in direction. With displayed trails, users drew slower but more accurately in both length and direction. The results are consistent with the general underestimation of distance and size in virtual environments [31, 51, 56], but the significantly smaller length error in the Z-axis reflects a distinct feature of hand movement.

In Study 2, we asked participants to perform the same line-drawing task but assessed the effect of visual references including cluttered environments and a virtual table. The results showed that, compared with cluttered environments, the existence of a virtual desktop effectively reduced the error in length and straightness, but slowed down the drawing speed. Adding more objects to the table did not further enhance its error suppression.

Finally, we evaluated the generalizability of the findings in Study 2 in two real tasks in VR: dragging and scaling objects. We asked participants to drag objects in the target direction and distance, and scale shapes so that they have the specified side length. The results showed that consistent with Study 2, the virtual table also resulted in higher length accuracy and lower speed in both tasks. Interestingly, while the dragging task revealed the same phenomenon of length-lengthening, the scaling task showed an opposite trend of negative length error.

In brief, our work revealed that the user's hand moves significantly longer than the task length due to the underestimation of stroke length, yet the error of the Z-axis movement is smaller than that of the X-axis and the Y-axis, and a simple virtual desktop can effectively reduce errors. Our findings serve as guidelines for designing interfaces and interactions for many precision-first 3D applications in virtual reality that require users to accurately perceive spatial distances and perform delicate manipulations (e.g., 3D

*e-mail: yixin@tsinghua.edu.cn
†e-mail: wang-xy22@mails.tsinghua.edu.cn
‡e-mail: li-jq21@mails.tsinghua.edu.cn
§e-mail: lihewu@cernet.edu.cn

2023 IEEE Conference Virtual Reality and 3D User Interfaces (VR) | 979-8-3503-4815-6/23/$31.00 ©2023 IEEE | DOI: 10.1109/VR55154.2023.00058

2642-5254/23/$31.00 ©2023 IEEE
DOI 10.1109/VR55154.2023.00058

modeling, assembly, sketching, etc.).

The contributions of this paper were three-folded:

- We systematically examined the user's fine motor control ability of linear hand movement in VR, with factors of *trail visibility*, *drawing tool*, *direction*, and *length*.
- We investigated the effect of various visual references and found that compared with an empty room or cluttered indoor/outdoor scenarios, providing only a virtual table yielded higher input precision and user preference.
- We validated the findings in real dragging and scaling tasks and distilled our findings into design implications for hand interactions in VR.

2 Related Works

2.1 Spatial Perception in VR

High immersion is one of the main goals pursued by virtual reality, which requires the system to provide a high-fidelity experience of the depicted virtual scenes. However, due to the hardware and display technology limitations of current virtual reality headsets, perceptual distortions of the spatial properties of scenes or included objects are unavoidable [29]. Quantifying the deviation of the user's spatial perception ability and how it affects the user's performance in action-based tasks has been a research hotspot.

Many studies have investigated the perception of egocentric distances in virtual environments (VEs), and most of them show that people consistently underestimate distances in VEs. It has been reported that the mean estimation of egocentric distances in virtual environments is about 74% of modeled distances [51]. Recent works [30, 31, 42, 63] have extensively studied the various factors that affect human perception of egocentric distance in VEs, including device attributes (brand, weight, etc.), display characteristics (luminance, resolution, field of view, etc.), virtual environment (type, richness, shadows, etc.), and human factors (experience in VR, vision condition, etc.). They concluded that the compression of the user's perception of distances is eased with a wider horizontal FOV, higher spatial resolution, reduced device weight, and more cluttered environments. Other works compared user performance of distance perception in VR HMDs with AR displays [2, 50] and Video See-Through head-mounted displays [49, 62]. In addition to distance, visual perceptual errors of object size [7, 20, 47, 57, 71] in VR have also been extensively studied. It is revealed that people perceive an object's size as smaller [56], which is related to the underestimation of distance perception.

Most of the quantitative studies above analyzed the perception of people only in observation tasks rather than input tasks. For example, the verbal report is the most commonly used verification method in distance perception research [2], but it does not involve any body movement. Some distance perception studies have tested perceptual matching tasks such as blind-walking [42, 62] or blind-throwing [52] tasks, while it splits human perception and movement in time. In addition, it is noted that fine control of mid-air hand movement is based on both proprioception and visual perception [14, 46], and provides a different kind of information for different stages of movement planning [34, 54]. The synergy and interaction of multiple senses and the effects of perceptual biases during human movement (such as fine motor control of the hand) have not been fully studied. It is also worth noting that, perceptual matching tasks usually adopted relative lengths [7, 20, 23], while in verbal estimation protocols [3, 32, 35, 39] the observer states depth in terms of some familiar unit, such as feet, meters, etc. In this work, absolute lengths in a standard unit (cm) were used in the instruction given to the participants. We designed it this way because many precision-first 3D applications in virtual reality (e.g., 3D modeling, assembly, sketching, etc.) require the user to have not only an accurate perceptual match but also an accurate estimate of the absolute spatial distance in standard units.

2.2 Hand Movement Based Interactions in VR

Moving hand in mid-air is one of the most fundamental interactions in virtual reality. It has become a standard interaction paradigm where people move their hand (or hand controller) in VR to select, acquire, drag, and manipulate virtual objects. Linear movement is the most common type of movement in the above scenarios. It is shown that the trajectories of almost all aimed hand movements follow approximately a straight line [1].

In recent years, 3D content creation, education and training, virtual medical treatment, and other VR-based applications have developed rapidly. In these applications, the need for fine motor control of the hand often arises. For example, VR-based design and sketching tools [11, 23, 65, 69] provide professional designers with pen and paper-like functions, allowing free creation of 3D curves and deformation of surfaces. Although aided by algorithms, to achieve aesthetic and accurate artwork, users must have the ability to finely control the three-dimensional movement of the hand. In 3D modeling and scene design software [28, 68], users often need to rotate and scale the model to an appropriate size, which also requires users to accurately judge and control the distance and direction of hand movement.

The freedom and expressiveness of free-hand 3D sketching make it appealing to users, but the increase in spatial dimension also makes it more challenging than 2D drawing. The user's ability to sketch in VR has been extensively studied, including the effect of the physical surface [6], the user's spatial ability [12], and the transparency of the hand and pen [9]. To help users sketch more accurately, many works propose interaction technologies as assistance [8, 21, 40, 61].

The precise pointing, acquisition, and manipulation of a 3D object also require precise control of hand movements [13, 59]. Recently, many out-of-view interactions have been proposed in target search and acquisition [25, 66, 67]. This new type of interaction requires not only the establishment of spatial memory but also precise control of hand movements. Understanding user preferences and factors that affect the accuracy of user movements is crucial to the development of VR applications.

2.3 Behavioral Models for Hand Movement in VR

Much research is focused on building models to quantify the performance of hand movements (e.g., speed and accuracy). Classic works that modeled human performance of accuracy and efficiency were built for 2D tasks (e.g., Fitts' law [22], Meyer's law [44], and Steering law [70]). In contrast to table-supported planar hand movements, mid-air hand movements in VR exhibit full 3D degrees of freedom, and extend the range of motion to the limits of the human arm's reach. In this context, many recent works have attempted to extend Fitts' law into 3D space [18, 27, 33, 60]. However, these works all focused on pointing tasks, which did not restrict the movement's trajectory.

In contrast to task performance models, dynamic models describe the entire dynamics of motion. Some works [10, 38] have studied dynamic models of aimed movements in VR. These models aim to predict the full-time series of position, velocity, and acceleration of aimed movements. With the popularity of deep learning technologies, some works used kinematics-based regressive models for continuously predicting human hand [17, 24], head [26], and eye [5] movement in VR. Although these models derived from data-driven algorithms can predict the process of hand movements, the interpretability of the models is limited, and there is still a lack of systematic exploration of factors that affect users' behavioural patterns (e.g., visual references).

3 Study 1: Effect of Interaction Tool

In this study, we asked participants to draw straight lines with specified directions and lengths, which was the simplest linear hand movement task in VR. Because visual feedback plays an important role in improving the speed and accuracy of mid-air interactions (e.g., visual feedback makes size [20] and distance [49] perception more accurate), we controlled the visibility of drawn strokes and compared participants' behavioural patterns in terms of speed and accuracy.

3.1 Participants and Apparatus

We recruited 24 participants from the campus (11 females, 13 males) with ages ranging from 18 to 26 (M = 21.7, SD = 2.4). All participants were right-handed. They reported an average experience with VR of 3.7 hours and 2 of them had used VR for no more than 5 hours (SD = 10.2), but none of them had used VR sketching tools (e.g., Tilt Brush and Gravity Sketch). Each participant was paid $15.

We used an HTC Vive Cosmos Elite HMD as the apparatus. The HMD had a refresh rate of 90Hz and a resolution of 1440×1700 per eye. Similar to existing works [47, 55], we attached a Leap Motion controller to the HMD (see Figure 1), which could track the 3D finger position during interaction with an accuracy of 1.2mm at 120 Hz. The average spatial positioning errors of the Vive controller and Leap Motion controller are both less than 5 mm and close to each other [45, 64]. The experimental platform was developed in C# using Unity 3D 2021.3.8f1c1.

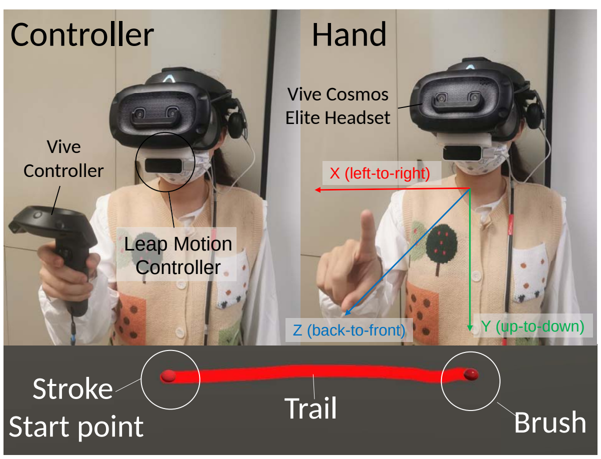

Figure 1: Upper left: Experiment apparatus. The picture shows the participant drawing with the controller; Upper right: The illustration of 3 *Stroke Direction* The picture shows the participant drawing with the hand; Lower: The illustration of the line-drawing task.

3.2 Experiment Design

The goal of this study was to examine user behavioural patterns during line-drawing tasks with different drawing tools and trail visibility. Specifically, we used a within-subject design with four factors:

- *Tool (Hand vs. Controller)*. We asked participants to complete the tasks both with the index finger of their dominant hands and using the handheld controller of the apparatus.

- *Trail Visibility (Visible vs. Invisible)*. Displaying the trail during drawing as visual feedback may help users improve accuracy, but it costs more time due to the trade-off of speed and accuracy.

- *Stroke Direction*. Based on a pilot study in which another 5 participants used Tilt Brush freely, we designed the stroke direction to be the X-axis (left-to-right), the Y-axis (up-to-down), and the Z-axis (back-to-front). The illustration of directions is shown in the right part of Figure 1.

- *Stroke Length*. Based on the pilot study above, we set four stroke lengths (5cm, 10cm, 20cm, and 30cm), which were all comfortable to reach and consistent with ergonomic guidelines [48].

Figure 1 shows the experimental platform. In each task, we used a sphere with a radius of 0.5cm to indicate the starting position of the stroke (which was fixed at the same height as the participants' chin, and 30cm away according to the pilot study), and a cursor (another red sphere with the same radius) to indicate the current location of the fingertip or controller. In the visible condition, the trail was visualized in red with a width of 1 cm. Under both conditions, the hand is not rendered.

3.3 Procedure

Before the experiment, we arranged a 3-minute warm-up session to help participants strengthen their muscle memory of drawing lines of different lengths. We showed cardboard with 4 painted lines. Line lengths were 5cm, 10cm, 20cm, and 30cm, respectively. And the participants were allowed to observe and trace the lines freely.

During the experiment, the participants stood still. We first measured the height of the participant's chin using a tape measure and set the location of the drawing starting point accordingly. They first spent another 1 minute familiarizing themselves with the use of the apparatus, and then completed two drawing tasks, each corresponding to a drawing tool. In each session, they completed 12 blocks of tasks, corresponding to different combinations of *Direction* × *Length*, and each block contained 3 repetitive trials. The order of sessions and blocks was counterbalanced using Latin Square. For each trial, participants first move the cursor to the starting point, and "draw a straight line with the specified length and direction as accurately as possible." In the *Controller* condition, they pressed and released the trigger to indicate the start and end of the stroke, respectively. In the *Hand* condition, they used the trigger of a controller on the left hand instead, as the right hand was used for drawing. A short break was enforced between the different blocks.

3.4 Results

In total, we collected $2\,tools \times 2\,visibility \times 3\,direction \times 4\,length \times 3\,reps \times 24\,participants = 3,456$ strokes from all participants. We did not remove any outliers. In this paper, we used RM-ANOVA for all statistical tests. When our data violated the assumption of sphericity, we reported results with a Greenhouse-Geisser correction. We performed post-hoc pairwise comparisons using Bonferroni-corrected paired t-tests.

3.4.1 Drawing Speed

We calculated the drawing speed as the target stroke length divided by the time taken to draw (in cm/sec). Figure 2(a) showed the average drawing speed under different conditions. *Trail Visibility* produced a significant effect on drawing speed ($F_{1,23} = 17.9, p < .001$). As expected, participants drew slower when trails were visible (M = 10.8, SE = 1.0) than when trails were invisible (M = 13.1, SE = 1.2). This may be because the presence of visual feedback affects the type of motor control applied by the users in the tasks [53]. If there is no visual feedback and no knowledge of instantaneous accuracy, the movements are performed in forward control, relying on the relatively limited information provided by the proprioceptive system. With visual feedback, users apply feedback control, which involves a corrective loop and reduces the error between the target and the instantaneous movement state. In addition, it is noted that

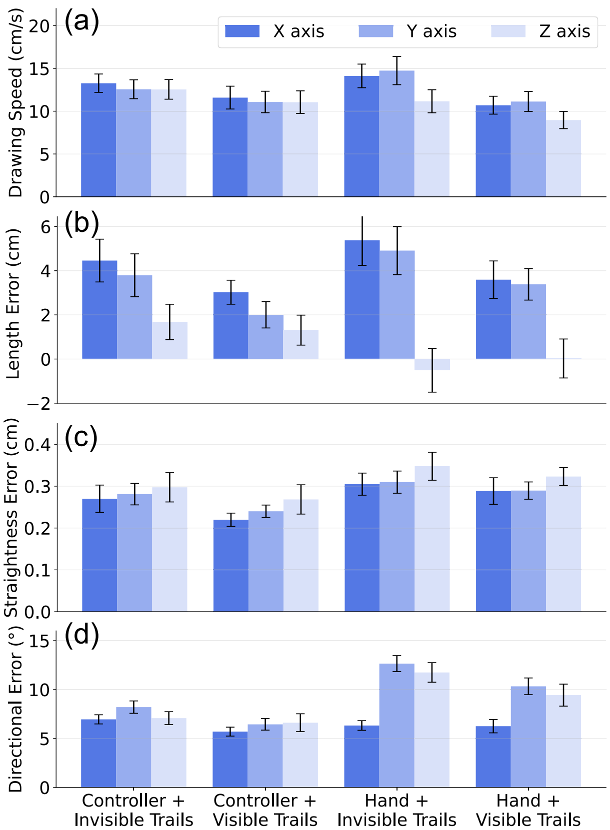

Figure 2: Main effects of *Trail Visibility*, *Tool*, and *Stroke Direction* for (a) Drawing Speed, (b) Length Error, (c)Straightness Error, and (d) Directional Error. Error bars indicate the SE.

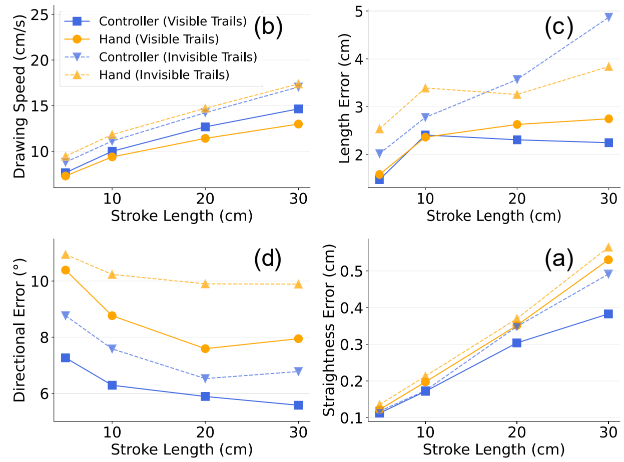

Figure 3: Mean (a) Drawing Speed, (b) Length Error, (c) Straightness Error, and (d) Directional Error in different *Trail Visibility* and *Tool* by *Stroke Length*.

the eyes-free approach gained a speed advantage perhaps because it did not require users to turn their heads or search for targets in the view, which was time-consuming [67]. In comparison, no significant difference in drawing speed was found between different *Tools* (controller vs. hand) ($p = .83$).

Stroke Direction also had a significant impact on the drawing speed ($F_{2,46} = 16.7, p < .001$). The drawing speed in the X-axis (M = 12.4, SE = 1.0) and the Y-axis (M = 12.4, SE = 1.1) were very close and higher than in the Z-axis (M = 10.9, SE = 1.1). Moreover, for both the hand and the controller, drawing speed increased monotonically with stroke length (Figure 3(a)), suggesting that participants tended to draw faster for longer strokes.

3.4.2 Length Error

We measured the length error as the difference between the length of the exhibited stroke and the target stroke (in cm). A positive length error indicated that the participant drew longer than perceived, and vice versa. Figure 2(b) showed the average length error under different conditions. Interestingly, participants generally drew longer than the task length, whether trails were visible (M = 2.2 cm) or not (M = 3.3 cm). The literature [31, 51, 56] indicated that users generally underestimate distances and object sizes in VEs, so the increase in stroke length may be due to the underestimation of the length of the trail.

Trail Visibility ($p = .06$) and *Tool* ($p = .88$) did not have a significant effect on the length error. However, the displayed trails would result in significantly lower values of the *Relative Length Error* (0.27 vs. 0.38, $F_{1,23} = 23.8, p < .001$), which is the absolute value of the Length Error divided by the target *Stroke Length* (in the range 0-100%). This confirmed that, with visual feedback, the participants were able to draw strokes with more precise lengths. The mean relative length error when drawing with hands is 35.2% (SE = .045), which is greater than when drawing with a controller (M = 30.3%, SE = .026), but the difference is not statistically significant ($p = .12$).

As shown in Figure 2(b), *Stroke Direction* had a significant impact on length error ($F_{2,46} = 40.1, p < .001$). The exhibited trail length was significantly longer when drawing in the X-axis (M = 4.11, SE = .75), $p < .001$, and the Y-axis (M = 3.52, SE = 0.73), $p < .001$ than when drawing in the Z-axis (M = 0.63, SE = 0.76). Significant differences may come from a more difficult estimation of length and fatigue when drawing in the Z-axis. Participants pointed out that the observed length was compressed compared to the actual drawn length, especially in the Z-axis, which increases the difficulty of length judgment. As a result, they tended to be conservative in their movements, resulting in shorter strokes.

From Figure 2(b), when drawing in the X-axis and the Y-axis by hand, the length error is larger than by the controller, but lower and closer to 0 when drawing in the Z-axis. This reflects that the control of length with the bare hand is more unstable and more susceptible to different directions. As shown in Figure 3(b), the length error tended to increase with stroke length, except for controller + visible trails.

3.4.3 Straightness Error

The straightness error was calculated as the average distance of the points of the exhibited trail from the fitted 3D line (in cm) [36]. This measurement reflects how close the trail is to a straight line. Figure 2(c) showed the average straightness error under different conditions. *Trail Visibility* had a significant impact on the Straightness Error ($F_{1,23} = 6.32, p < .05$). The straightness error was lower when trails were visible (M = 0.271, SE = 0.016) than when trails were invisible (M = 0.30, SE = 0.02). The mean straightness error when drawing with a hand is 0.31cm (SE = 0.02), which is higher than the mean of 0.26cm (SE = 0.02) when drawing with a controller, but the difference is not statistically significant.

As shown in Figure 3(c), the straightness error increased almost linearly with *Stroke Length*. This was probably because strokes are more likely to deviate as the drawing distance increases.

3.4.4 Directional Error

The directional error is the inner angle between the directional vector of the fitted 3D line and the target *Stroke Direction* (in the range

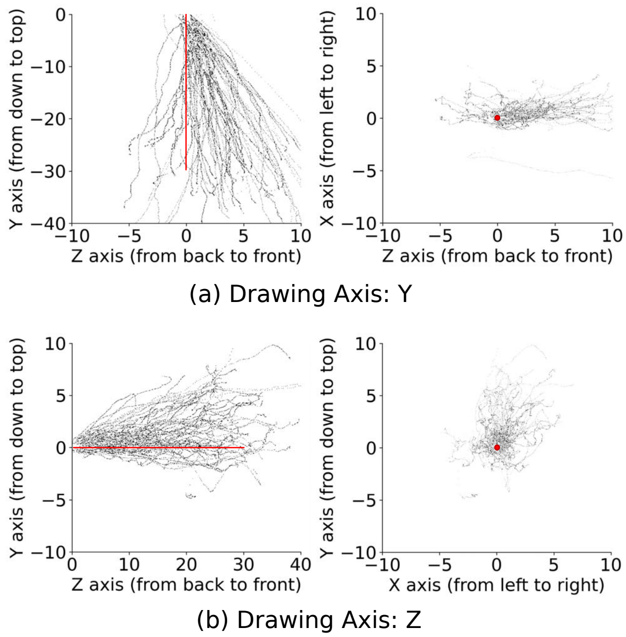

Figure 4: Visualization of projected deviation for trails when drawing with hand and drawing in (a) the Y-axis and (b) the Z-axis. The red line (point) is a reference for the target direction and length.

0-90°). This measure reflects the deviation of the exhibited trail's direction from the target *Stroke Direction*. Figure 2(d) showed the average directional error under different conditions. *Trail Visibility* had a significant impact on directional error ($F_{1,23} = 20.6, p < .001$). The directional error was lower when trails were visible (*M* = 7.46, *SE* = 0.39) than when trails were invisible (*M* = 8.83, *SE* = 0.35). This shows that visual feedback can effectively guide the judgment of hand movement direction.

The *Tool* also had a significant effect on the directional error ($F_{1,23} = 33.7, p < .001$). Using a controller (*M* = 6.83, *SE* = 0.37) produces less directional deviation than using a single hand (*M* = 9.46, *SE* = 0.44). As shown in Figure 2(d), this difference is mainly because when drawing in the Y-axis and the Z-axis with hands, the directional error was significantly larger than when drawing in the X-axis ($F_{2,46} = 9.32, p < .001$), while the directional errors in the three directions were all similar to the errors in the X-axis with hands when using the controller. The above results indicate that directional control with bare hands is significantly more difficult than holding the controller in both the Y- and Z-axis directions. Participants compared the differences in the use of controllers and hands: Using the controller simulates the feeling of holding a pen when drawing and writing in real life, which is more realistic, and the weight of the controller makes the movement more stable; when drawing with the hand, not only is it easier to drift and shake, but it is also more prone to fatigue. To further analyze the directional bias when drawing with hand in the Y- and Z-axis, Figure 4 visualizes the trails with a target stroke length of 30cm and shows the direction deviation pattern. Specifically, when drawing in the Y-axis, the main offset direction is near-to-far, and when drawing in the Z-axis, the main offset direction is bottom-to-up.

In addition, the directional error decreased with the increase of *Stroke Length* (Figure 3(d)). Participants reported that the longer the trail length, the easier it is to visually judge its direction.

4 Study 2: Effect of Visual References

Study 1 showed that visual feedback could significantly improve participants' fine motion control ability in linear hand movement. In real life, people can also use the size of surrounding objects as visual references to help improve their input accuracy (e.g., [6, 42]). It was reported that the quality of the VE's graphics [35] and the level of graphical detail provided in a VE [62] affect users' ability to accurately judge distance. Some works have also revealed the difference in distance underestimation in indoor and outdoor environments [4, 19, 42]. Therefore, in this study, we asked participants to perform the same drawing tasks and explored the effect of different visual references. In this study, participants drew using only the controller, and the trails were all visible. Three *Stroke Directions* and four *Stroke Lengths* from Study 1 were preserved.

4.1 Participants and Apparatus

We recruited 28 right-handed participants from the campus (15 females, 13 males) with a mean age of 20.8 (SD = 2.2). None of them participated in Study 1. They reported an average VR experience of 10.7 hours and 25 of them had used VR for no more than 6 hours (SD = 38.4, Median = 1.0), and 2 of them had used VR sketching tools (e.g. Tilt Brush and Gravity Sketch). Each participant was paid $15. We used the same apparatus as in Study 1.

4.2 Experiment Design

The goal of this study was to examine the users' behavioural patterns during line-drawing tasks with different visual references. As shown in Figure 5, we constructed 5 different virtual environments with realistic elements and real-world scales as visual references (We built the virtual references with resources downloaded from Unity3D Asset Store[1 2 3].):

- *Empty Room* (see Figure 5(a)): the same simplified room as the one used in Study 1.
- *Cluttered Indoor* (see Figure 5(b)): a 10m×7m library with a 4m high ceiling, bookshelves along both sides of the room, 3 sofas, and desks with laptops. One side of the room was the fireplace, and the other side was glass facing a yard. In the experiment, participants were placed in the library by the fireplace, next to two couches, and facing the glass.
- *Cluttered Outdoor* (see Figure 5(c)): an intersection with trees and buildings on either side of the road. Participants were placed in the center of the intersection, facing a zebra crossing and a stationary car.
- *Empty Desktop* (see Figure 5(d)): a virtual empty glass desktop in the same room as an *empty room*. The length, width, and height of the desktop were 2m, 1m, and 0.7m.
- *Cluttered Desktop* (see Figure 5(ef)): a virtual cluttered desktop with common office items such as pens, coffee cups, mobile phones, ID cards, folders, laptops, etc. The room and the desktop were the same as the *Empty Desktop*.

We used a within-subject design with three factors: *Visual Reference (Empty Room, Cluttered Indoor, Cluttered Outdoor, Empty Desktop, and Cluttered Desktop)*, *Stroke Direction (X-axis, Y-axis, and Z-axis)*, and *Stroke Length (5cm, 10cm, 20cm, 30cm)*. Noted that only the directions in the X-axis and Z-axis were preserved when drawing on empty and cluttered desktops to simulate the real experience of drawing on the desktop.

[1]https://assetstore.unity.com/packages/3d/environments/urban/library-interior-archviz-160154; retrieved 2022-10-11

[2]https://assetstore.unity.com/packages/3d/environments/urban/street-new-york-183319; retrieved 2022-10-11

[3]https://assetstore.unity.com/packages/3d/props/interior/office-propspack-44111; retrieved 2022-10-11

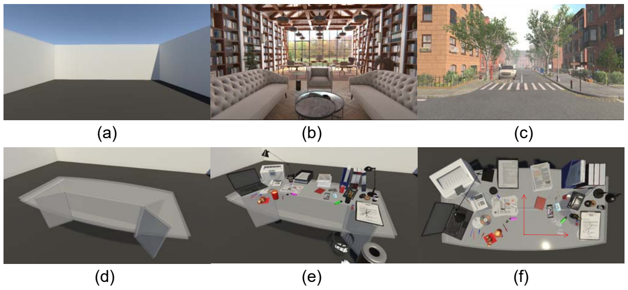

Figure 5: Visual references used in Study 2: (a) an empty room, (b) a cluttered indoor environment, (c) a cluttered outdoor environment, (d) an empty desktop, and (e) a cluttered desktop. (f) The top view of the cluttered desktop. Red arrows indicate the start position and two directions (the X- and Z-axis) when drawing on the desktop.

4.3 Procedure

Before the experiment, a 3-minute warm-up session was arranged to help participants familiarize themselves with the interaction. They then completed five sessions of line-drawing tasks in random order, each corresponding to a visual reference scenario. Each session contained 8 blocks of tasks, corresponding to different combinations of *Direction* and *Length*, in random order. In each block, the participants completed the drawing task three times repeatedly. The experimental platform was the same as in Study 1, except that we provided virtual indoor and outdoor environments and tables as visual references. Participants were asked to "draw a straight line with the specified length and direction as accurately as possible". They sat in a chair in the *Empty Desktop* and *Cluttered Desktop* sessions and stood still in the other three sessions. After the experiment, we used a questionnaire to collect their subjective ratings.

4.4 Results

In total, we collected $(3 scenarios \times 3\, direction + 2 scenarios \times 2\, direction) \times 4\, length \times 3\, reps \times 28\, participants = 4,368$ strokes.

4.4.1 Drawing Speed

Figure 6(a) showed the average drawing speed under different conditions. *Visual Reference* produced a significant effect on the drawing speed ($F_{2.2,59.0} = 10.8, p < .001$). Compared with drawing in an empty room (*M* = 10.53, *SE* = 1.29), participants drew slower when both drawing on an empty desktop (*M* = 8.27, *SE* = 1.04), $p < .01$, and cluttered desktop (*M* = 7.63, *SE* = 0.78), $p < .001$. However, drawing speeds in cluttered indoor (*M* = 10.50, *SE* = 1.43) and cluttered outdoor (*M* = 10.31, *SE* = 1.38) environments were very close to drawing in the empty room. Moreover, the speeds of drawing on an empty desktop and a cluttered desktop had no noticeable difference. The slower drawing on the desktop may be because participants need to draw more slowly to make the trails fit the desktop surface without tactile feedback. Consistent with Study 1, *Stroke Direction* had a significant impact on the drawing speed ($F_{2,54} = 19.2, p < .001$), and the drawing speed in the X-axis (*M* = 10.1, *SE* = 1.1) was higher than in the Z-axis (M = 8.8, *SE* = 1.2), $p < .001$.

4.4.2 Length Error

Figure 6(b) showed the average length error for different conditions. *Visual Reference* produced a significant effect on length error ($F_{2.9,77.1} = 12.6, p < .001$). Post-hoc pairwise comparison showed that the length error was significantly lower when both drawing on an empty desktop (*M* = 0.37, *SE* = 0.62), $p < .001$, and cluttered desktop (*M* = -0.31, *SE* = 0.57), $p < .001$, than an empty room (*M* = 2.42, *SE* = 0.76). There was also a noticeable difference in relative length error ($F_{2.4,65.4} = 7.21, p < .001$). Compared with drawing in

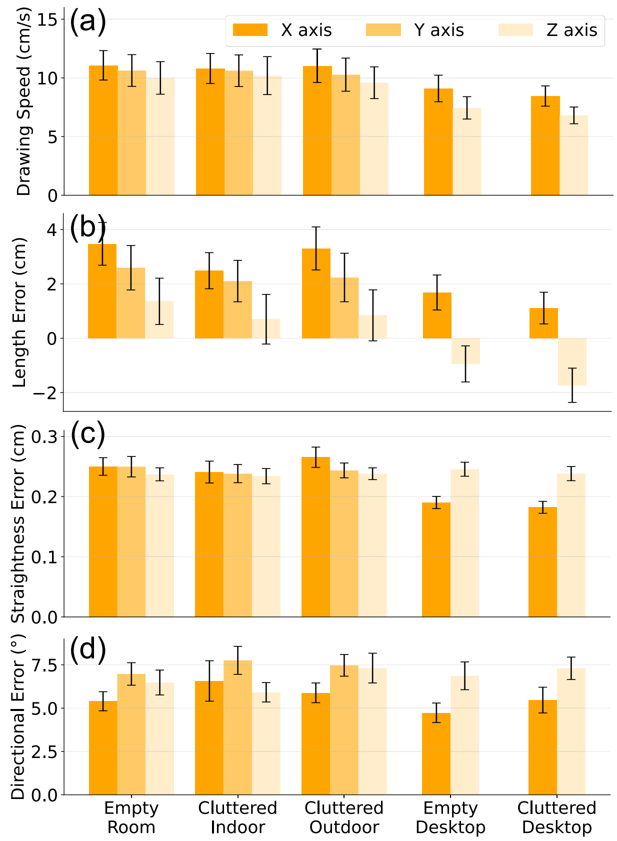

Figure 6: Main effects of *Visual Reference* for (a) Drawing Speed, (b) Length Error, (c) Straightness Error, and (d) Directional Error. Error bars indicate the SE.

an empty room (*M* = 32.0%, *SE* = 0.04), both drawing on an empty desktop (*M* = 24.8%, *SE* = 0.02), $p < .05$, and cluttered desktop (*M* = 22.0%, *SE* = 0.02), $p < .05$, produced less relative length error. However, cluttered indoor and outdoor environments were not significantly different from an empty room in terms of length error and relative length error. Although it appears from Figure 6(b) that the length error is smaller when drawing on a cluttered desktop than on an empty desktop, the difference is not statistically significant. While drawing on the desktop, on the one hand, the desktop served as a spatial reference, and on the other hand, participants needed to remain attentive and careful to keep the trail aligned with the virtual surface of the desktop (which was confirmed by the slower speed). As a result, they were able to judge stroke length more accurately.

Consistent with Study 1, *Stroke Direction* had a significant impact on the length error ($F_{1,27} = 28.9, p < .001$), and the exhibited trail length was significantly longer when drawing in the X-axis (*M* = 2.41, *SE* = 0.62) than in the Z-axis (*M* = 0.05, *SE* = 0.74), $p < .001$.

4.4.3 Straightness Error

Figure 6(c) showed the average straightness error under different conditions. *Visual Reference* had a noticeable effect on straightness error ($F_{2.5,68.3} = 7.83, p < .001$). Post-hoc pairwise comparison showed that the straightness error was significantly lower when both drawing on an empty desktop (*M* = 0.22, *SE* = 0.01), $p < .05$, and cluttered desktop (*M* = 0.21, *SE* = 0.01), $p < .001$, than an empty room (*M* = 0.24, *SE* = 0.01). However, cluttered indoor (*M* = 0.24, *SE* = 0.01) and outdoor (*M* = 0.25, *SE* = 0.01) environments had no significant difference with an empty room in straightness error. There was also no significant impact between the two types

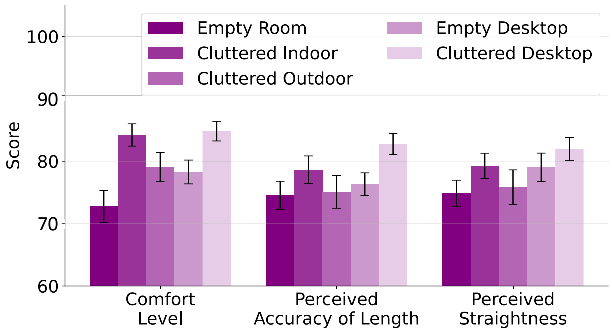

Figure 7: Main effects of *Visual Reference* on participants' subjective scores. Error bars indicate the SE.

of desktops. We hypothesized that the desktop could be used as a reference to help judge stroke straightness, helping participants make their strokes more straight.

4.4.4 Directional Error

Figure 6(d) showed the average directional error under different conditions. *Visual Reference* did not have a notable impact on *Directional Error* ($p = .54$). However, contrary to some participants' claims that cluttered objects on the desktop served as directional references, it can be seen from the figure that the directional error is smaller when drawing on an empty desktop than when drawing on a cluttered desktop, which may be because objects on the desktop can attract participants' attention and thus interfere with direction judgment.

4.4.5 Subjective scores

Participants were asked to complete a scale with a full score of 100 after the experiments. On the scale, participants assessed five *Visual Reference* from three dimensions of *Comfort Level*, *Perceived Length Accuracy*, and *Perceived Straightness*. A brief interview was also conducted.

Participants' subjective ratings varied with quantitative measures. Figure 7 shows the participants' subjective scores. They rated only the cluttered desktop significantly higher than the empty room in all three dimensions: *Comfort Level* ($p < .001$), *Perceived Length Accuracy* ($p < .01$), and *Perceived Straightness* ($p < .01$). Participants noted that desktop objects provided spatial reference and also increased realism and immersion.

Participants also noted that objects in cluttered indoor and outdoor scenes were far away, making it difficult to use as a spatial reference. However, participants rated that drawing in a cluttered indoor environment was more comfortable ($p < .01$) because it was more similar to the real drawing environment.

5 Study 3: Interaction Behavior in Real Tasks

Study 3 is to verify that the findings of visual reference based on the spatial line-drawing tasks in Study 2 can be applied to other practical tasks in virtual environments. We asked the participants to perform two basic interactions in VR, including dragging mid-air objects and creating 3D shapes. The five visual references tested in this study were the same as in Study 2, but the participants' hand trajectories were not visible while dragging and scaling. 3 *Stroke Direction* and 4 *Stroke Length* from Study 1 and 2 were retained, but no repetition was required in this study.

5.1 Participants and Apparatus

We recruited a total of 8 participants from the campus (3 females, 5 males) with ages ranging from 19 to 24 (M=21.5, SD=2.0). No participants were replicated with Study 1 and 2. All participants were right-handed. Participants reported an average experience with VR of 9.33 hours and 6 of them had used VR for no more than 3 hours (SD=20.76, median=0.8), but none had used VR sketching tools (e.g. Tilt Brush, Gravity Sketch). Participants were paid $15. The experimental apparatus is the same as Study 1 and 2.

For objects participants need to drag, we used prefabs with real-world scales from 2 assets that were downloaded from the Unity3D Asset Store[4][5].

5.2 Experiment Design

The experiment consists of two stages, corresponding to the *Dragging* and *Scaling* tasks in VR. As shown in Figure 8, each task contains two subtasks, which are to manipulate flat objects and solid objects, corresponding to the two most common object types in the virtual environment. We used the following within-subject designs:

- *Dragging*: Participants were asked to move two types of objects a specified distance in a specified direction: a plane-like object (a card, see Figure 8(a)) and a solid object (a can, see Figure 8(b)). The dragging task was designed with four factors: *Subtask* (Dragging a card with the real size vs. Dragging a can with the real size), *Visual Reference*, *Direction* (The X-, Y-, and Z-axis), and *Length* (5cm, 10cm, 20cm, and 30cm). When the participant placed the cursor on the object, the object would emit a red light to indicate that the participant's brush and the object were in contact. Then the participant held the trigger to drag the object to move the specified *Length* in the specified *Direction* and released the trigger to complete.

- *Scaling*: Participants were asked to create the two types of objects with a specified side length by scaling: a plane-like object (a square, see Figure 8(c)) and a solid object (a cube, see Figure 8(d)). The scaling task was designed with three factors: *Subtask* (Scaling a square vs. Scaling a cube), *Visual Reference*, and *Length* (5cm, 10cm, 20cm, and 30cm). Participants pressed the trigger and moved the controller in any direction to scale the shape until they thought the side length of the shape was the same as the target *Length* and released the trigger to complete.

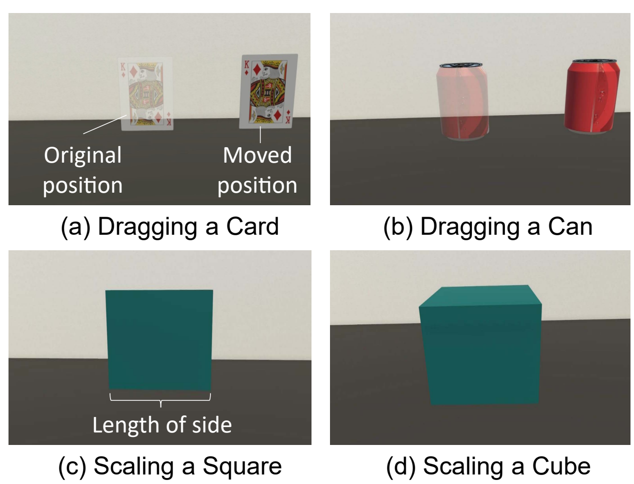

Figure 8: Four different real tasks were evaluated in Study 3.

[4]https://assetstore.unity.com/packages/3d/props/playing-cards-pack-21876; retrieved 2022-10-11

[5]https://assetstore.unity.com/packages/3d/props/soda-can-201045; retrieved 2022-10-11

5.3 Procedure

Before the experiment, a 3-minute warm-up session was also arranged to help the participants familiarize themselves with different lengths. Participants were also provided with a real card and a real can to familiarize themselves with the scales of the object. They then completed two stages, each containing five sessions (each corresponding to a visual reference) of real tasks in random order. Each session contained 8-12 blocks of tasks, corresponding to different combinations of *Direction* and *Length*, in random order. No repetition was required in this study. Participants took forced breaks between sessions and experimented in a single session lasting 30-45 minutes.

5.4 Results

In total, for the *Dragging* task, we collected $2\,subtask \times (3\,scenarios \times 3\,direction + 2\,scenarios \times 2\,direction) \times 4\,length \times 8\,participants = 832$ operations, and for the *Scaling* task, we collected $2\,subtask \times 5\,scenarios \times 4\,length \times 8\,participants = 320$ operations.

5.4.1 Speed

In both tasks, speed is defined as the controller's displacement in completing the task divided by the task execution time, which is similar to the Drawing Speed. Figure 9(a) showed the average speed influenced by visual references under different tasks. Although not statistically significant for dragging ($p = .12$) and scaling ($p = .71$) tasks, it can still be seen that the speed of performing all tasks is reduced on desktops compared to in the empty room, which is consistent with drawing lines. Dragging and scaling tasks on the desktop are more time-consuming, perhaps due to the need to align the movement with the virtual surface.

For scaling tasks, from Figure 9, the speed of both scaling tasks is reduced in cluttered indoor and outdoor environments, which may be because the complex background affects the size judgment of shapes. And as with drawing strokes, the clutter of the desktop did not affect the speed of the tasks. The speeds of the two subtasks of scaling had no significant difference ($p = .32$). However, for dragging tasks, dragging a card was significantly slower than dragging a can ($F_{1,7} = 16.7, p < .01$), perhaps because picking and moving a thin card is more difficult than a can with three-dimensional volume.

5.4.2 Length Error

Figure 9(b) showed the length error affected by visual references under different tasks. For dragging tasks, *Visual Reference* yielded a significant effect on length error ($F_{4,28} = 3.16, p < .05$). The length error was lower when dragging on an empty desktop (M = 1.81, SE = 0.79) and cluttered desktop (M = 1.35, SE = 0.79) than an empty room (M = 3.42, SE = 1.02). This shows that similar to drawing lines, the actual distance dragged by participants is often longer than the target distance, and a virtual desktop can also serve as a visual reference and reduce the length error. Moreover, *Subtask* also had a significant effect ($F_{1,7} = 19.6, p < .01$), and the length error when dragging a can (M = 3.13, SE = 0.87) was much higher than dragging a card (M = 1.70, SE = 0.72). This may be because the can has a three-dimensional volume compared to the flat card, which makes it appear larger and harder to identify its boundaries, which disrupts the judgment of drag distance. We speculate that showing movement trajectories when dragging may help participants visually judge the dragging distance more accurately.

Figure 10(a) shows the length error in three directions for dragging tasks. Consistent with the findings of Study 2, *Stroke Direction* had a significant effect on the length error ($F_{1,7} = 8.18, p < .05$), and the exhibited drag distance was significantly longer than the target distance when dragging in the X-axis (M = 3.50, SE = 0.91), but only slightly longer when dragging in the Z-axis (M = 1.33, SE = 0.82).

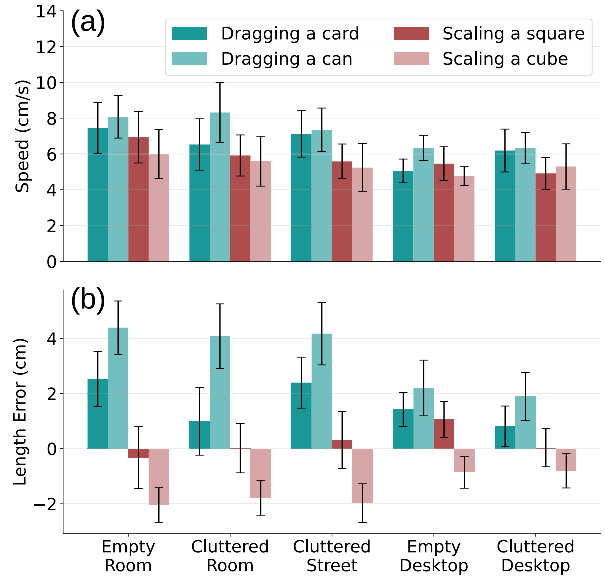

Figure 9: Main effects of *Visual Reference* for (a) Speed and (b) Length Error under different tasks. Error bars indicate the SE.

For scaling tasks, although there was no significant effect on the length error, *Visual Reference* produced a significant effect on the relative length error (the absolute value of the length error divided by the target) ($F_{4,28} = 2.93, p < .05$). Compared with scaling in an empty room (M = 0.20, SE = 0.03), both scaling on an empty desktop (M = 0.15, SE = 0.02) and cluttered desktop (M = 0.16, SE = 0.03) produced less relative length error. It is worth noting that the scaling task exhibits a distinct pattern from the stroke drawing and dragging tasks. Participants typically created shapes with sides shorter than the target length, rather than longer like drawn lines. This may be due to different tasks: the visual feedback of created shapes and drawn strokes is different, which deserves further investigation in the future. The two scaling subtasks also showed significant differences in the length error ($F_{1,7} = 16.7, p < .01$). The length error in scaling cubes (M = -1.49, SE = 0.50) was much lower than in scaling squares (M = 0.21, SE = 0.77) Maybe it's because, for squares and cubes with the same side lengths, the cube appears to have longer side lengths.

5.4.3 Straightness Error

Since the scaling task did not specify the direction of movement, here we only discuss the straightness error of the dragging task. Unlike the phenomenon that virtual desktops can significantly reduce straightness errors in stroke drawing, different visual references had no significant effect on motion straightness in dragging tasks ($p = .11$). This can be attributed to differences in line-drawing tasks versus dragging tasks. When drawing lines, participants were able to directly observe the straightness of the lines, while participants in the dragging task had no visual feedback on the movement trajectory. Visible motion trajectories may be effective in reducing straightness errors.

5.4.4 Directional Error

Here we also discuss the directional error of the dragging task. Figure 10(b) showed the average directional error under different conditions. Consistent with the findings of Study 2, *Visual Reference* did not have a significant impact on *Directional Error* ($p = .22$), but the figure shows that the directional error is smaller when dragging in the X-axis (M = 3.87, SE = 0.38) than dragging in the Z-axis (M = 4.95, SE = 0.56).

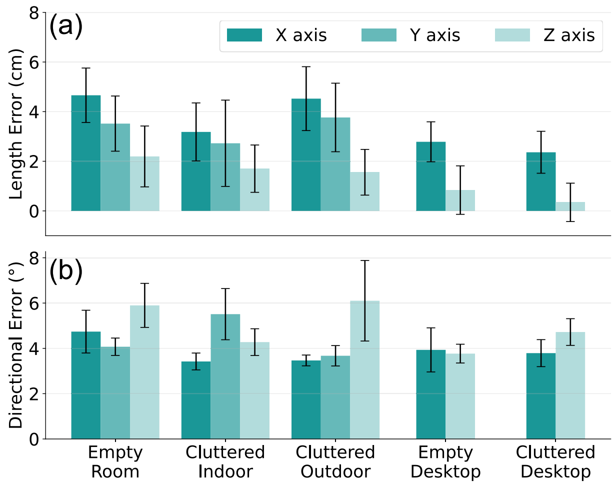

Figure 10: Main effects of *Visual Reference* for (a) Length Error and (b) Directional Error for dragging tasks. Error bars indicate the SE.

6 Discussion

6.1 The Pattern of Linear Hand Movement in VR

Taking the findings of the three studies together, we summarize the linear hand movement patterns as follows. In line with the results of behavioural research [14, 46], the performance gain of the displayed trails proved that, in the process of vision and proprioceptive cooperation to complete motor control, vision can effectively perceive hand movement deviation and guide behavioural adjustment. The high speed when the trails were invisible also confirms the efficiency of proprioceptive perception [67]. Users generally move longer than the target length in the X- and Y-axis directions. This may be because the user underestimated the length of the trail, which is consistent with the general underestimation of size and distance in VEs in the literature [31, 51, 56]. However, the length error in the Z-axis direction is significantly smaller. This may be explained by the fact that in the competition between visual bias (making the movement distance longer) and unnatural movement and perspective (making the movement distance shorter), the latter prevailed.

The consistency of most of the findings among the three studies demonstrates the generalizability of the findings. In all three studies, smaller error values in speed and length in the Z-axis direction were repeated. The slower speed and smaller length error when drawing on the desktop found in Study 2 were also verified in Study 3. Interestingly, in Study 3, compared to the stroke drawing and dragging tasks, scaling exhibited completely different characteristics in terms of length error (with negative values), and significant differences in length error also appeared between subtasks. Both indicate that the task itself is also an important factor affecting the hand movement pattern, which we leave to future exploration.

6.2 Design Implications

Based on the experimental results and user preferences, we make the following recommendations for hand movement-based VR applications.

For applications that require the user to carefully control hand movements, we recommend showing the hand trajectory to improve movement control accuracy, although this may slow down movements. Although hand movement in the Z-axis shows a small length error, due to the slower speed and poor user feedback, we recommend careful consideration of hand movement in this direction. Specifically, in applications where length error is less important, Z-axis movement should be minimized from a user experience perspective.

In applications that require fine-grained control of the distance and direction of motion, we recommend the availability of virtual planes or grids [6] as visual references. Due to the accumulation of length and straightness errors that increase with movement distance, we recommend controlling the movement distance within an appropriate range based on the application's tolerance for motion errors. While hand tracking [47] and controller-free interactions [43] have become popular in VR, weaknesses in directional control accuracy and user preference make the bare hand an unfavourable tool for fine hand movement control.

7 Limitation and Future Works

Due to experimental conditions, our study tested only one VR headset, and all participants were right-handed, which was insufficient to cover all real-world situations. In order to control the total duration of the experiment and avoid participant fatigue (the duration of our experiments ranged from 45 minutes to 1 hour), the number of repetitions we set is relatively low considering the number of conditions and the number of variables in the comparison. However, in order to ensure the quality of our data, we designed practice sessions to help participants become sufficiently familiar with the operations and tasks. In addition, we have recruited enough participants (60 in total) that we believe our data volume is sufficient.

The scenario we are targeting is precision-first 3D applications in virtual reality. Therefore, our guidance for participants is to draw as accurately and straight as possible, without requirements on speed. Therefore, the analysis of speed is beyond our scope. However, for the sake of the completeness of the reported results, we also report these results truthfully. Past studies have followed a similar research paradigm [15, 67]. We leave a more rigorous study of hand movement speed for future work.

The visual references in our research involved only the cluttered environment and desktops. However, some studies show that cues embodied in Social VR [16] and the scale of the self-avatar [47] affect the perception of distance and size. It is noted that the size of one's virtual hand directly influences estimations of virtual object size in VR [37]. For future work, more visual references, such as the effect of self-avatar scale on hand linear motion control, are worth further exploration. In addition, for the extended movement distance found in our results, interactive techniques and interfaces can be designed for error correction to improve human performance in practical tasks. For example, recent work has found that the appended virtual body parts mimicking real body parts can provide spatial reference to virtual targets [58]. We need more similar technologies to help people build accurate spatial perception.

8 Conclusion

In this paper, we systematically examined the user's fine motor control ability of linear hand movement in VR with three user studies. In Study 1, we examined the participants' behavioural patterns when drawing straight lines in various directions and lengths, and carefully investigated the factors such as trail visibility and drawing tools. We found that the exhibited stroke length tended to be longer than perceived, while displaying the trails could help increase the accuracy but reduce speed. In Study 2, we further assessed the influence of various visual references and found that the mere existence of a virtual desktop resulted in higher input accuracy and user preference. In Study 3, we verified the generalizability of the findings in real dragging and scaling tasks. Finally, we distilled our findings into design implications for hand interactions in VR.

Acknowledgments

This work was supported by the Natural Science Foundation of China (NSFC) under Grant No. 62132010, and the grant from the Institute for Guo Qiang, Tsinghua University No. 2019GOG0003.

REFERENCES

[1] W. Abend, E. Bizzi, and P. Morasso. Human arm trajectory formation. *Brain: a journal of neurology*, 105(Pt 2):331–348, 1982.

[2] H. Adams, J. Stefanucci, S. Creem-Regehr, and B. Bodenheimer. Depth perception in augmented reality: The effects of display, shadow, and position. In *2022 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 792–801. IEEE, 2022.

[3] I. V. Alexandrova, P. T. Teneva, S. De La Rosa, U. Kloos, H. H. Bülthoff, and B. J. Mohler. Egocentric distance judgments in a large screen display immersive virtual environment. In *Proceedings of the 7th Symposium on Applied Perception in Graphics and Visualization*, pp. 57–60, 2010.

[4] J. Andre and S. Rogers. Using verbal and blind-walking distance estimates to investigate the two visual systems hypothesis. *Perception & Psychophysics*, 68(3):353–361, 2006.

[5] E. Arabadzhiyska, O. T. Tursun, K. Myszkowski, H.-P. Seidel, and P. Didyk. Saccade landing position prediction for gaze-contingent rendering. *ACM Transactions on Graphics (TOG)*, 36(4):1–12, 2017.

[6] R. Arora, R. H. Kazi, F. Anderson, T. Grossman, K. Singh, and G. W. Fitzmaurice. Experimental evaluation of sketching on surfaces in vr. In *CHI*, vol. 17, pp. 5643–5654, 2017.

[7] R. Arora, J. Li, G. Shi, and K. Singh. Thinking outside the lab: Vr size & depth perception in the wild. *arXiv preprint arXiv:2105.00584*, 2021.

[8] R. Arora and K. Singh. Mid-air drawing of curves on 3d surfaces in virtual reality. *ACM Transactions on Graphics (TOG)*, 40(3):1–17, 2021.

[9] J. Auda, R. Heger, U. Gruenefeld, and S. Schneegass. Vrsketch: Investigating 2d sketching in virtual reality with different levels of hand and pen transparency. In *IFIP Conference on Human-Computer Interaction*, pp. 195–211. Springer, 2021.

[10] M. Bachynskyi and J. Müller. Dynamics of aimed mid-air movements. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, pp. 1–12, 2020.

[11] S.-H. Bae, R. Balakrishnan, and K. Singh. Ilovesketch: as-natural-as-possible sketching system for creating 3d curve models. In *Proceedings of the 21st annual ACM symposium on User interface software and technology*, pp. 151–160, 2008.

[12] M. D. Barrera Machuca, W. Stuerzlinger, and P. Asente. The effect of spatial ability on immersive 3d drawing. In *Proceedings of the 2019 on Creativity and Cognition*, pp. 173–186. 2019.

[13] J. Bergström, T.-S. Dalsgaard, J. Alexander, and K. Hornbæk. How to evaluate object selection and manipulation in vr? guidelines from 20 years of studies. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*, pp. 1–20, 2021.

[14] A. Blank, A. M. Okamura, and K. J. Kuchenbecker. Identifying the role of proprioception in upper-limb prosthesis control: Studies on targeted motion. *ACM Transactions on Applied Perception (TAP)*, 7(3):1–23, 2008.

[15] C. Chen, M. Yarmand, Z. Xu, V. Singh, Y. Zhang, and N. Weibel. Investigating input modality and task geometry on precision-first 3d drawing in virtual reality. In *2022 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, pp. 384–393. IEEE, 2022.

[16] Z. Choudhary, M. Gottsacker, K. Kim, R. Schubert, J. Stefanucci, G. Bruder, and G. F. Welch. Revisiting distance perception with scaled embodied cues in social virtual reality. In *2021 IEEE Virtual Reality and 3D User Interfaces (VR)*, pp. 788–797. IEEE, 2021.

[17] A. Clarence, J. Knibbe, M. Cordeil, and M. Wybrow. Unscripted retargeting: Reach prediction for haptic retargeting in virtual reality. In *2021 IEEE Virtual Reality and 3D User Interfaces (VR)*, pp. 150–159. IEEE, 2021.

[18] L. D. Clark, A. B. Bhagat, and S. L. Riggs. Extending fitts' law in three-dimensional virtual environments with current low-cost virtual reality technology. *International Journal of Human-Computer Studies*, 139:102413, 2020.

[19] S. H. Creem-Regehr, J. K. Stefanucci, W. B. Thompson, N. Nash, and M. McCardell. Egocentric distance perception in the oculus rift (dk2). In *Proceedings of the ACM SIGGRAPH symposium on applied perception*, pp. 47–50, 2015.

[20] A. G. de Siqueira, R. Venkatakrishnan, R. Venkatakrishnan, A. Bhargava, K. Lucaites, H. Solini, M. Nasiri, A. Robb, C. Pagano, B. Ullmer, et al. Empirically evaluating the effects of perceptual information channels on the size perception of tangibles in near-field virtual reality. In *2021 IEEE Virtual Reality and 3D User Interfaces (VR)*, pp. 1–10. IEEE, 2021.

[21] H. Elsayed, M. D. Barrera Machuca, C. Schaarschmidt, K. Marky, F. Müller, J. Riemann, A. Matviienko, M. Schmitz, M. Weigel, and M. Mühlhäuser. Vrsketchpen: unconstrained haptic assistance for sketching in virtual 3d environments. In *26th ACM Symposium on Virtual Reality Software and Technology*, pp. 1–11, 2020.

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

[23] Z. Fu, R. Xu, S. Xin, S. Chen, C. Tu, C. Yang, and L. Lu. Easyvrmodeling: Easily create 3d models by an immersive vr system. *Proceedings of the ACM on Computer Graphics and Interactive Techniques*, 5(1):1–14, 2022.

[24] N. M. Gamage, D. Ishtaweera, M. Weigel, and A. Withana. So predictable! continuous 3d hand trajectory prediction in virtual reality. In *The 34th Annual ACM Symposium on User Interface Software and Technology*, pp. 332–343, 2021.

[25] K. Grinyer and R. J. Teather. Effects of field of view on dynamic out-of-view target search in virtual reality. In *2022 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 139–148. IEEE, 2022.

[26] S. Gül, S. Bosse, D. Podborski, T. Schierl, and C. Hellge. Kalman filter-based head motion prediction for cloud-based mixed reality. In *Proceedings of the 28th ACM International Conference on Multimedia*, pp. 3632–3641, 2020.

[27] T. S. Gunasekaran, R. Hajika, C. D. S. Y. Haigh, Y. S. Pai, D. Lottridge, and M. Billinghurst. Adapting fitts' law and n-back to assess hand proprioception. In *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems*, pp. 1–7, 2021.

[28] N. Hagbi, R. Grasset, O. Bergig, M. Billinghurst, and J. El-Sana. In-place sketching for content authoring in augmented reality games. In *2010 IEEE Virtual Reality Conference (VR)*, pp. 91–94. IEEE, 2010.

[29] H. Ida, S. Mohapatra, and A. S. Aruin. Perceptual distortion in virtual reality and its impact on dynamic postural control. *Gait & Posture*, 92:123–128, 2022.

[30] J. W. Kelly. Distance perception in virtual reality: A meta-analysis of the effect of head-mounted display characteristics. *IEEE Transactions on Visualization and Computer Graphics*, 2022.

[31] J. W. Kelly, L. A. Cherep, B. Klesel, Z. D. Siegel, and S. George. Comparison of two methods for improving distance perception in virtual reality. *ACM Transactions on Applied Perception (TAP)*, 15(2):1–11, 2018.

[32] E. Klein, J. E. Swan, G. S. Schmidt, M. A. Livingston, and O. G. Staadt. Measurement protocols for medium-field distance perception in large-screen immersive displays. In *2009 IEEE virtual reality conference*, pp. 107–113. IEEE, 2009.

[33] P. Kourtesis, S. Vizcay, M. Marchal, C. Pacchierotti, and F. Argelaguet. Action-specific perception & performance on a fitts's law task in virtual reality: The role of haptic feedback. *IEEE Transactions on Visualization and Computer Graphics*, 2022.

[34] E. Kruijff, J. E. Swan, and S. Feiner. Perceptual issues in augmented reality revisited. In *2010 IEEE International Symposium on Mixed and Augmented Reality*, pp. 3–12. IEEE, 2010.

[35] B. R. Kunz, L. Wouters, D. Smith, W. B. Thompson, and S. H. Creem-Regehr. Revisiting the effect of quality of graphics on distance judgments in virtual environments: A comparison of verbal reports and blind walking. *Attention, Perception, & Psychophysics*, 71(6):1284–1293, 2009.

[36] R. Larson. *Precalculus: a concise course*. Cengage learning, 2013.

[37] S. A. Linkenauger, M. Leyrer, H. H. Bülthoff, and B. J. Mohler. Welcome to wonderland: The influence of the size and shape of a virtual hand on the perceived size and shape of virtual objects. *PloS one*, 8(7):e68594, 2013.

[38] L. Liu, R. van Liere, C. Nieuwenhuizen, and J.-B. Martens. Comparing aimed movements in the real world and in virtual reality. In *2009 IEEE*

Virtual Reality Conference, pp. 219–222. IEEE, 2009.
[39] J. M. Loomis, J. M. Knapp, et al. Visual perception of egocentric distance in real and virtual environments. *Virtual and adaptive environments*, 11:21–46, 2003.
[40] M. D. B. Machuca, W. Stuerzlinger, and P. Asente. Smart3dguides: Making unconstrained immersive 3d drawing more accurate. In *25th ACM Symposium on Virtual Reality Software and Technology*, pp. 1–13, 2019.
[41] V. J. Manyam. A psychophysical measure of visual and kinaesthetic spatial discriminative abilities of adults and children. *Perception*, 15(3):313–324, 1986.
[42] S. Masnadi, K. Pfeil, J.-V. T. Sera-Josef, and J. LaViola. Effects of field of view on egocentric distance perception in virtual reality. In *CHI Conference on Human Factors in Computing Systems*, pp. 1–10, 2022.
[43] A. Masurovsky, P. Chojecki, D. Runde, M. Lafci, D. Przewozny, and M. Gaebler. Controller-free hand tracking for grab-and-place tasks in immersive virtual reality: Design elements and their empirical study. *Multimodal Technologies and Interaction*, 4(4):91, 2020.
[44] D. E. Meyer, J. K. Smith, S. Kornblum, R. A. Abrams, and C. E. Wright. Speed—accuracy tradeoffs in aimed movements: Toward a theory of rapid voluntary action. *Attention and performance XIII*, pp. 173–226, 2018.
[45] D. C. Niehorster, L. Li, and M. Lappe. The accuracy and precision of position and orientation tracking in the htc vive virtual reality system for scientific research. *i-Perception*, 8(3):2041669517708205, 2017.
[46] A. Nieto-Guisado, M. Solana-Tramunt, A. Marco-Ahulló, M. Sevilla-Sánchez, C. Cabrejas, J. Campos-Rius, and J. Morales. The mediating role of vision in the relationship between proprioception and postural control in older adults, as compared to teenagers and younger and middle-aged adults. In *Healthcare*, vol. 10, p. 103. MDPI, 2022.
[47] N. Ogawa, T. Narumi, and M. Hirose. Virtual hand realism affects object size perception in body-based scaling. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 519–528. IEEE, 2019.
[48] J. Panero and M. Zelnik. *Human dimension & interior space: a source book of design reference standards*. Watson-Guptill, 1979.
[49] K. Pfeil, S. Masnadi, J. Belga, J.-V. T. Sera-Josef, and J. LaViola. Distance perception with a video see-through head-mounted display. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*, pp. 1–9, 2021.
[50] J. Ping, Y. Liu, and D. Weng. Comparison in depth perception between virtual reality and augmented reality systems. In *2019 ieee conference on virtual reality and 3d user interfaces (vr)*, pp. 1124–1125. IEEE, 2019.
[51] R. S. Renner, B. M. Velichkovsky, and J. R. Helmert. The perception of egocentric distances in virtual environments-a review. *ACM Computing Surveys (CSUR)*, 46(2):1–40, 2013.
[52] C. S. Sahm, S. H. Creem-Regehr, W. B. Thompson, and P. Willemsen. Throwing versus walking as indicators of distance perception in similar real and virtual environments. *ACM Transactions on Applied Perception (TAP)*, 2(1):35–45, 2005.
[53] F. R. Sarlegna and R. L. Sainburg. The effect of target modality on visual and proprioceptive contributions to the control of movement distance. *Experimental Brain Research*, 176(2):267–280, 2007.
[54] F. R. Sarlegna and R. L. Sainburg. The roles of vision and proprioception in the planning of reaching movements. *Progress in motor control*, pp. 317–335, 2009.
[55] V. Schwind, P. Knierim, C. Tasci, P. Franczak, N. Haas, and N. Henze. " 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*, pp. 1577–1582, 2017.
[56] J. K. Stefanucci, D. A. Lessard, M. N. Geuss, S. H. Creem-Regehr, and W. B. Thompson. Evaluating the accuracy of size perception in real and virtual environments. In *Proceedings of the ACM Symposium on Applied Perception*, pp. 79–82, 2012.
[57] B. H. Thomas. Examining user perception of the size of multiple objects in virtual reality. *Applied Sciences*, 10(11):4049, 2020.
[58] Y. Tian, Y. Bai, S. Zhao, C.-W. Fu, T. Yang, and P. A. Heng. Virtually-extended proprioception: Providing spatial reference in vr through an appended virtual limb. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, pp. 1–12, 2020.
[59] E. Triantafyllidis, W. Hu, C. McGreavy, and Z. Li. Metrics for 3d object pointing and manipulation in virtual reality. *arXiv preprint arXiv:2106.06655*, 2021.
[60] E. Triantafyllidis and Z. Li. The challenges in modeling human performance in 3d space with fitts' law. In *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems*, pp. 1–9, 2021.
[61] R. Türkmen, K. Pfeuffer, M. D. Barrera Machuca, A. U. Batmaz, and H. Gellersen. Exploring discrete drawing guides to assist users in accurate mid-air sketching in vr. In *CHI Conference on Human Factors in Computing Systems Extended Abstracts*, pp. 1–7, 2022.
[62] K. Vaziri, M. Bondy, A. Bui, and V. Interrante. Egocentric distance judgments in full-cue video-see-through vr conditions are no better than distance judgments to targets in a void. In *2021 IEEE Virtual Reality and 3D User Interfaces (VR)*, pp. 1–9. IEEE, 2021.
[63] C. Vienne, S. Masfrand, C. Bourdin, and J.-L. Vercher. Depth perception in virtual reality systems: Effect of screen distance, environment richness and display factors. *IEEE Access*, 8:29099–29110, 2020.
[64] A. Vysockỳ, S. Grushko, P. Oščádal, T. Kot, J. Babjak, R. Jánoš, M. Sukop, and Z. Bobovskỳ. Analysis of precision and stability of hand tracking with leap motion sensor. *Sensors*, 20(15):4088, 2020.
[65] G. Wesche and H.-P. Seidel. Freedrawer: a free-form sketching system on the responsive workbench. In *Proceedings of the ACM symposium on Virtual reality software and technology*, pp. 167–174, 2001.
[66] H. Wu, Y. Deng, J. Pan, T. Han, Y. Hu, K. Huang, and X. L. Zhang. User capabilities in eyes-free spatial target acquisition in immersive virtual reality environments. *Applied Ergonomics*, 94:103400, 2021.
[67] Y. Yan, C. Yu, X. Ma, S. Huang, H. Iqbal, and Y. Shi. Eyes-free target acquisition in interaction space around the body for virtual reality. In *Proceedings of the 2018 CHI conference on human factors in computing systems*, pp. 1–13, 2018.
[68] E. Yu, R. Arora, T. Stanko, J. A. Bærentzen, K. Singh, and A. Bousseau. Cassie: Curve and surface sketching in immersive environments. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*, pp. 1–14, 2021.
[69] X. Yu, S. DiVerdi, A. Sharma, and Y. Gingold. Scaffoldsketch: Accurate industrial design drawing in vr. In *The 34th Annual ACM Symposium on User Interface Software and Technology*, pp. 372–384, 2021.
[70] S. Zhai and R. Woltjer. Human movement performance in relation to path constraint-the law of steering in locomotion. In *IEEE Virtual Reality, 2003. Proceedings.*, pp. 149–156. IEEE, 2003.
[71] Q. Zhou, G. Hagemann, D. Fafard, I. Stavness, and S. Fels. An evaluation of depth and size perception on a spherical fish tank virtual reality display. *IEEE transactions on visualization and computer graphics*, 25(5):2040–2049, 2019.