Rotational and Positional Jitter in Virtual Reality Interaction in Everyday VR

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Abstract One element that affects 3D tracking performance in virtual reality (VR) systems is fluctuations in the signal, i.e., jitter, which occurs regardless of the sensor technology used. In real-life VR systems, positional and rotational jitter can be found in all tracked objects, including the headset, controllers, or other trackers. Previous work had identified that ±0.5° rotational jitter negatively affects user performance for distal pointing. Yet, they also found that even using a second controller to reduce the "Heisenberg effect" introduced by the button press does not address the problem completely. Moreover, with jitter on the position of a virtual object, user performance significantly decreases with jitter above one fourth of the size of that virtual object. Still, users preferred to have positional jitter on a virtual target rather than rotational jitter on a VR controller. In this chapter, we extended the previous literature by conducting a user study on angular jitter with controllers held with two different grip styles and targets at two different depth distances. The results revealed that user performance decreases (already) with ±0.25° additional jitter. Thus, we suggest that practitioners/developers who design 3D user interfaces, controllers, and interaction techniques for daily 3D VR usage should focus on reducing jitter. Decreasing jitter not only improves user performance but also decreases frustration, which improves the user experience.

1 Introduction

For 3D interaction with a virtual environment and its 3D objects through a virtual reality (VR) systems, selection plays a critical role in everyday VR. In VR systems, pointing is thus one of the first and most frequent tasks that a user executes.

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During 3D pointing, the user has to point toward the desired target. The pointing device has to be in the correct position and orientation to enable accurate pointing within the virtual world. To facilitate such pointing, the user is (usually) provided with some form of feedback, such as a color change, when they correctly point to a target. Once the cursor is on the desired target, then the user confirms the target selection, typically with a button click.

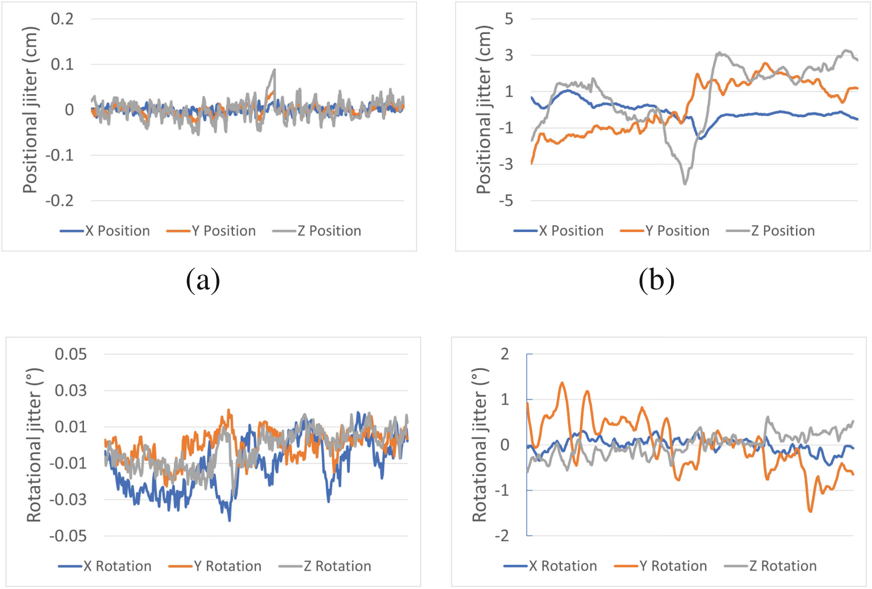
As mentioned above, there are two aspects to selection: the user points to the correct target, and the input system transfers the pointing pose from the real world to the virtual world. During this transfer, a signal is generated by the controller and sent to the end-user application or software. This generated signal also contains fluctuations, called jitter. Such jitter can be observed in all stages of pointing in everyday VR.

When the user points the cursor toward a target, hand tremor might affect the pointing performance, which is usually between 4 and 12 Hz (Ang 2004; Elble et al. 1990; Hefter et al. 1987; Stiles 1980). This type of unintentional hand movement is included as jitter in the signal measured by the input device. Other biological factors, such as body sway or breathing, can also add additional jitter.

The 3D tracking system used by the input device can also generate different types of jitter (Fang et al. 2017). For instance, most current VR controllers contain an Inertial Measurement Unit (IMU) to measure the acceleration and orientation of the device by using the data from accelerometers and gyroscopes. The digital signal generated by the accelerometer and gyroscopes typically contains jitter due to imperfections in the transformation of the world pose data into a digital form. This jitter is usually the result of a combination of different issues, such as thermal noise, electrical noise, and quantization noise. Moreover, this jitter value changes with environmental conditions, including temperature and humidity.

Another type of jitter is generated by different form of light sensors for 3D tracking, such as infrared or visible light cameras (Oh et al. 2016). It is possible to observe such jitter with the all kinds of VR trackers, including cameras on headsets, hand tracking systems such as Leap Motion (Guna et al. 2014), and the Kinect (Xi et al. 2018). These sensors aim to detect the absolute pose of the input device; which could be a VR controller of a commercial VR HMDs or the hands of the user for the Leap Motion. These sensors detect visually salient entities, including beacons, shapes, or markers, which allows the tracking algorithm to detect the pose of the device. However, these beacons, shapes, or markers might not be always fully visible to the sensors because of occlusion. In this case, the tracking algorithm might not always work properly and the user can observe a sudden change in the pose of the virtual VR controller. Even when all markers or beacons are fully visible, the output of the tracking algorithm can contain noise in the pose due to simplifying assumptions in the algorithm (such as local linearity) or sensor limitations.

When the pose data of the input device(s) is received by a software on a computer, this data is typically processed with a filtering algorithm, such as the One-Euro filter (Casiez et al. 2012) or Kalman Filter (Welch 2009). These filtering algorithms can also add (temporal) jitter due to the phase shift they introduce.



(a) (b)

(c) (d)

Fig. 1 An exemplar jitter recording on a VR Controller. Positional jitter in cm when the VR controller is **a** immobilized or **b** held in mid-air. Rotational jitter in degrees when the VR controller is **c** immobilized or **d** held in mid-air

Apart from these different types of jitter that impact user interaction even when the device is stably hovering in mid-air, different interaction actions can also add additional jitter. For instance, pulling a trigger or pushing a button on a VR controller can cause an unintentional pose changes. Such changes were previously investigated under the term "Heisenberg effect" for spatial interaction, and the results identified that user performance can decrease (Wolf et al. 2020).

Apart from all the information regarding input devices, such as a VR controller, jitter can be also observed in other parts of a VR system, such as the head-mounted display. Moreover, jitter can even be observed in input devices that are not attached to or held by the user. For instance, current tracking devices can be attached to static objects in the real environment, so that the real world objects' pose can be transferred into the VR system. Such tracking devices are also prone to exhibit jitter.

When a 2D mouse is left stable on a table, the amount of jitter recorded by the system is usually practically zero, due to the surface friction and high-resolution sensors. On the other hand, if a VR controller is left stable on a table, it is possible to observe tracking jitter in its pose (Fig. 1a, c). This jitter is even more visible when the user points a target on mid-air, as shown in Fig. 1b, d where there is then substantial movement even outside the human tremor band (4–12 Hz).

Previous work in the VR and AR literature focused on more precise and accurate interactions to eliminate the impact of jitter. For instance, the handlebar method supports more precise movement actions in mid-air, but requires bi-manual hand manipulation (Song et al. 2012). The 7-handle technique used triangle shaped widgets with seven points and subjects found this method less tiring and more efficient than the simple virtual hand (Nguyen et al. 2014). The MAiOR method used mid-air rails and widgets to increase the precision of object manipulation by separating DoFs (Mendes et al. 2016). Recent work presents a method that uses pivot points (Gloumeau et al. 2020) to further increase precision. All these techniques were proposed to decrease the detrimental impact of the jitter in state-of-the art systems.

With a series of experiments, we previously explored the change of user pointing performance due to jitter in VR systems (Batmaz et al. 2020b; Batmaz and Stuerzlinger 2019a, b). In our first experiment, we showed that user performance significantly decreases above ±0.5° rotational jitter. In a second experiment reported in that work, we showed that using a second controller's trigger as an selection confirmation does not mitigate the jitter observable in a VR controller. In our final experiment, we showed that user performance also significantly decreases with jitter on the targets.

Here, we use the same terminology as in our previous work. We refer to "rotational jitter" as the orientation jitter that affects user performance with VR controllers. In VR environments, there are two common interaction methods, ray casting and virtual hand (Argelaguet and Andujar 2013). For VR controllers, rotational jitter has the most detrimental effect for one of the most common selection methods, ray casting, which works similar to a laser pointer. With the ray casting method, a small change in the rotation of the VR controller results in a larger change at a further distance. For instance, if a VR controller is rotated 5°, the cursor shifts 8.7 cm at 1 m but 17.4 cm at 2 m. Positional jitter at the controller has (relatively) less impact, as identified in previous work (Batmaz et al. 2020b). As jitter affects VR trackers attached to real world objects, which is particularly relevant for AR applications, we additionally explore "positional target jitter" as our second objective. This positional target jitter has a (relatively) larger impact on pointing, since rotational jitter at the center of a spherical target has (near to) zero impact during selection while positional jitter can change the object's center coordinates.

One major finding of our previous work on jitter was that our results identify potential explanations for other results of research on novel input devices. Pham and Stuerzlinger (Pham and Stuerzlinger 2019) showed that, compared to commercial VR controllers typically held in a power grip, using a pen-like device improves user performance in a 3D pointing task. However, another investigation of a pen-like device exhibited lower user performance (Batmaz et al. 2020a). When investigating several potential explanations for this difference, we realized that participants were complaining about hand tremor in the latter work. The analysis on the mid-air jitter data revealed that the pen-like device used in (Batmaz et al. 2020a) exhibited sufficiently large pose jitter to reduce user performance. Like in the previous studies, we use describe situations where it takes a user longer to execute a task, they make more errors, and/or their throughput reduces as a *decrease* in user performance.

We are investigating jitter levels observable in everyday VR/AR systems to make sure our results are directly applicable to current work. All electronic systems exhibit jitter, and jitter adds noise to signals during data transfer. On the other hand, 3D mid-air pointing is already an unusual interaction method—few things float in mid-air in the real world, e.g., (Stuerzlinger and Wingrave 2011)—and is thus more challenging than, e.g., 2D pointing, such as with a mouse. Thus, the additional jitter introduced by 3D tracking systems can affect user performance and their experience during interaction with everyday VR/AR systems relatively stronger. The impact of jitter in everyday VR/AR can be observed in various scenarios. For instance, drawing and writing is an important part in everyday VR/AR, and high levels of jitter in an input device can impact the communication between users and content annotation (Kern et al. 2021). Another example of the impact of jitter in everyday VR/AR is observable in VR shooting games, where the user has to aim toward to a target by pointing the controller. Any non-trivial level of jitter typically lowers the precision of the user in this task and thus affects the user experience negatively.

In this study, we investigated the effects of rotational and positional jitter on user performance with two different input devices, an HTC Vive Pro VR controller and a Logitech© VRInk pen, with targets placed at two different target depths. The position of the targets was chosen based on angular measures. Our results show that user performance significantly decreases with more than ±0.5° positional and rotational jitter.

2 Previous Work

In this section, we discuss previous work related to jitter and also to the experimental conditions that we investigated in our study. We first focus on the existing literature that is used to assess human motor performance in VR systems for different jitter levels. Then, we review previous research conducted on jitter in VR systems and the impact of jitter, including human motor performance assessment in VR systems.

2.1 Fitts' Law

Fitts' law (Fitts 1954) models human movement times for pointing. For Euclidean measures, Eq. 1 shows the Shannon formulation (MacKenzie 1992).

$$\text{Movement Time} = a + b * \log_2\left(\frac{A}{W} + 1\right) = a + b * \text{ID} \qquad (1)$$

In Eq. 1, a and b are empirical constants, typically identified by linear regression. A is the amplitude of the movement, which is the distance between two targets, and W the target width. The logarithmic term in Eq. 1 represents the task difficulty and is called the *index of difficulty*, ID.

For pointing tasks in 3D environments, several variations that use an angular ID have been proposed in the literature (Barrera Machuca and Stuerzlinger 2019; Cha

Table 1 Models proposed by previous work for 3D versions of Fitts’s law

Paper	Model
Murata and Iwase (2001)	$\mathrm{MT} = a + b\sin(\phi) + c(\mathrm{ID})$
Kopper et al. (2010)	$\mathrm{MT} = a + b\mathrm{ID}_{\mathrm{DP}}$
Stoelen and Akin (2010)	$\mathrm{MT} = a + b(\mathrm{ID}_{\mathrm{rotation}} + \mathrm{ID}_{\mathrm{translation}})$
Vetter et al. (2011)	$\mathrm{MT} = a \times d - \beta \times \log_2(TS) + \gamma \times \sin(2\theta) + \delta \times \sin(\theta) + c$
Cha and Myung (2013)	$\mathrm{MT} = a + b\sin(\phi) + c\theta + d\mathrm{ID}$
Barrera Machuca and Stuerzlinger (2019)	$\mathrm{MT} = a + b(\mathrm{ID}) + c(\mathrm{CTD})$
Clark et al. (2020)	$\mathrm{MT} = a + b(\mathrm{ID}) + c(\theta) + d(\theta * \mathrm{TS})$

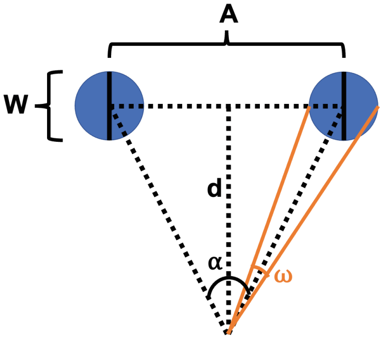


Fig. 2 Top view of angular pointing. A is the Euclidean distance between two targets, W is the target width and d is the distance from the user to the targets. Similarly, α represents the angular distance and ω the angular target width

and Myung 2013; Clark et al. 2020; Kopper et al. 2010; Murata and Iwase 2001; Vetter et al. 2011; Stoelen and Akin 2010). These are shown in Table 1.

Our work does not aim to propose a novel angular ID equation. For simplicity, we thus used Kopper et al.’s angular ID formula:

$$\mathrm{ID}_{\mathrm{angular}} = \log_2\left(\frac{\alpha}{\omega^k} + 1\right) \tag{2}$$

In Eq. 2, α represents the angular distance between targets and ω the angular target width. The constant k represents a relative weight between α and ω. For simplicity, we set $k = 1$. We used the same method to convert Euclidean distances to angular measures as Kopper et al. (2010), which is also illustrated in Fig. 2.

We also use throughput (based on effective measures), as defined in the ISO 9241-411:2012:

$$\mathrm{Throughput} = \left(\frac{\mathrm{ID}_e}{\text{Movement Time}}\right) \tag{3}$$

In Eq. 3, movement time is the time between initiation of the movement and the selection of the target. The effective index of difficulty (ID_e) incorporates the user’s accuracy in the task (ISO 2012):

$$\mathrm{ID}_e = \log_2\left(\frac{A_e}{W_e} + 1\right) \tag{4}$$

In Eq. 4, A_e represents the effective distance, the actual movement distance to the target position, and W_e is the effective target width, the distribution of selection coordinates, calculated as $W_e = 4.133 \times \mathrm{SD}_x$, where SD_x is the standard deviation of selection coordinates along the task axis. SD_x represents the precision of the task performance (MacKenzie and Isokoski 2008; MacKenzie and Oniszczak 1998).

2.2 3D Pointing Methods in VR

3D pointing is one of the essential components of interaction with the virtual environment through a VR system (LaViola et al. 2017). To select targets in a VR environment, the user has to first point at the target (and then confirm the selection). While pointing at targets is relatively easy within peri-personal space, i.e., within arm's reach, the task becomes more challenging for further targets.

To afford pointing at distal targets the most common solution is raycasting, which resembles a real-life task: using a laser pointer (LaViola et al. 2017). Nevertheless, as with laser pointing, ray casting is not very effective for accurate selection of small and/or distant targets. One simple method that aims to improve the accuracy and visibility of the cursor position with ray casting displays a virtual ray between the controller and the respective intersected surface of the virtual environment to give the user better visual feedback.

To facilitate the selection of distal targets various methods have been proposed, e.g. (Vanacken et al. 2007; De Haan et al. 2005; Liang and Green 1994), but none of these proposed methods support high-precision pointing at objects in distant dense object groups. This creates a need to understand the limitations for user performance when using the ray casting method.

2.3 Selection Methods

After the user points the cursor/ray at a target, a corresponding action is needed to activate the selection. Several multimodal methods to select a target in VR have been previously investigated, e.g., through voice or the blink of an eye (Vanacken et al. 2009). Current state-of-the-art VR controllers afford selection simply by pulling a trigger or pushing a button on the device. Since the VR controller hovers in mid-air, there is no physical feedback to counterbalance the force applied to the buttons or triggers. In this case, the VR controller's pose can be altered by the trigger/button press, and this error is called the "Heisenberg effect" of spatial interaction (Bowman et al. 2001).

The effect of the Heisenberg effect increases for farther targets, since even the slightest noise in the orientation of the VR controller magnifies with distance (Batmaz and Stuerzlinger 2019a). To eliminate the negative impact of the Heisenberg effect, previous studies used various bi-manual interaction methods, such as using the space bar of the keyboard or a second controller's trigger, both operated with the non-dominant hand (Batmaz and Stuerzlinger 2019b; Batmaz et al. 2020a).

2.4 Different Grip Styles in VR Systems

New VR controllers are being introduced with the aim of increasing the user's accuracy (Barber et al. 2018), precision (Romat et al. 2021), or the ergonomics (Kartick et al. 2020) of VR systems. Since previous work showed that arm, elbow, forearm, wrist, hand, finger, and fingertip position and rotation can play a crucial role in terms of user performance, the design of a VR controller is also critical (Yan and Downing 2001; Shih 2005; Schwarz and Taylor 1955; Liao 2014; Cutkosky and Wright 1986). This also includes the main design attributes of the controller, such as the size of the main handle. In addition, required grip strength, hand posture, and ergonomic factors all can affect user performance.

In current commercial VR systems, VR controllers support either one of two major grip styles. Our previous work (Batmaz et al. 2020a) used Napier's *prehensile movement* classification to anatomically and functionally categorize grip styles, and studied their effects in VR. The first major grip style is the precision grip, where the tool is pinched between multiple fingertips and the opposing thumb. The second one is the power grip: the object is held in the palm, while the fingers form a clamp position, with the thumb applying pressure counter to the fingers. HTC Vive's and Oculus' controllers are examples of controllers designed to be used in a power grip. The Massless and Logitech© VR Ink controllers are designed to be held in a precision grip.

Pham and Stuerzlinger's comparison of pointing performance with the precision and power grip showed that the precision grip significantly increased performance in terms of time, error rate, and throughput (Pham and Stuerzlinger 2019). Based on the Pham and Stuerzlinger's work, another study investigated the effects of the precision vs power grip with the Logitech© VRInk, which revealed that the power grip significantly decreased the error rate (Batmaz et al. 2020a). However, the throughput performance of the participants was lower compared to Pham and Stuerzlinger's work. More detailed analysis in the lead up to the current paper identified that the jitter exhibited by the pen controller in this second study was high enough to reduce the throughput performance of the participants. This motivated us to revisit jitter.

2.5 The Impact of Jitter in VR Systems

The adverse effect of jitter in VR systems was first analyzed by Teather et al. (2009), showing that an average of 0.3 mm spatial jitter in the input device decreased the user performance. A further study identified that the negative impact of a larger level of jitter increases with smaller targets (Pavlovych and Stuerzlinger 2009).

In the work discussed below in this section, all positional jitter mentioned was applied to the three positional axes of the targets objects and rotational jitter was applied to all three Euler axes of the VR controller used to point.

2.5.1 Effects of Jitter with a Uniform Distribution

Based on the results of the Teather et al. (2009), Batmaz and Stuerzlinger investigated the effects of jitter on user performance with a VR controller (Batmaz and Stuerzlinger 2019a). This study used an HTC Vive Pro system, which was one of the best tracking systems available on the market at that time. When the authors generated artificial jitter to add to the system, they used a uniform distribution, as uniformly distributed jitter is a simple way to characterize noise in complex systems.

In their study with 12 participants, Batmaz and Stuerzlinger focused on four levels of (added) rotational jitter: None, ±0.5° jitter, ±1° jitter and ±2° jitter. To analyze the results with Fitts' law, they also used three target distances: 10, 20, and 30 cm and three target sizes: 1.5, 2.5, and 3.5 cm .

The researchers placed the targets 50 cm away from the user for distal pointing and placed the cursor 30 cm away from the controller. This setup allowed researchers to limit potential issues with the control-display ratio and potential confounds of visual depth and visibility for their initial results.

During the task execution, the authors asked participants to select a target by pulling the trigger on the VR controller. With this interaction method, the researchers aimed to include the negative impact of the "Heisenberg effect" in their results.

The results of this study showed that there is no significant difference between ±0.5° jitter and none for execution time. On the other hand, their error rate significantly increased, and participants' throughput performance decreased significantly starting with ±1° jitter. The researchers concluded that practitioners and designers must take care with systems above ±0.5 ° jitter and test the user performance in terms of error rate.

In the detailed analysis of multiway interactions, the researchers investigated the effects of jitter on task difficulty. The authors used the task difficulty formula with the Euclidean target distance and target size (see Eq. 1). The results revealed that target distance does not have an impact on jitter. However, this approach is prone to errors: when the size of the target increased, the impact of the jitter was also (artificially) increased. Angular measures offer a better approach here.

While this study was the first step to analyze the negative impact of the rotational jitter, the authors used only a single depth distance, only uniform distribution noise, and the selection was subject to the "Heisenberg effect."

2.5.2 Effects of Different Selection Techniques and Discrete Uniform Distribution Noise on Rotational Jitter

In a subsequent study, Batmaz and Stuerzlinger analyzed the negative impacts of the jitter using White Gaussian Noise (WGN) and by eliminating the effects of the "Heisenberg effect" with a bi-manual selection techniques, again using an HTC Vive Pro setup (Batmaz and Stuerzlinger 2019b).

WGN is used to model random processes in information theory. Using WGN for jitter more closely models the cumulative impact of multiple sources of jitter on a controller in real life. To generate WGN, the authors used a standard normal distribution generator, the Marsaglia Polar Method (Marsaglia and Bray 1964), which yields random values with a mean of 0 and a standard deviation of 1.

Similar to the previous study (Batmaz and Stuerzlinger 2019a), the researchers used five different (added) levels of rotational jitter: None, ±0.5° jitter, ±1° jitter and ±2° jitter and WGN. The authors also used the same three target distances: 10, 20, and 30 cm and three target sizes: 1.5, 2.5, and 3.5 cm to analyze the results. They also used the same depth distance (50 cm) with the same ray length (30 cm) to keep their study comparable with previous work (Batmaz and Stuerzlinger 2019a).

To mitigate the impact of the Heisenberg effect, the authors also investigated two different bi-manual selection techniques: participants selected the targets by pulling the trigger of the VR controller held in the non-dominant hand or by pressing the space bar key on the keyboard with their non-dominant hand. They compared the results with a condition that included the "Heisenberg effect," where the participants selected targets by pulling the trigger on the VR controller that is used to point targets.

The results showed that using a single controller to both point and select targets increased the error rate compared to bi-manual hand selection techniques. Yet, the time and throughput performance of the participants did not change when using a second controller or the space bar. However, the post-questionnaire results revealed that one-third of the participant preferred a single controller, one-third of the participants preferred two controllers, and one-third of the participants preferred one controller with the keyboard selection technique, which means that the selection technique is also subject to user preferences.

Batmaz and Stuerzlinger (2019b) also investigated the effects of different jitter values on user performance. The results were similar to their previous work (Batmaz and Stuerzlinger 2019a), where higher levels of jitter increased the participants' execution time and error rate, while also decreasing effective throughput performance. As in the previous work, the authors observed significant negative effects of jitter at and above ±1° rotational jitter.

One of the interesting findings of this study concerned the speed accuracy tradeoff of the participants under the impact of jitter. Subjects were taking longer with an increased amount of jitter, but their error rate did not decrease, and effective throughput results also did not increase. The authors observed that when the participants had to select a target with a VR controller with jitter, the participants were waiting for a "better moment" to select targets, i.e., when the cursor might have stabilized temporarily. Yet, since the jitter was generated continuously, the cursor never stabilized. Thus, the participants' strategy simply took longer to select targets, which explains why there were no performance improvements.

The study of Batmaz and Stuzerlinger (2019b) showed that using bi-manual selection techniques improves user performance in terms of error rate. Also, WGN exhibited a decrease in user performance compared to a constant, uniform distribution. However, this study work did not investigate the impact of depth distance on target selection with jitter nor the effect of positional target jitter.

2.5.3 Effects of Target Depth on Rotational Jitter and Target Jitter

To investigate the negative impact of target depth and positional target jitter, Batmaz et al. (2020b) ran a study with an HTC Vive Pro setup. As in their previous work, they invited 12 participants to their study but used only WGN in their artificially generated jitter. To analyze the results based on Fitts' law, they used three target distances, 10, 20 and 30 cm, and two target sizes, 1.5 and 2.5 cm.

Different from their other work (Batmaz and Stuerzlinger 2019a, b), the authors tested their approach with three depth distances, 0.75, 1.5 and 2.25 m, to analyze the impact of the control-display ratio.

Moreover, the authors used three different (added) levels of positional jitter relative to the target size. The first level was 1/4 of the first target size (1.5 cm/4 = ±0.375 cm), and the second 1/4 of the second target size (2.5 cm/4 = ±0.625 cm). The third level had no jitter on the target.

Apart from positional jitter, the authors also added rotational jitter to the VR controller and looked at the interaction between positional and rotational jitter. For rotational jitter, they used none, ±0.5° and ±1°.

The results revealed that user performance significantly decreases when the depth distance increases in terms of time, error rate, and throughput. Similarly, the user performance decreases with increased target jitter.

The authors observed an interesting effect of positional jitter: the user performance significantly decreases for both positional jitter at 0.75 and 1.5 m, but at 2.25 m depth distance, they did not report a significant difference between positional jitter conditions. Since the targets are already far away and appear small beyond 1.5 m, no impact of positional jitter was observed – meaning that reducing the positional jitter at 2.25 m did not affect user performance.

Another finding of this study was the impact of jitter on fatigue. Except for a single person, all participants reported high fatigue after the experiment. Based on the questionnaire results, the study identified an overall negative impact of jitter on the user experience. Since one of their participant commented "No Jitter Please" in the questionnaire, the authors included this phrase in their title to highlight the severity of the problem. The authors did not report any significant interaction between positional and rotational jitter.

Even though (Batmaz et al. 2020b) investigated positional jitter and the impact of the depth distance on user performance, these values were based on Euclidean measures, i.e., all the target distances and target size were defined in centimeters, and the positional jitter was relative to target sizes.

In general, previous work on jitter revealed that

- Starting with ±1° uniform and WGN jitter, user's error rate increases and throughput performance decreases.
- Changing the interaction style to bi-manual technique decreases the negative effect of jitter.
- When there is jitter in the system (either on a controller or target) (naive) participants wait for a "better moment" to select targets, which increases the execution time, but does not decrease the error rate. This might also increase fatigue and thus decrease the user experience.
- Reducing the positional jitter in far targets, such as 2.25 m, does not improve user performance.

3 Motivation and Hypotheses

Previous work investigated WGN rotational and positional jitter relative to the target size at different depth distances using different selection methods (Batmaz et al. 2020b; Batmaz and Stuerzlinger 2019a, b). However, all the target distances, target sizes and positional jitter ranges were based on Euclidean measures.

In this study, we decided to extend previous work and analyze rotational and positional jitter with *angular measures*. This enables us to correlate angular jitter with angular target size and target distances, i.e., make the results independent of the actual distances and sizes, which should enable a generalization of the outcomes to arbitrary target distances.

Based on the previous research, we investigated the following hypotheses:

H1. Angular size plays a critical role for user performance when jitter is present. Hypotheses in previous work were solely based on Euclidean measures (Batmaz et al. 2020b; Batmaz and Stuerzlinger 2019a, b). In this work, we define target sizes and target distances in terms of angles. Our previous work had identified that user motor performance in terms of time, error rate, and throughput decreases at ±1 ° rotational jitter and with 1/4 of the target size (Batmaz et al. 2020b). Yet, we believe that user performance is affected by even lower levels of jitter and that the performance decrease really depends on the angular size of the targets - after all, ray casting involves (mostly) rotational movements.

H2. User performance depends on the depth distance used in the virtual environment. Even though we recast all the target sizes and distances into angular measures, we still believe that user performance will decrease with increased depth distances. Previous work identified that user performance can be negatively affected by visual depth cues conflicts in VR systems, such as the vergence and accommodation conflict (Batmaz et al. 2019; Barrera Machuca and Stuerzlinger 2018; Batmaz et al. 2022). Even though a constant target angle implies that the target size increases with further targets, visual depth cue conflicts would still impact user performance depending on target distance.

H3. A precision grip improves user performance when tracking jitter is present in the system. Previous work indicated that user performance significantly increases when a precision grip is used (Pham and Stuerzlinger 2019). However, other work claimed that the precision grip decreases user performance and explained their findings with the tracking issues related to the input device (Batmaz et al. 2020a). In this study, we used a more current version of the Logitech© VRInk pen, which does not suffer from tracking issues. Eliminating tracking issues should increase user accuracy and precision and thus improve the effective throughput of a participant. We believe that the increase in the precision and accuracy also increases the user performance when we add artificial jitter to the system.

4 User Study

To investigate our hypotheses, we conducted a user study using targets with different angular sizes at two different depth distances (1 and 2 m) with two different input devices that support two different grip styles (power grip and precision grip). We added three levels of jitter (None, 0.25° and 0.5°) to the controller for angular jitter and to the targets for positional jitter. All participants performed pointing tasks in all conditions.

Previous work on rotational and positional jitter used linear Euclidean measures, e.g., all target sizes and distances were characterized in (centi-)meters, and the findings were presented based on the corresponding metrics. In this work, we use angular measures rather than the Euclidean measures to make the findings more generalizeable. We still use the same Fitts' task as in previous work, to enable comparisons of our results with the literature.

4.1 Participants

Eight (8) right-handed participants (3 female and 5 male) attended our experiment. The average age was 28.62 (SD 4.56). All our participants were university students from the local department of the institution. They studied various disciplines, such as arts, engineering, computer science, or design. None of them had a prior experience with VR games or VR application development.

4.2 Apparatus

As in previous studies on jitter (Batmaz et al. 2020b; Batmaz and Stuerzlinger 2019a, b), we used an HTC Vive PRO VR system with three Lighthouses (trackers). The reason behind using a third Lighthouse was to increase the visibility of input devices to the tracking system and to increase the quality of the tracking data.

We used a PC with an Intel (R) Core (TM) i7-5890 CPU with 16 GB RAM and an NVIDIA GeForce RTX 1080 graphics card. Subjects used an HTC Vive Pro controller and a Logitech© VRInk pen controller as pointing devices, and the space bar of a Logitech desktop keyboard to indicate selection.

4.3 Procedure

After filling a demographic pre-questionnaire, participants were seated in a chair positioned (roughly) in the middle of the three HTC Vive Pro Lighthouses. Before starting the experiment, the experimenter explained and demonstrated the procedure to each participant and allowed participants to perform practice trials for a few minutes until they felt ready to start the experiment. After the main experiment, we asked participants to fill a post-questionnaire about their perceptions and insights.

In the virtual environment, subjects were placed in an empty room with pictorial depth cues. To assess user performance with 3D pointing, we used an ISO 92411-411 task (ISO 2012) with 11 targets distributed at equal distances in a circular arrangement. The first target was chosen randomly by the software for each repetition. The subjects experienced a clockwise and counter-clockwise target sequence, again selected randomly.

The eleven (11) potential target spheres, which are shown in Fig. 3, were gray at the beginning of each trial. We indicated the current target sphere by changing its color to orange. When the participant moved the ray/cursor using the controller, we

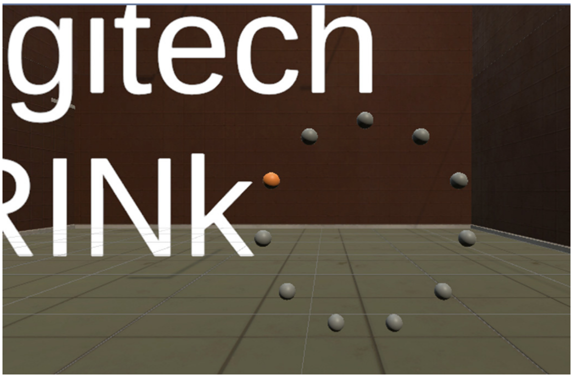


Fig. 3 Experimental environment view in the VR headset. Behind the experimental area, we showed the name of the input device that had to be used for the current round of trials as a text in the background

compared the distance between the target and cursor. If the cursor was inside of a sphere, we changed the color of that sphere to blue. If the participant selected the correct target while the cursor was inside of it, we changed the target's color to green and recorded a "hit." However, if the cursor was outside of the target upon selection, we showed the target in red, recorded a "miss," and played an error sound. As usual in Fitts' law studies, we asked participants to select targets as fast and as precise as possible.

In our study, participants used two different input devices with two different grip styles. As in previous comparisons of the precision grip and power grip, we asked participants to use a Logitech© VRInk pen with a precision grip and an HTC Vive Pro VR controller with a power grip, i.e., we investigated **Grip Style**, 2_{GS} = **precision grip and power grip**. This allowed us to investigate the impact of jitter on different grip styles (with different input devices). During the experiment, the name of the device that needed to be used to select targets was shown as text in the background, outside of the target area.

We also used two different **Depth Distances** (2_{DD} = **1 and 2 m**). We chose these depth distances based on previous work; we did not want targets within arm's length, i.e., closer than 70 cm and we wanted targets to be closer than 2.25 m, to be able to reliably observe the impact of jitter (Batmaz et al. 2020b).

We applied three different levels of rotational jitter on all three rotation axes of the controllers. For the first jitter level, the "none" condition, we did not add artificial jitter. For the second level of rotational jitter, we added ±WGN/4°, and for the third, we applied ±WGN/2°. In other words, the software generated WGN rotational jitter, and we multiplied this jitter with 0.25 for the second condition and 0.5 for the third one. For simplicity, we use only the coefficients for reporting **Rotational jitter**, 3_{RJ} = **None**, ±0.25°, **and** ±0.5°.

Similarly, we applied three different levels of positional jitter on all three positional axes of the targets. For the first level of positional jitter, we did not apply any artificial jitter, as the "none" condition. For the second level of positional jitter, we added ±WGN/4 cm, and in the third, we applied ±WGN/2 cm. Specifically, the software generated WGN positional jitter, and we multiplied this jitter value with 0.25 for the second condition and 0.5 for the third. As for rotational jitter, we refer to WGN coefficients for simplicity as **Positional jitter** 3_{PJ} = **None**, **±0.25 cm, and ±0.5 cm**.

For positional and rotational jitter, we used the Marsaglia Polar Method (Marsaglia and Bray 1964) to generate WGN. We did not discard or cut off random values generated by this method.

For target distance, i.e., the diameter of the "circle of targets," we used two **Angular Target Distances** (2_{TD} = **5 and 20**°), and for each depth distance, we converted the angular measures to Euclidean target sizes and distances for Unity. We also used three different **Angular Target Sizes** (3_{TS} = **0.5, 1, and 1.5**°).

At the end of the experiment, we asked participants to fill a short questionnaire and asked about their insights for the experiment. We also asked participants about the perceived impact of jitter on their performance using 7-point Likert scale questions. Finally, we queried participants about their physical and mental fatigue.

4.4 Experimental Design

Since previous work on jitter did not report an interaction between positional and rotational jitter (Batmaz et al. 2020b), we decided to investigate the effects of these two forms of jitter independently. To mitigate the adverse effects of jitter, we decided to reduce the number of trials relative to previous work, taking also the potential impact of fatigue caused by jitter into account (Batmaz et al. 2020b). Thus, we prepared two separate studies for positional and rotational jitter.

For rotational jitter, all participants performed the experiment in three experimental conditions: two grip styles (2_{GS} = power grip and precision grip) at two different depth distances (2_{DD} = 1 and 2 m) with three different rotational jitter (3_{RJ} = none, ±0.25°, and ±0.5°) conditions. For positional jitter, the same participants performed the experiment in three experimental conditions: two grip styles (2_{GS} = power grip and precision grip) at two different depth distances (2_{DD} = 1 and 2 m) with three different positional jitter (3_{PJ} = none, ±0.25 cm and ±0.5 cm) conditions.

We counterbalanced rotational and positional jitter conditions across subjects to avoid learning effects. We collected data for movement time (s), error rate (%), and effective throughput (bits/s) as dependent variables to analyze user performance.

We also varied the index of difficulty (ID), by using three angular target sizes (3_{TS} = 0.5, 1, and 1.5°) and two angular target distances (3_{TD} = 5 and 20°), which yields 6 unique ID between 2.12 and 5.36. Each subject performed ($2_{\mathrm{GS}} \times 2_{\mathrm{DD}} \times 3_{\mathrm{RJ}}$ x $3_{\mathrm{TS}} \times 2_{\mathrm{TD}} \times$ 11 repetitions) + ($2_{\mathrm{GS}} \times 2_{\mathrm{DD}} \times 3_{\mathrm{PJ}}$ x $3_{\mathrm{TS}} \times 2_{\mathrm{TD}} \times$ 11 repetitions) = 1584 trials.

5 Data Analysis

To assess the user performance, we used Repeated Measures (RM) ANOVA in SPSS 24.0. We used Skewness (S) and Kurtosis (K) to analyze the normality. As in previous work, (Batmaz et al. 2020b; Mallery and George 2003; Mayer et al. 2018), we considered the data to be normally distributed if S and K were between ±1.

For *brevity*, we only report and focus on significant results. We used the Bonferroni method for post-hoc analyses. Results are illustrated as means and standard error of means in figures. We applied Huynh-Feldt correction when $\epsilon < 0.75$ and used the Bonferroni method for post-hoc analyses.

Since participants experienced two different types of jitter, we first share the rotational jitter results, then the positional jitter results.

Table 2 Main factor results for rotational jitter

	Rotational jitter	Grip style	Depth distance	ID
Time	$F(1.08, 7.5) = 0.78$ n.s., $\eta^2 = 0.100$	$F(1, 7) = 3.88$ n.s., $\eta^2 = 0.357$	$F(1, 7) = 67.39$ $p < 0.001, \eta^2 = 0.906$	$F(1.74, 12.28) = 101.837$ $p < 0.001, \eta^2 = 0.936$
Error rate	$F(2, 14) = 241.524$ $p < 0.001, \eta^2 = 0.972$	$F(1, 7) = 0.99$ n.s., $\eta^2 = 0.115$	$F(1, 7) = 18.06$ $p < 0.01, \eta^2 = 0.721$	$F(3.74, 26.12) = 259.85$ $p < 0.001, \eta^2 = 0.974$
Throughput	$F(2, 14) = 141$ $p < 0.001, \eta^2 = 0.953$	$F(1, 7) = 1.37$ n.s., $\eta^2 = 0.164$	$F(1, 7) = 1.25$ n.s., $\eta^2 = 0.152$	$F(3.96, 27.77) = 1827.5$ $p < 0.001, \eta^2 = 0.996$

5.1 Results for Rotational Jitter

In this part of the results section, we first present the main factor results in Table 2 for rotational jitter, followed by the corresponding interaction results from the two four-way RM ANOVAs. For rotational jitter data, time ($S = 0.94$, $K = 0.52$), error rate ($S = 0.056$, $K = -0.68$) and throughput ($S = 0.04$ $\text{K} = -0.99$) were normally distributed.

5.1.1 Rotational Jitter Main Factor Results

Time: For rotational jitter and ID, Mauchly's sphericity test was violated for time ($\chi^2(14) = 69.29$, $\text{p} < 0.001$ and $\chi^2(2) = 13.39$, $p < 0.001$, respectively). According to the results in Table 2, subjects were slower with targets at farther distances (Fig. 4a).

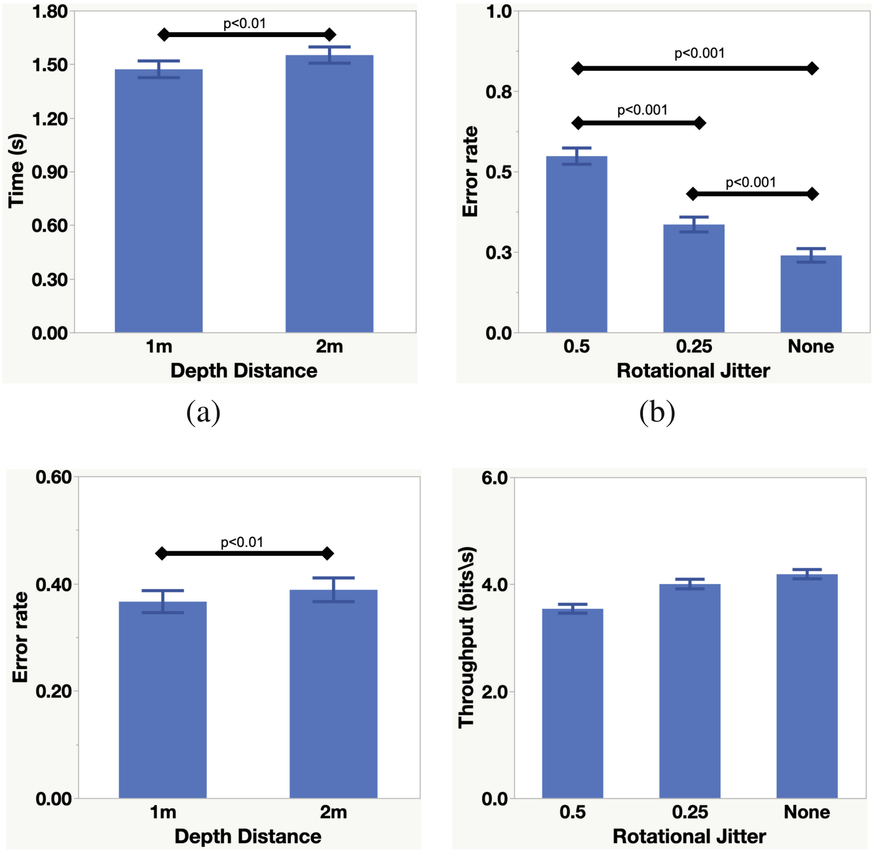
Error rate: For the ID, Mauchly's sphericity test was violated for error rate ($\chi^2(14) = 61.21$, $\text{p} < 0.001$). According to the results in Table 2, subjects made more errors when the rotational jitter increased (Fig. 4b) and when the targets were closer (Fig. 4c).

Throughput: For the ID, Mauchly's sphericity test was violated for throughput ($\chi^2(14) = 50.72$, $\text{p} < 0.001$). The results in Table 2 illustrate that the effective throughput performance of the participants decreased with increased rotational jitter (Fig. 4d).

5.1.2 Rotational Jitter Interaction Results

We found significant interactions between grip style and rotational jitter for error rate ($F(2, 14) = 3.778$, $p < 0.05$, $\eta^2 = 0.49$) and throughput ($F(2, 14) = 14.45$, $p < 0.05$, $\eta^2 = 0.674$). According to these results, participants made more errors (Fig. 5a) and their throughput performance decreased (Fig. 5b) with the precision grip while interacting with distant targets.

We also found a significant interaction between the depth distance and grip style ($F(1, 7) = 6.34$, $p < 0.05$, $\eta^2 = 0.475$). Results showed that user's throughput decreases with the precision grip and ±0.5° rotational jitter (Fig. 5c).



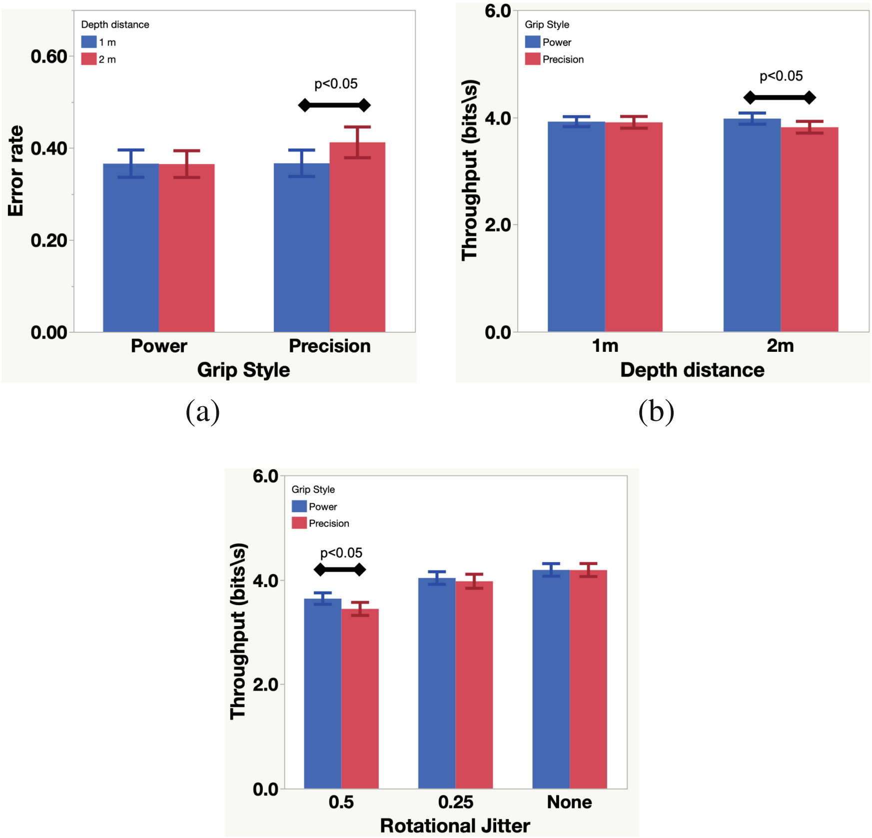
(a) (b)

(c) (d)

Fig. 4 Analysis of rotational jitter data. Time results for **a** depth distance, error rate results for **b** rotational jitter and **c** depth distance, and effective throughput results for **d** rotational jitter

5.2 *Positional Jitter Results*

In this subsection, we first present the main factor results in Table 3 for positional jitter, followed by the corresponding interaction results from the two four-way RM ANOVAs. For positional jitter data, error rate ($S = 0.057$, $K = -0.75$) and throughput ($S = 0.5$, $K = -0.9$) were normally distributed. The dependent variable time was log-normal ($S = 0.07$, $K = -0.31$).



(a) (b)

(c)

Fig. 5 Analysis of rotational jitter interaction. Error rate results for **a** grip style and depth distance and throughput results for **b** grip style and depth distance, and **c** rotational jitter and grip style

5.2.1 Positional Jitter Main Factor Results

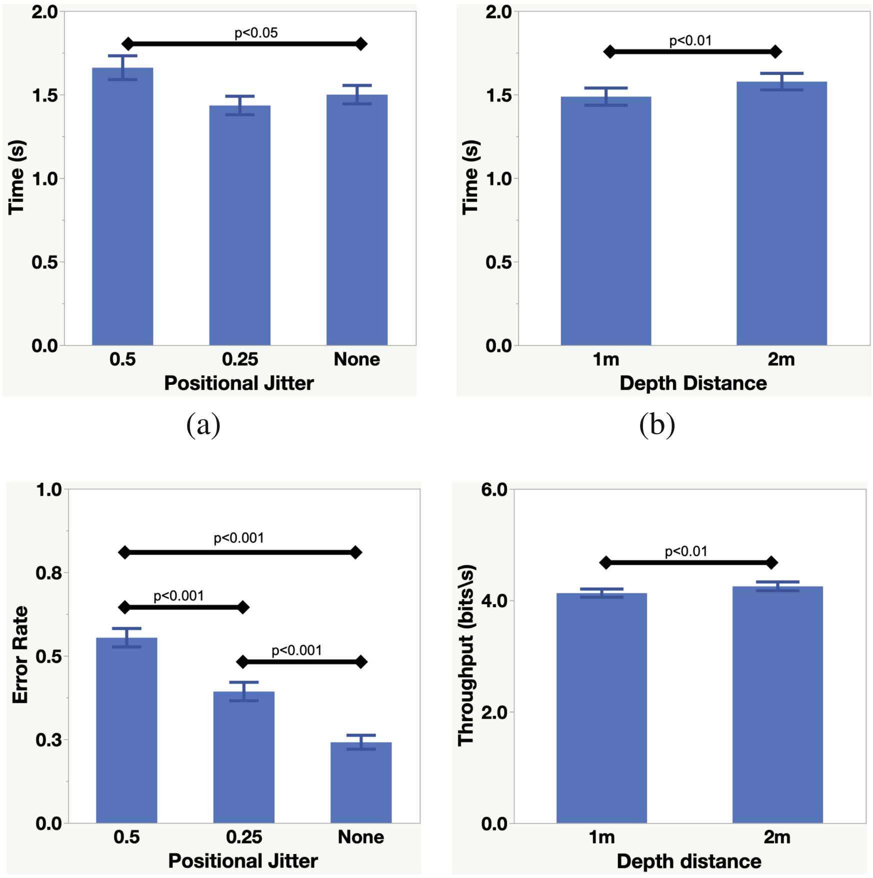
Time: For the ID, Mauchly's sphericity test was violated for time ($\chi^2(14) = 34.51$, $p < 0.01$). According to the results in Table 3, subjects were slower with a higher level of positional jitter (Fig. 6a) and with targets at farther distances (Fig. 6b).

Error rate: For the ID, Mauchly's sphericity test was violated for error rate ($\chi^2(14) = 40.06$, $p < 0.001$). According to the results in Table 3, subjects made more errors when the positional jitter increased (Fig. 6c).

Throughput: Results in Table 3 showed that the effective throughput performance of the participants decreased with an increased depth distance (Fig. 6d).

Table 3 Main factor results for positional jitter

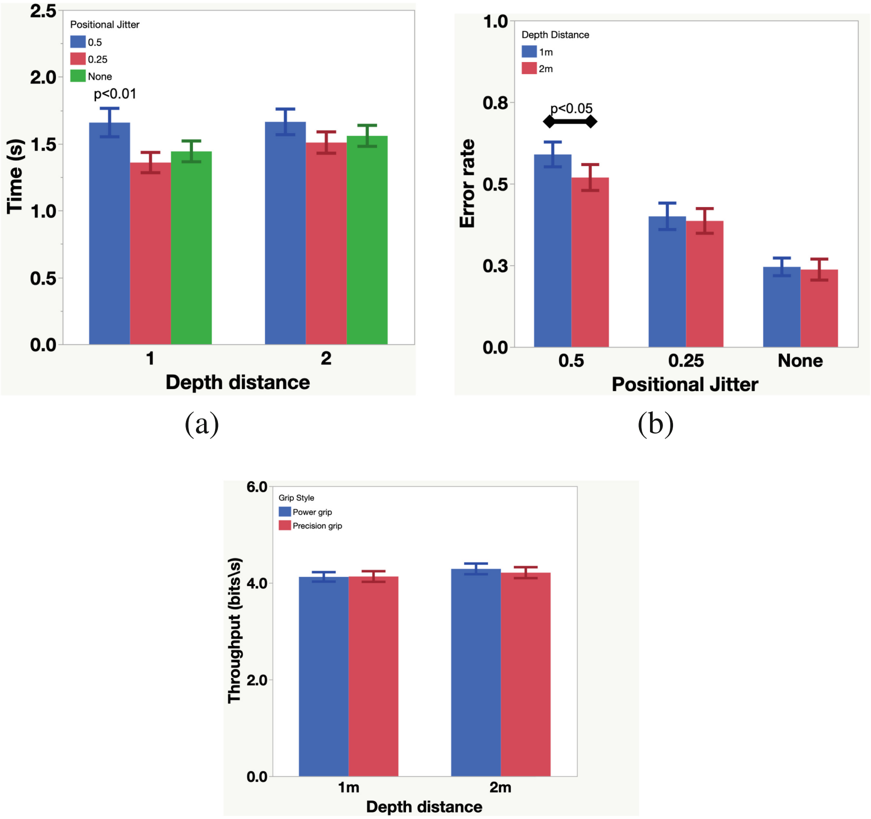
	Positional jitter	Grip style	Depth distance	ID
Time	$F(2, 14) = 4.602$ $p < 0.5, \eta^2 = 0.367$	$F(1, 7) = 0.416$ n.s., $\eta^2 = 0.56$	$F(1, 7) = 55.426$ $p < 0.001, \eta^2 = 0.888$	$F(2.16, 15.12) = 215.68$ $p < 0.001, \eta^2 = 0.969$
Error rate	$F(2, 14) = 124.537$ $p < 0.001, \eta^2 = 0.975$	$F(1, 7) = 0.8$ n.s., $\eta^2 = 0.401$	$F(1, 7) = 3.38$ n.s., $\eta^2 = 0.326$	$F(1.77, 12.43) = 275.07$ $p < 0.001, \eta^2 = 0.975$
Throughput	$F(2, 14) = 0.176$ n.s., $\eta^2 = 0.026$	$F(1, 7) = 0.306$ n.s., $\eta^2 = 0.042$	$F(1, 7) = 45.45$ $p < 0.001, \eta^2 = 0.867$	$F(5, 35) = 814.826$ $p < 0.001, \eta^2 = 0.991$



(a) (b)

(c) (d)

Fig. 6 Analysis of positional jitter data. Time results for **a** jitter range and **b** depth distance, error rate results for **c** positional jitter, and effective throughput results for **d** depth distance



(a) (b)

(c)

Fig. 7 Analysis of positional jitter interaction. Time results for **a** positional jitter and depth distance, error rate results for **b** positional jitter and depth distance, and throughput results for **c** grip style and grip depth distance interaction

5.2.2 Positional Jitter Interaction Results

For positional jitter, we found significant interactions between depth distance and positional jitter for time ($F(2, 14) = 7.27$, $p < 0.05$, $\eta^2 = 0.510$) and error rate ($F(2, 14) = 11.544$, $p < 0.01$, $\eta^2 = 0.623$). According to the results in Fig. 7a, participants were slower with ±0.5° jitter at 1 m depth distance compared to the ±0.25° and no jitter conditions. Similarly, participants made more errors at 1 m compared to the 2 m condition when there was ±0.5° positional jitter (Fig. 7b). We also found a marginally significant interaction between depth distance and grip style for throughput ($F(1, 7) = 5.31$, $p = 0.55$, $\eta^2 = 0.431$), where participants' throughput was slightly higher with the power grip at 2 m (Fig. 7c).

Table 4 Fitts' law analysis results for positional and rotational jitter

		Movement time					
		Rotational jitter			Positional jitter		
		a	*b* (*ID)	R^2	*a*	*b* (*ID)	R^2
Jitter range	None	0.1740327	0.3705272	0.93	0.1615238	0.3757853	0.94
	0.25	0.1692218	0.3666509	0.96	0.1112581	0.3655716	0.96
	0.5	0.2729441	0.3556668	0.97	0.4294787	0.3406824	0.97
Grip style	Precision grip	0.1894118	0.3500515	0.98	0.2803358	0.3496736	0.96
	Power grip	0.2135234	0.3813734	0.95	0.193603	0.3707219	0.97
Depth distance	1m	0.0842535	0.3851425	0.94	0.2536366	0.3420209	0.97
	2m	0.3274077	0.3438672	0.97	0.2162922	0.3794306	0.96

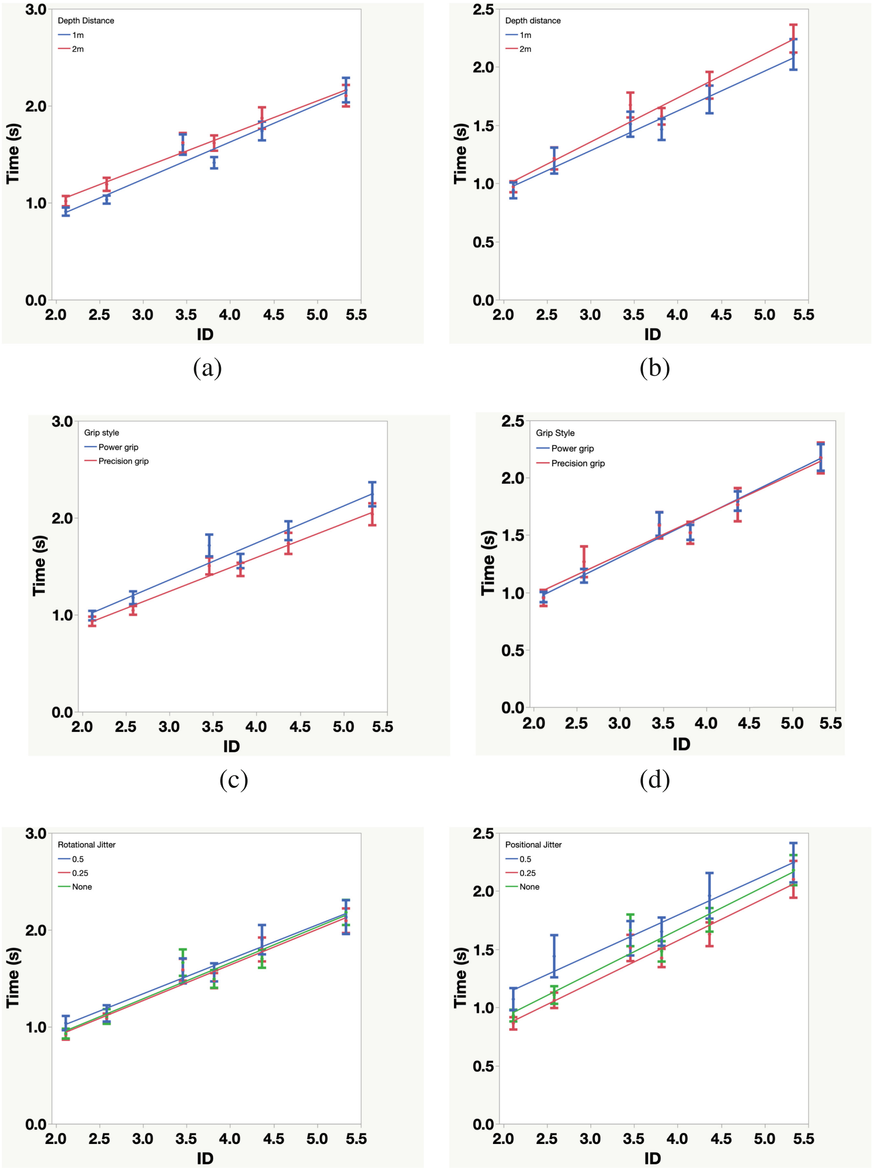
5.3 Fitts' Law Analysis

The results for a Fitts' law analysis for both positional and rotational jitter are given in Table 4 and Fig. 8 for jitter range, grip style, and depth distance. The regression analyses results show that all the determination coefficients (R^2) were above 0.9.

5.4 Subjective Results

According to the subjective results, only one out of eight participants preferred the VRInk pen. Most participants commented that "*(The HTC Vive Pro Controller was) more comfortable and [required] smaller movements,*" "*My hand was shaking with the Pen device [VRInk]. The [HTC Vive Pro] controller was a lot [more] comfortable and therefore easier to point,*" "*[HTC Vive Pro Controller was] less tiring, flexible,*" "*[HTC Vive Pro Controller] was easier and more familiar to control compared to the ink pen,*" and "*It was easier for me to grab the [HTC] vive controller since it's heavier and easier to control compared to the pen. The pen was light and controlling it in the air to select the objects made my hand to shake more.*" The participant who preferred the VRInk with the precision grip commented "*It's more precise and easy to work with.*"

According to the 7-point Likert scale questions, all the participants thought that jitter reduced their performance (1-Very likely, 7-Very Unlikely, Mean(M) = 1, Standard Deviation (SD) = 0). Participants also thought that while they could see themselves "somewhat likely" using an HTC Vive Pro with jitter (1-Very likely, 7-Very Unlikely, $M = 3$, SD = 0.53), it is unlikely that they will use a VRInk pen with jitter (1-Very likely, 7-Very Unlikely, $M = 4.625$, SD = 1.18).



(a) (b)

(c) (d)

(e) (f)

Fig. 8 Fitts' law results. Top row: depth distance Fitt's law results for **a** rotational jitter and : positional jitter. Middle row: grip style Fitt's law results for (**c** rotational jitter and **d** positional jitter. Bottom row: jitter range Fitt's law results for **e** rotational jitter and **f** positional jitter)

After the user study, the participants did not report any significant physical fatigue (1-I feel extremely rested, 7-I feel extremely fatigue $M = 4.625$, SD = 0.51) nor mental fatigue (1-I feel extremely rested, 7-I feel extremely fatigued, $M = 4.25$, SD = 1.16).

6 Discussion

In this study, we examined how positional and rotational jitter impact user performance with targets at in different depth distances and with different controller grip styles.

Our results support the findings of previous work on both positional and rotational jitter: user performance significantly decreases when there is jitter in the system (Batmaz et al. 2020b; Batmaz and Stuerzlinger 2019a, b). Extending previous findings, the results in this work revealed that user throughput performance decreases and error rate increases with a higher level of rotational jitter. Similarly, the participants' execution time and error rate increased with ±0.5° of jitter. Overall, when a new VR input device is designed for interaction with virtual environment in Everyday VR/AR applications, the designed system should exhibit less than ±0.5° jitter, to increase the user performance in terms of time, error rate, and throughput.

Previous work had showed that user performance can decrease with ±1° rotational jitter. Our current study indicates that participants' error rate already decreases with (only) ±0.25° added rotational and positional jitter. We believe that this result is an outcome of conducting a study with angular measures in VR. Since we converted Euclidean distances to angular measures and applied WGN jitter to these angular measurements, we were able to correlate the amount of jitter to the target sizes and distances. This also confirms our hypothesis *H1*, i.e., that angular size plays a critical role for user performance when jitter is present. Thus, we suggest practitioners and developers evaluate the performance of their selection hardware and software methods in terms of angular measures, (and not simply in Euclidean distances) for everyday VR/AR applications.

Since we used angular sizes, we also increased the Euclidean target sizes and distances at farther distances. This allowed us to present the same size target as seen by a perspective camera. In this case, one could expect a similar user performance for targets at different distances. However, previous work had hypothesized that VR headsets suffer from various stereo deficiencies, such as the vergence and accommodation conflict, which has detrimental effects on the user performance (Barrera Machuca and Stuerzlinger 2018, 2019; Batmaz et al. 2019, 2022). Based on this previous work, we also hypothesized that user performance at increasing depth distances might decrease. And our result indeed confirmed that the participants' error rate and throughput performance decrease with farther targets, which also supports our hypothesis *H2*, i.e., that user performance depends on the depth distance in the virtual environment. Even though we increased the size of the targets for farther targets, the user performance was negatively affected, likely due to the stereo deficiencies of the VR headsets. This negative impact was also observed in the interaction between depth distance and positional jitter: the participants were faster with lower jitter levels at 1 m. However, they got slower with lower jitter levels at targets at a farther distance. We speculate that stereo deficiencies increased the execution time of the participants with the targets at 2 m, even with smaller jitter ranges.

In this study, we examined the effects of two different input devices with different grip styles. The first one was the precision grip, i.e., the grip that a VRInk is designed to be held in. The second one was the power grip, which is how a HTC Vive Pro controller is typically held. Both input systems were commercially available when this manuscript was written. Further, they were used in everyday VR/AR applications. Based on the previous literature, we hypothesized that we observe better user performance in terms of time, error rate and throughput, for the precision grip with higher levels of jitter. Since previous work had indicated that the precision grip increases user performance, we also expected to see a positive impact of the precision grip in the presence of jitter. However, the results of our study showed that user throughput decreases with the precision grip with ±0.5° rotational jitter. Therefore, this result does not support our hypothesis *H3*, i.e., that the precision grip improves user performance when jitter is present in the system.

Since the previous work highlighted technical issues with the VRInk (Batmaz et al. 2020a), we used a current version of the device, and confirmed that there are no obvious technical tracking issues with the hardware. However, the subjective results of our study were similar to previous work that compared the precision and power grip (Batmaz et al. 2020a). Our participants commented that the Vive Pro controller was heavier and easier to control compared to the VRInk and that the interaction with the VRInk pen was not as precise. Thus, even though the device we used is technically capable enough for a pointing experiment, we believe that the current hardware design had an negative impact on the participants' user performance and experience.

As in previous work, in this experiment, we used an HTC Vive Pro HMD, one of its controllers and a Logitech VRInk pen with three V2 Lighthouses. We deliberately chose this VR setup because it has a relatively low level of noise. Previous work had used only two V2 Lighthouses (Batmaz et al. 2020b; Batmaz and Stuerzlinger 2019b), which might explain why we could observe differences at lower jitter levels: it seems that our inclusion of a third Lighthouse for tracking, pointed directly at where the controllers were held in space, improved tracking performance. The HTC Vive Pro system includes one of the best tracking systems currently available on the market. Even though the system is precise and accurate enough to collect data for VR pointing experiments (Batmaz and Stuerzlinger 2020; Pham and Stuerzlinger 2019), the data still contains some level of jitter, caused by a combination of measurement errors, human errors, signal processing artifacts, and other noise sources.

Another potential limitation of this work is the relatively low number of participants. In this study, we had eight participants. Still, according to statistical effect size calculations, the minimum effect size we observed in this work is $\eta^2 = 0.36$, i.e., a large effect, commonly defined through a criterion of $\eta^2 > 0.14$. These large effect sizes are evidence that our research findings are robust and have practical significance. Furthermore, the results we found in this work confirm the findings of previous work on jitter in virtual environments.

In this work, we deliberately did not conduct a user study with a full-factorial design and did not compare rotational and positional jitter. First, previous work identified that participants report a higher level of fatigue when they perform jitter experiments (Batmaz et al. 2020b). Hence, we thought that a more complex experiment might negatively impact the performance of the participants, which can hinder and affect the outcomes. Second, previous work did not identify a significant interaction between positional and rotational jitter (Batmaz et al. 2020b). Thus, we decided to focus on both jitter types separately.

The questionnaire we used in this work is in line with previous work on VR jitter. This allows us to compare the user experience across different studies. As a general finding, we can conclude that an increased level of jitter decreases the user performance and participants do not prefer to interact with targets in virtual environment where the jitter levels are high.

Another result of this work concerns the angular ID. In this study, we used Kopper et al.'s angular ID formula (Kopper et al. 2010), and set $k = 1$ for simplicity. With this, the minimum R^2 value we observed in this work was 0.93, which is a very respectable fit. Our work did not aim to compare different angular ID formulations, but based on the R^2 results found in this paper, Kopper et al.'s angular ID formula can be used to analyze angular 3D pointing studies for VR systems.

The importance of this work for everyday VR/AR research is evident when one considers that both positional and rotational jitter is present in current 3D tracking systems. Thus, while the researcher and developers design a new input device, they have to consider the impact of jitter on user performance and their experience. Furthermore, jitter is a part of electronic tracking systems of VR/AR headsets that are used every day and we know that 3D pointing performance does not differ between VR and AR headsets (Batmaz et al. 2019)—which means that the results reported here naturally apply to AR systems. Still, it is essential to investigate the effects of jitter further to improve the quality of user interaction during everyday usage of VR/AR systems.

7 Conclusion

In this work, we studied the effects of positional and rotational jitter for targets at different depth distances while participants used two different input systems with two different grip styles. Our results indicate that user performance significantly declines already with ±0.25° added jitter in terms of error rate and throughput. Based on our outcomes, we also suggest practitioners evaluate their VR systems and report user performance based on angular measures, as this methodology can have an impact on research on everyday VR/AR applications. We also saw some indications that stereo display deficiencies can aggravates the negative impacts of jitter for farther targets. Moreover, our results indicate that the power grip can better compensate the detrimental effects of jitter compared to the precision grip. We believe that our outcomes are useful for increasing the user performance and improving the user experience for everyday VR and AR applications and also to inform the development of future, improved 3D tracking systems.

Acknowledgements The raw data of the this study can be found in https://osf.io/kyz7f/.

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