No Jitter Please: Effects of Rotational and Positional Jitter on 3D Mid-Air Interaction

Anil Ufuk Batmaz, Mohammad Rajabi Seraji, Johanna Kneifel, and Wolfgang Stuerzlinger

Simon Fraser University, Vancouver BC, Canada,
abatmaz@sfu.ca, mrajabis@sfu.ca, jkneifel@sfu.ca, w.s@sfu.ca,
WWW home page: https://vvise.iat.sfu.ca

Abstract. Virtual Reality (VR) 3D tracking systems are susceptible to minor fluctuations in signal (jitter). In this study, we explored how different levels of jitter affect user performance for 3D pointing. We designed a Fitts' Law experiment investigating target positional jitter and cursor rotational jitter at 3 different depth distances. Performance was negatively affected when up to $\pm$ 0.5° rotational jitter was applied to the controller and up to $\pm$ 0.375 cm positional jitter was applied to the target. At 2.25 m distance, user performance did not improve with decreasing positional jitter or rotational jitter compared to the no jitter condition. Our results can inform the design of 3D user interfaces, controllers, and interaction techniques in VR. Specifically, we suggest a focus on counteracting controller rotational jitter as this would globally increase performance for ray-based selection tasks.

Keywords: 3D pointing, Jitter, Input devices, Tracking devices, Fitts' law

1 Introduction

Recent Virtual Reality (VR) applications designed for specific tasks, such as surgical training systems, typically require precise and accurate interaction between a user and the virtual environment (VE), including selection, positioning, and pointing tasks in 3D. However, such interaction might be negatively affected by jitter, which is defined as unintentional fluctuations in movement which overlap with the original information in the signal intended through the action of the user.

When a signal is acquired by the sensors of a VR tracking device, such as an Inertial Measurement Unit, the data is affected by several noise sources, such as thermal, flicker, and coupled noise. When this data is transferred to the VR system, additional noise could be added in the transmission, e.g., due to slight delays. Similarly, the data received from optical sensors and cameras is also affected by the noise introduced by image processing.

Moreover, when a user holds a controller, the data received by the VR system is affected by natural user behaviours, such as hand tremors, breathing, or body sway. For instance, hand tremor frequencies vary between 4 Hz and 12 Hz [1, 15, 19, 33] in healthy humans, and this tremor can have detrimental effects on the tracking data. Specifically, these detrimental effects become more visible with increasing (depth) distances from the user. A 0.5° rotation at the controller can alter the position of a cursor by 0.65 cm at 75 cm, by 1.13 cm at 1.5 m, and by 1.96 cm at 2.25 m. Such small changes may also occur when user a user selects a target through physically interacting with the controller, such as pulling a trigger. This kind of error is called the “Heisenberg effect” [9].

After the position and rotation data of the trackers are received by the VR system, they may be further processed to mitigate noise-related effects. Various filtering algorithms, such as the Extended Kalman Filter, e.g., [36], or the One-Euro filter [11], are frequently used to reduce signal noise in VR. However, such filters can add additional noise because of the phase shift introduced by the filtering. Moreover, even after the filtering, the positional and rotational tracking data still exhibits fluctuations. Examples of rotational jitter and positional jitter are shown in Figure 1 (a) and Figure 1 (b), respectively. In these figures, the position and the rotation of the cursor and the target are expected to be at 0 ° and 0 cm, respectively. However, due to jitter, there is a notable deviation from the reference. Additionally, the figures also show substantial variation in the magnitude of the jitter. If we compare this with data for a 2D mouse on a desktop, there would be no visible jitter at this scale, due to a combination of substantially better sensors, surface friction, fewer degrees of freedom, and support for the hand holding the mouse. Previous work [31] has compared different input devices, including a VR controller and 2D mouse, but this topic is outside the scope of this project.

In real-life VR systems, positional and rotational jitter can be found in all tracked objects, including the headset, the controllers, and other trackers[1], which all record the real-world position and rotation of the head, hands, or anything that the trackers are attached to, so that they can be used within the virtual environment.

Both positional and rotational jitter have significant effects on VR system design. Especially for the design of novel VR input devices, jitter affects both user performance in the VE and the usability of the system. Recent work by Batmaz et al. [5] showed that the presence of jitter significantly decreases user performance for a novel pen-like input device. In their research, they also showed that pen-like controllers are affected by rotational jitter and hypothesized that user performance decreased due to that. The subjective results and the quantitative jitter data analysis for the input device supported their hypothesis. Thus, even though current hardware and software designs are improving in terms of decreasing jitter, research on the relationship between jitter and user performance enables our results to be used in system design and to let system system designers make more educated decisions on the various trade-offs they are faced with.

Previous studies showed that user performance significantly decreases above $\pm 0.5°$ rotational jitter [6]. Moreover, Batmaz and Stuerzlinger showed that using a second VR controller to perform the selection action, i.e., pressing a trigger button, does not mitigate the negative effects of the rotational jitter [7]. Here, we define positional jitter as the jitter that affects the 3D position of the target, and rotational jitter as the jitter that affects the 3D rotation of the VR input device. We chose to vary the target position, as jitter in the controller position has (relatively speaking) less effect on pointing. On the other hand, jitter on the controller rotation affects pointing clearly more than jitter on target rotation [22]. With current VR controllers, the level of residual rotational jitter can easily be observed when pointing at distant objects, which has detrimental effects for distal pointing. Positional jitter is mostly observed in the position data of the trackers

[1] A representative example of a current state-of-the-art tracker is the HTC VIVE system, https://www.vive.com/us/vive-tracker

themselves, which is observable when the tracked device is static and/or if the user is trying to match real world object positions with the virtual environment.

With this work, we extend previous work on the effects of rotational jitter for targets at a single distance [6, 7], by studying the effect of jitter on targets at different depth distances. Further, we also explore the effects of positional jitter and compare the effects of positional and rotational jitter.

In this study. we investigate the following research questions: At which jitter level does user performance start to significantly decrease at different depth distances? And how much do different levels of jitter affect cursor positioning in VEs, in terms of time and throughput?

Research on the accuracy and precision of current state-of-the art VR devices, e.g., [29], helps to identify new ways to improve the quality of the VR experience and to apply such innovations within new systems. We believe that the analysis of the effects of jitter on user performance presented here will inform the design of new input devices by manufacturers and decrease the adverse effects of tracking limitations on pointing precision and accuracy.

2 Previous work

Here we review relevant previous work, including Fitts' law, 3D selection methods for VR, and previous work on the effects of jitter.

2.1 Fitts' Law

Fitts' law [16] models human movement times for pointing. Equation 1 shows the Shannon formulation [23].

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

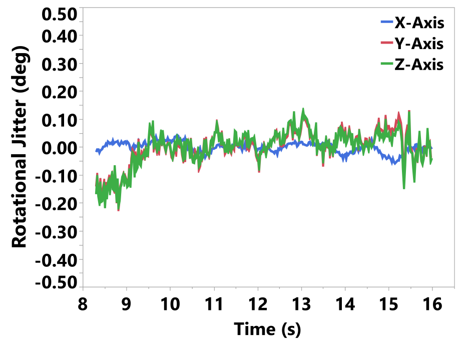
In Equation 1, a and b are empirical constants, typically identified by linear regression. A is the amplitude of the movement, which is the distance between two targets, and W the target width. The logarithmic term in equation 1 represents the task difficulty and is called the *index of difficulty, ID*.

We also use throughput (based on effective measures), as defined in the ISO 9241-411:2012 [20]:

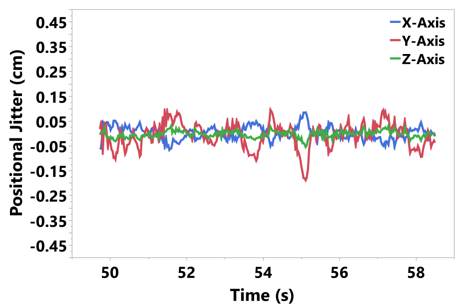
$$Throughput = \left(\frac{ID_e}{Movement\,Time}\right) \tag{2}$$

In Equation 2, 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 accuracy in the task [20]:

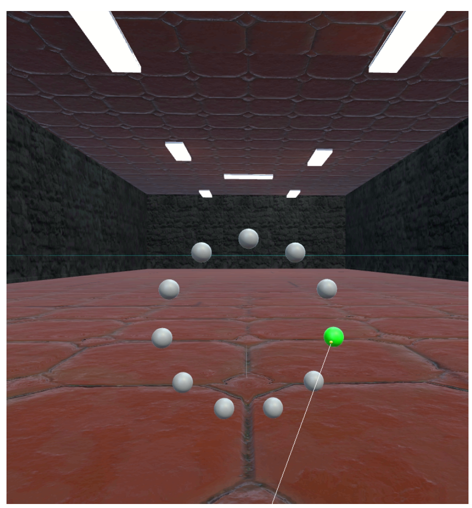
$$ID_e = \log_2\left(\frac{A_e}{W_e} + 1\right) \tag{3}$$



(a)



(b)



(c)

Fig. 1. An example of (a) cursor jitter and (b) target jitter. For measuring cursor jitter, a user pointed the controller at a (distant) target in a VE. For target jitter, the HTC VIVE controller was placed on a table. (c) Experimental virtual environment.

In Equation 3, 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 $W_e = 4.133 \times SD_x$, where SD_x is the standard deviation of selection coordinates along the task axis. SD_x represents the precision of the task performance [24, 25].

2.2 3D Pointing in Virtual Environments

Pointing is a fundamental task for users interacting with an environment [14]. Various studies in the literature have explored pointing tasks, e.g., in real life or on 2D desktops. However, 3D pointing in VEs is relatively more complex and less explored compared to other pointing tasks. A recent survey reviewed 3D pointing and investigated various devices and approaches [2]. Different mid-air selection methods have also been evaluated, e.g., [10, 25].

2.3 Ray Casting

While selection with a virtual hand metaphor is easy in VR, it is challenging to select targets that are further away with this technique [22]. For the selection of a distant object, ray casting is the preferred interaction technique in many VR systems [14]. Still, as it requires accurate pointing, ray casting does not perform well for small and/or distant targets [32], similar to how a laser pointer behaves in the real world. Usually, a virtual ray is shown between the pointing device and the cursor position on the respective intersected surface of the virtual environment to facilitate keeping track of the pointing direction and to increase the visibility of the cursor [14].

2.4 Selection Method

To select an object in VR, the user has to interact with the system to activate the corresponding selection action. If that action is communicated by physical interaction, such as pulling a trigger or pushing a button, this can affect the cursor position or ray rotation, and an error called the "Heisenberg effect" of spatial interaction [9] can occur. Especially for distant target selection, ray casting is prone to this effect, since the smallest noise at the origin of the ray is magnified at larger distances [6]. To reduce the Heisenberg effect, previous studies, e.g., [34], [7], proposed to use asymmetric bi-manual interaction, where the user points with the dominant hand while they press the button to select with the non-dominant hand.

2.5 3D Tracking Noise in VR

While jitter and how it affects a signal has been studied in many domains, to our knowledge, how jitter affects user performance during 3D pointing tasks in VR has not been studied in detail.

Previous work on rotational jitter showed that user performance significantly decreases with $\pm 0.5°$ of jitter [6]. In this study, the authors used a Fitts' task with a constant ray length, but previous studies showed that user performance with an infinite and fixed ray length is not equal [8]. Batmaz and Stuerzlinger also explored White Gaussian Noise rotational jitter and tried to reduce the negative effects of jitter by using a second controller [7] to avoid the "Heisenberg" effect upon the button press [9]. However, interestingly, using a second controller did not decrease the effects of rotational jitter on pointing.

Previous work on positional jitter in 2D positioning tasks with a mouse showed that 0.3 mm of positional jitter did not affect user performance [35]. Yet, larger levels of positional jitter significantly reduced user performance for smaller targets [30].

3 Motivation & Hypotheses

Previous work showed that 0.5° rotational jitter significantly reduces user performance, even when the distance between target and user is as small as 50 cm [6, 7]. These studies did not investigate target jitter, i.e., signal fluctuations on a tracker attached to an object in the real world and represented as a virtual object in the VE. Since the user performance in VR is significantly affected by stereo display deficiencies, e.g., through the vergence and accommodation conflict [3, 4], how such jitter affects user performance at different depth distances still needs to be investigated to guide both practitioners and developers. Based on these results, we formulated the following hypotheses:

H-1 When the distance between user and target increases, user performance significantly decreases above 0.5° rotational jitter for larger depth distances.

H-2 Similar to rotational jitter, user performance significantly decreases with increased target jitter in VR. Moreover, this detrimental effect is larger when the depth distance increases.

4 User Study

To investigate the above-mentioned hypotheses we designed a user study as follows.

4.1 Participants

Eighteen participants (ten female, eight male) with ages ranging from 21 to 33 (mean 26 ± 4.16) took part in the experiment. All participants were right-handed. While most reported that their dominant eye is the right one, one of them was left-eye dominant. Sixteen of them indicated previous experience with VR environments. However, the majority of users (thirteen of them) reported using VR devices and environments less than four times in a month and only three of them reported six times or more. Fourteen participants played computer games and/or used 3D CAD systems 0-5 hours/week, and four of them 5-10 hours/week.

4.2 Apparatus

We used a PC with an Intel(R) Core(TM) i7-4790 CPU @ 3.60GHz Processor, 16GB of DDR4 RAM, and a nVIDIA GeForce(R) GTX 1080 Ti graphics card. We used an HTC Vive Pro with two V2 Light houses, with two HTC Vive Pro controllers as input devices.

4.3 Procedure

After completing an informed consent form, participants first filled out a demographic questionnaire. The researchers then briefed the participants by explaining the tasks. To assess pointing performance in 3D, we used a ISO 9241-411 task [20]. To get used to the VR system and environment, subjects were allowed to practice the task before beginning trials. For the study, participants were asked to select targets as quickly and precisely as possible. After completing the tasks, participants filled out a post-questionnaire about their perceived pointing speed and accuracy with each condition and their preferences. The study lasted about 40 minutes.

Before each task, participants were asked to fixate at a cross at eye-level, which ensured that the targets would appear at a comfortable, yet consistent position. The targets appeared as grey spheres arranged in a circular pattern at the eye level of the subjects (Figure 1 (c)). Participants were asked to point at the targets with the pointer ray emanating from the right controller and to click the trigger of the left controller to select a target, eliminating any potential "Heisenberg effect" [9]. When the cursor interacted with the target, the target color was changed to green. If the user selected the target while it was green, we record a successful "hit". If the user "missed" the target, the target turned red and an error sound was played to ensure adequate feedback.

We selected our Target Distance TD_3 and Target Size TS_2 conditions based on previous work [4, 7]. For the closest depth distance, we chose 0.75 m, since just beyond the edge of peri-personal space, i.e., the user could not reach the targets with a virtual hand. Other depth distances were chosen as linear increments of 0.75 m [17].

We artificially added $\pm$ 0.5° and $\pm$ 1° of rotational jitter to the starting point of the ray from the controller. Similarly, we added either 0.375 cm of artificial positional jitter to the target position, which is 1/4 of the first target size ($TS_1/4$), or 0.625 cm, which is 1/4 of the second target size ($TS_2/4$). All artificial jitter was generated with the Marsaglia Polar Method [27] as White Gaussian Noise and applied to all three dimensions. For rotational jitter, we artificially added noise to all 3 Euler axes of the VR controller rotation data received from the software. Analogously, we added artificial noise to the position of virtual targets along all 3 coordinate axes for positional jitter.

4.4 Experimental Design

The 18 participants selected 11 targets in 27 experimental conditions: three positional Target Jitter (TJ_3: 0, $\pm TS_1/4$ cm, and $\pm TS_2/4$ cm), three Rotational Jitter (RJ_3: $0, \pm 0.5°, and \pm 1°$), and three Depth Distances (DD_3: 0.75, 1.5 and 2.25 meter) in a TJ_3 x CJ_3 x DD_3 within-subject design. We counterbalanced Target and Cursor Jitter conditions across the experiment. The Depth Distance condition was counterbalanced across participants. As common in Fitts' law experiments, and to enable us to analyze internal validity, we also varied the task difficulty ID, by using three Target Distances (TD_3: 10, 20, and 30 cm) and two Target Sizes (TS_2: 1.5 and 2.5 cm), which means we evaluated 6 unique ID's between 1.94 and 4. Subjects' movement time (ms), error rate (%), and (effective) throughput (bit/s) were measured as dependent variables. In total, each subject performed TJ_3 x CJ_3 x DD_3 x ID_6 x 11 repetitions, corresponding to a total of 1782 trials.

5 Data analysis

The results were analyzed using three-way repeated measures (RM) ANOVA with α = 0.05 in SPSS 24. For the normality analysis, we used Skewness and Kurtosis and, based on results from previous work [18, 26], considered the data as normally distributed when Skewness and Kurtosis values were within ± 1.5. We used the Sidak method for post-hoc analyses. We only report significant results here. Results are illustrated with *** for p < 0.001, ** p < 0.01, and * for p < 0.05 in figures. One-way ANOVA RM results are shown in Table 1. We first present the results for the main factors and then mention interactions from the three-way RM ANOVA.

Table 1. One-Way RM ANOVA results

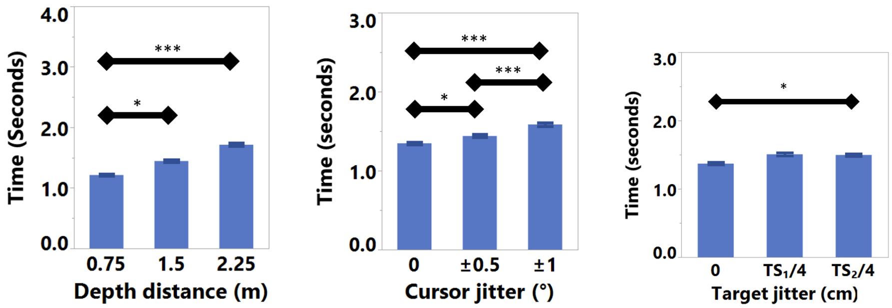
	Depth Distance	Cursor Jitter	Target Jitter	ID
Time	F(2,34)=17.085 p<0.001 η^2=0.51	F(1.55, 26.4)=20.31 $p < 0.001$ $\eta^2 = 0.544$	F(1.39, 23.58)=5.94 $p < 0.05$ $\eta^2 = 0.26$	F(2.61, 44.37)= 212.89 p<0.001 $\eta^2 = 0.93$
Error rate	F(2,34)= 75.36 p<0.001 η^2=0.81	F(2,34)= 537.9 p<0.001 η^2=0.97	F(2,34)= 159.2 p<0.001 η^2=0.91	F(5,85)= 213.87 p<0.001 η^2=0.82
Throughput	F(2,34)= 8.21 p<0.001 η^2=0.32	F(1.31,22.31)= 0.23 Not Significant	F(1.54,26.24)= 3.65 p<0.05 η^2=0.177	F(2.76,9.31)= 10.45 p<0.001 η^2=0.38

5.1 Time Results for One-Way RM ANOVA

The dependent variable "time" was normal after log-transform (Skewness=0.4, Kurtosis:0.29). The sphericity test was violated for ID, $\chi^2(14) = 45.108$, p<0.001, $\varepsilon = 0.522$, Target Jitter, $\chi^2(2) = 9.33$, p<0.01, $\varepsilon = 0.693$, and Cursor Jitter, $\chi^2(2) = 7.57$, p<0.01, $\varepsilon = 0.77$. We used Hunyn-Feldt correction for ID and Cursor Jitter, and Greenhouse-Geisser correction for Target Jitter, based on the ε values. According to the results in Figure 2, subjects were slower when the targets were further away (with $R^2 = 0.99$) and when the jitter level in targets or the cursor ray increased.

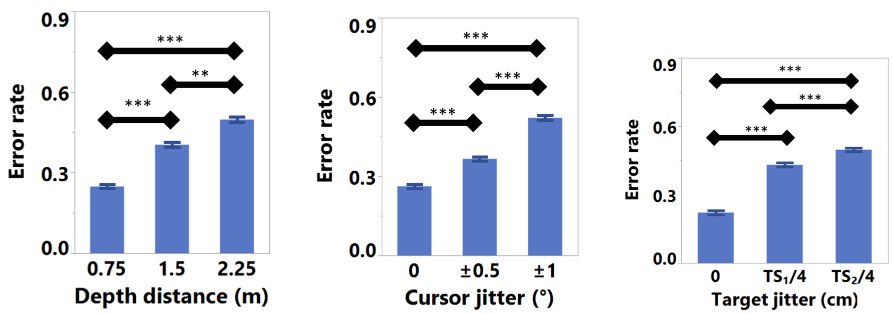
5.2 Error Rate Results for One-Way RM ANOVA

The error rate dependent variable was normal (Skewness = 0.27, Kurtosis = -0.97). None of the independent variables violated the Sphericity assumption. According to the error rate results in Figure 3, subjects' error rate significantly increased when the targets were further away. Moreover, their error rate also increased when the jitter in target positions or cursor rays increased.



(a) (b) (c)

Fig. 2. Means and standard error of means for time for: (a) Depth distance, (b) Cursor jitter, and (c) Target jitter.



(a) (b) (c)

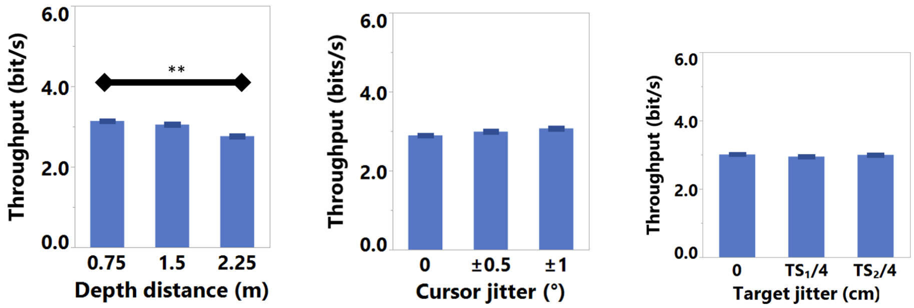
Fig. 3. Means and standard error of means for error rate for: (a) Depth distance, (b) Cursor jitter, and (c) Target jitter.

5.3 Throughput Results for One-Way RM ANOVA

The throughput dependent variable was normal after log-transform (Skewness = 0.01, Kurtosis = 1.5). The sphericity test was violated for ID, $\chi^2(14) = 43.05$, p<0.001, $\varepsilon = 0.522$, Target Jitter, $\chi^2(2) = 7.75$, p<0.05, $\varepsilon = 0.77$ and Cursor Jitter, $\chi^2(2) = 11.88$, p<0.01, $\varepsilon = 0.689$. We used Hunyn-Feldt for ID and Target Jitter, and Greenhouse-Geisser for Cursor Jitter conditions. According to the throughput results in Figure 4, user performance significantly decreased when targets appeared at the furthest distance. Further, increasing target jitter decreased the pointing throughput of users.

5.4 Interactions Results

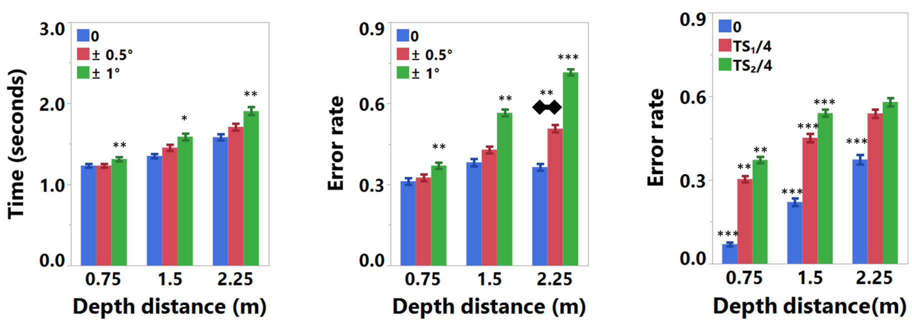
We found a significant interaction between depth distance and cursor jitter for time F(4,68)= 2.99, p<0.05, η^2=0.15 and error rate F(4,68)= 83.164, p<0.001, η^2=0.83. According to the results, subjects were getting slower (Figure 5(a)) and made more errors (Figure 5(b)) with $\pm 1°$ jitter for each depth distance. Moreover, the error rate



(a) (b) (c)

Fig. 4. Means and standard error of means for throughput for: (a) Depth distance, (b) Cursor jitter, and (c) Target jitter.

significantly increased for ±0.5° at 2.5 meters. Further, there was significant interaction between depth distance and target jitter for error rate F(4,68)= 5.29, p<0.001, η^2=0.26. These results also show that there is no significant difference between $TS_1/4$ and $TS_2/4$ at 2.25 m for error rate.



(a) (b) (c)

Fig. 5. Interaction results between depth distance and (a) cursor jitter for time, and (b) cursor jitter and (c) target jitter for error rate. Columns represent means and standard error of means.

5.5 Subjective Results

The participants completed a pre-test demographic questionnaire. They also reported their fatigue levels before the experiment using a 7-point Likert scale (1= I feel extremely rested, 7= I feel extremely tired). A mean self-reported score of 3.27 with standard deviation of 1.48 and median of 4, indicates that most of the users started the experiment in a close-to-normal state.

After the experiment, participants completed a questionnaire about their perceived speed and accuracy in the experiment and also about their current level of fatigue using the same 7-point Likert scale as in the pre-questionnaire. These self-reported scores (*M*=5.19, *SD*=1.05) with a median score of 5.5 indicated that the experiment increased their overall fatigue levels. Only two of the participants reported scores that were below 4 (indicating a state that is somewhat rested). One of the subjects stated that they felt extremely fatigued after the experiment.

A majority of the subjects (16 out of 18) users reported that both rotational and positional jitter had a negative effect on their speed and accuracy during the target selection tasks. However, it is interesting that the participants also indicated that the jitter on a target (positional jitter) did not have as strong of an effect as the controller jitter (rotational jitter); in fact, when asked about the main factor of influence on their overall speed and accuracy, 66% of them chose controller jitter and only 22% reported target jitter. When we asked them about the main influence on overall speed and accuracy, 10 out of 18 participants chose controller jitter, 7 out of 18 chose depth distance, and only a single participant chose target jitter.

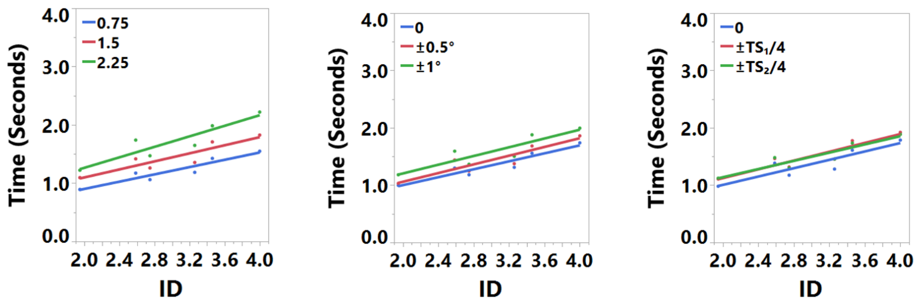
Moreover, 17 out of 18 users indicated that the controller jitter had a negative effect on both their speed and accuracy. Surprisingly, the second-most important factor that affected them negatively was not target jitter, but target depth.

5.6 Fitts' Law Analysis

A Fitts' law analysis based on Equation 1 is shown in Figure 6 and Table 2. Results showed that the 2.25 m depth distance has the highest slope with $MT = 0.36 + 0.45 * ID$, $R^2 = 0.83$, which was the most difficult condition to execute.

Table 2. Fitts' Law Results

Condition	Factor Level	Movement Time	R^2
Depth Distance	0.75	0.27+0.31 × ID	0.89
	1.5	0.41+0.34 × ID	0.82
	2.25	0.36+0.45 × ID	0.83
Cursor Jitter	0	0.27+0.36 × ID	0.81
	±0.5°	0.35+0.38 × ID	0.88
	±1°	0.42+0.35 × ID	0.86
Target Jitter	0	0.31+0.35 × ID	0.9
	$TS_1/4$	0.3+0.38 × ID	0.85
	$TS_2/4$	0.44+0.38 × ID	0.81



(a) (b) (c)

Fig. 6. Fitts' Law results for: (a) Depth distance (b) Cursor jitter and (c) Target jitter.

6 Discussion

In this work, we explored two rotational and two positional jitter conditions at various depth distances. Results showed that user performance significantly decreases with increased target jitter, cursor jitter, and depth distance.

Previous studies showed that user performance significantly starts to decrease above $\pm 0.5°$ rotational jitter [6]. Our results support this finding, but we also show that this result is only supported until a depth distance of 2.25m (see Fig 5(b) for error rate). At 2.25 m, user performance is already negatively affected by the $\pm 0.5°$ rotational jitter on the cursor. This result supports our H-1, stating that user performance decreases with increasing depth distance.

Similar to cursor jitter, target jitter also had a detrimental effect on user performance. When ± 0.375 cm positional jitter, which is equal to one fourth of the first target size, was applied to the target, the error rate of subjects significantly increased. ± 0.625 cm of positional jitter was worse as it both decreased selection time and increased the error rate. These results are in line with the results from previous studies [30, 35]. Further, we observed that user performance significantly decreases for both positional jitter at 0.75 m and 1.5 m. However, at 2.25 m depth distance, there was no significant difference between these the two positional jitter conditions, meaning that decreasing target jitter might not decrease user performance beyond 1.5 m depth distance. These results support our second hypothesis H-2: user performance significantly decreases with increased target jitter, and with increased depth distance.

As any change gets amplified along a ray, the control-to-display ratio naturally varies with depth for ray casting. Thus, pointing at larger distances is more susceptible to rotational jitter. Compared to the constant effect of positional jitter on a target, a small amount of rotational jitter can have a stronger detrimental effect on cursor position for further away targets with ray casting. This negative effect was also perceptible to the participants, who clearly identified a negative effect of rotational jitter on their speed and accuracy.

Since the control-to-display ratio varies for each depth condition with ray pointing, directly comparing the positional jitter on targets to rotational jitter on a controller might not yield useful insights. Yet, a comparison between the same amount of jitter on targets and the cursor at the same depth would be meaningful. However, in our study, subjects responded more negatively to rotational jitter.

The throughput results of our work are also interesting. As shown in the results section, while it took more time to execute the task and subjects made more errors with increased jitter, there was no change in their throughput performance. To reach the same level of throughput as specified by Equation 2, when the movement time increases due to cursor jitter, the effective index of difficulty also needs to increase proportionally. For this, either the effective distance A_e might increase, or the effective target width W_e might decrease with increasing jitter conditions. Due to the nature of jitter, we expect an increase in effective target width W_e, since it is defined as $W_e = 4.133 \times SD_x$ and jitter naturally increases the standard deviation of the selection points. However, an increase in the standard deviation of the selection points also means that there is an increase in the effective target distance A_e, which means subjects travelled a larger distance between two selections. We thus hypothesize that the increase in the effective distance with increased jitter also increased the throughput and as a result, we did not find any significant results in throughput for rotational jitter.

All participants preferred the conditions without jitter on the controller or target; to the point that when queried, one of them commented: “No jitter please”, which found its way into the title of this manuscript. Except for one, all of the participants reported an increase in fatigue and tiredness at the end of the experiment. This notable increase in fatigue could have been caused by the length of the experiment or different amounts of jitter which could have made the VR tasks demanding.

Based on the subjective fatigue results, the negative effect of jitter on user fatigue in VR is worth exploring further. Even though subjects were sitting and forced to take a break between conditions for at least 5 minutes, they reported a high fatigue level at the end. Since noise is always present in VR systems, quantifying its effect on the users’ experience is a first step towards objectively counteracting such noise, with the eventual goal to create better experiences for VR users.

While some of our results are not surprising in a qualitative sense, such as that subject performance decreases with increased depth distance or increased jitter levels, the work presented here quantifies the magnitude of these effects. A good example for an insight that might not have been obvious at the outset is that in our study halving the positional jitter for targets at far distances, e.g., 2.5 m, did not improve user performance, since the effect of the depth distance is more dominant.

One of the limitations of our work pertains to the positional jitter levels, which are specified relative to the target size. We made the decision to associate target jitter with size due to three factors. First, and as in mentioned in the introduction, when positional jitter is represented as angular jitter, it varies non-linearly with distance. For instance, 1 cm of positional target jitter translates to 0.74° at 75 cm, 0.34° at 1.5 m, and 0.25° at 2.25 m. Gori et al. [17] showed that, to prevent bias, Fitts’ law experiments should be designed with conditions that involve linear increments. Thus, we chose to use linear distance increments, a decision also simplifies our presentation. Second, if we had used the same angular jitter for different distances, the resulting positional jitter would have increased with increasing depth distance, which would have correlated positional jitter with depth distance and potentially biased the comparison. Finally, angular Fitts' law formulations are subject to ongoing research in VR, e.g., [3,12,13,21,28]. After all, there is currently no angular Fitts' law formulation that deals with the inherent speed-accuracy trade-off [24]. Thus, and also to simplify our exposition, we used positional jitter relative to the target size. Moreover, given that the positional jitter is small relative to the distance, the corresponding angular measure does also not change (that) much.

Another limitation of our work pertains to the presence non-zero tracking noise in the used input devices. Yet, to our knowledge, it is not possible to reliably separate natural human behaviours, such as hand tremors or body sways, from the tracking noise in current VR controllers. Thus the jitter data we measured is due to a combination of multiple noise sources. To reduce the most obvious sources of error, we used the most current Steam VR Software (Version 1.9) with the latest HTC Vive Pro headset and two V2 lighthouses (also called base station) in a room with only artificial lighting. While the system we used had thus a relatively low level of tracking noise, the amount of positional and rotational jitter artificially added do thus not correspond directly to absolute values. Thus, we suggest that other researchers also use HTC Vive Pro controllers as a baseline to make their work comparable with our results.

7 Conclusion & Future Work

In this paper, we explored rotational jitter on controllers and positional jitter on targets at three different depth distances. Results showed that user performance significantly decreases with target jitter as well as cursor jitter. Increased depth distance also decreased user performance. However, we suggest that practitioners/developers who design 3D user interfaces, controllers, or interaction techniques should mainly focus on cursor jitter, instead of target jitter, as our work identified that rotational jitter has a larger impact.

In the future, we want to replicate our results with more accurate devices, such as a 2D mouse, and with various grip styles, such as a precision grip, to further understand the effect of jitter on user performance. Moreover, we want to further investigate the user experience with various target depths and amounts of positional jitter to better understand user reactions to positional jitter.

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