Effect of Fixed and Infinite Ray Length on Distal 3D Pointing in Virtual Reality

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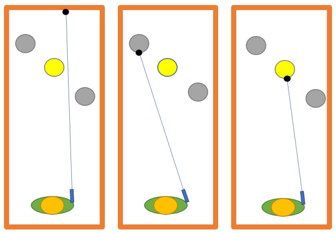
Abstract
Ray casting is frequently used to point and select distant targets in Virtual Reality (VR) systems. In this work, we evaluate user performance in 3D pointing with two different ray casting versions: infinite ray casting, where the cursor is positioned on the surface of the first object along the ray that said ray points at, and finite ray-casting, where the cursor is attached to the ray at a fixed distance from the controller. Twelve subjects performed a Fitts' law experiment where the targets were placed 1, 2, or 3 meters away from the user. According to the results, subjects were faster and made fewer errors with the infinite ray length. Interestingly, their (effective) pointing throughput was higher when the ray length was constrained. We illustrate the advantages of both methods in immersive VR applications and provide information for practitioners and developers to choose the most appropriate ray-casting-based selection method for VR.

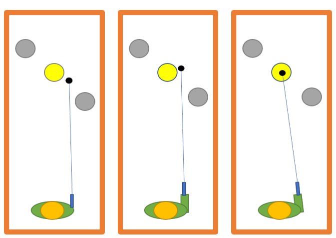
Author Keywords
Virtual Reality; Fitts' task; 3D pointing; ray casting; mid-air interaction

CCS Concepts
•**Human-centered computing** → **Virtual reality;** *Pointing devices; HCI theory, concepts and models;*



(a) (b) (c)

Figure 1: Infinite ray pointing, (a) a ray between is cast from the 6 DoF controller and the cursor is positioned at the collision point of the ray, (b) user sees the cursor when the ray intersects with a object, (c) cursor appears on the front surface of the target.



(a) (b) (c)

Figure 2: Fixed ray length pointing, (a) cursor is positioned at a constant distant from the 6 DoF controller and the ray is shown for visual feedback. (b) user has to extend their arm to position the cursor, (c) to select a target, cursor has to be positioned inside it.

Introduction

Ray casting is one of the most commonly used techniques to select and interact with distant objects [22]. User performance with the ray casting technique has been studied in various studies, e.g., [21]. However, while some studies [4, 6, 7, 15, 30] used a finite ray length in their work, many other ones [8, 13, 18, 31, 32, 35, 37] used an infinite ray length for a 3D pointing task. One core motivation for using a finite length for ray-based pointing is the controllable environment provided in 3D virtual environments (VE)s: designers and practitioners could vary the length of the ray attached to the 6 degree of freedom (6DoF) controller to meet the needs of a specific application scenario with the aim to provide more effective and agile interaction.

Infinite ray lengths are mostly used to select targets at arbitrary distances, subject to angular accuracy (Figure 1). As the user cannot always clearly see the endpoint of the ray, a cursor is shown at the first intersection. Then, the user has to intersect the ray (not the cursor) with the target to point at it. On the other hand, a fixed ray length limits the interaction space and provides a constant and fixed control-display gain (Figure 2). Here, the cursor is placed at a constant distance, and the ray provides visual feedback between the 6 DoF controller and cursor. Since the cursor at the end of the ray is often closer to the user compared to the infinite ray length technique, this technique provides additional depth cues and occludes other objects in the VE less. However, the user has to move the controller forward and backward to position the cursor in depth and place the cursor inside a target to select it. Both methods have their advantages. Thus, practitioners/developers/designers could use either one in a VR application, depending on their characteristics and user needs.

In this study, we investigated how infinite and fixed ray length pointing affect user performance in VR. To evaluate user performance, we asked subjects to perform a 3D pointing task with targets at three different (visual) depth distances (1, 2, or 3 meters).

Previous work

3D Pointing in Virtual Environments

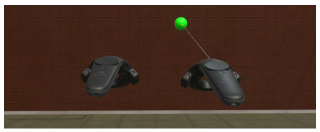
Pointing is a fundamental task while users interact with a VE [12]. There are various studies in the literature that explore pointing tasks in VE, see, e.g., a recent survey of devices and techniques for 3D pointing [3], or evaluations of different mid-air selection methods, e.g., [24]. More recent work compared different interaction styles for 3D mid-air pointing [10].

Ray casting

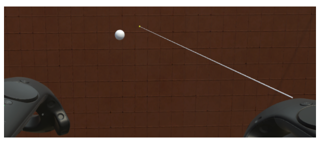
While selection with a virtual hand metaphor is easy in VR, it is challenging to select targets that are further away with this technique [22]. Ray casting is the preferred choice of interaction technique for the selection of distant objects in many VR scenarios [12]. Still, as it requires accurate pointing, ray casting does not perform well for small and/or distant targets [29], similar to how a laser pointer behaves in the real world. Thus, new techniques or combinations of existing techniques have been proposed to improve ray casting, such as the HOMER technique [9] or adjusting the ray-length [38]. Yet, some of these techniques require additional explicit user input to adjust the ray length, which is out of scope for the work presented here.

Fitts' Law

Fitts' law [14] models human movement time for pointing tasks. Its Shannon formulation [23] is shown in equation 1.



(a)



(b)

Figure 3: The empty room which acted as the VE for the experiments. The controller on the right was used with the dominant hand to position the yellow cursor at the end of the ray and the trigger on the left controller was used solely for selection with the non-dominant hand. (a) A green target indicates that the cursor is "on" the target for the infinite ray length; (b) a gray target indicates the cursor is not "inside" the target for the finite ray length.

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

In equation 1, a and b are empirical constants, 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.

Selection Method

The "Heisenberg effect" [8] is an error that occurs when a user physically interacts with a controller during selection, i.e., when they press a button, which affects the cursor position or ray rotation. Ray casting is prone to this effect, since the smallest noise in the origin at the ray is magnified along the ray distance [6]. To reduce the Heisenberg effect, previous work, e.g., [33, 7], used asymmetric bi-manual interaction, which allows user to point with the dominant hand and to activate selection with the non-dominant one. Previous work showed that such bi-manual pointing does not affect user performance [10].

Motivation & Hypothesis

Recently, Kim and Han showed that decreasing DoFs during mid-air 3D interaction increases user performance in VR [20]. In this work, we explore if decreasing DoFs for the control of the cursor affects 3D pointing performance. As mentioned in the introduction, with a fixed ray length the user has to consider depth movements while positioning the cursor, but does not have to focus on such movements with an infinite ray-length. Since the need to also control the position of the cursor (and controller) in depth requires additional effort [5], our hypothesis is that user performance would decrease with the fixed ray length condition.

User Study

Participants

Twelve subjects (3 female), average age 25.9 ± 4.6 years, participated in our experiment. Eleven were right-handed. All of them used their dominant hand to execute the task. We adjusted the headset to match the inter-pupillary distance of each individual.

Apparatus

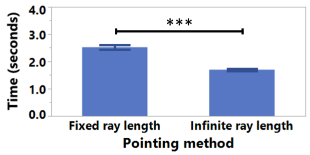
We used a PC with an Intel (R) Core (TM) i7-5890 CPU with 16 GB RAM and a Nvidia GeForce RTX 2080 graphics card. We used a HTC Vive Pro with two V2 Lighthouses as the VR headset. Subjects used two HTC Vive Pro controllers as input devices.

Procedure

In this study, we followed a similar procedure as previous work by Kooper et al. [21], but used an immersive VR headset instead of a large, immersive screen and added one additional target size to the conditions.

Participants were first asked to fill a demographics pre-questionnaire. Then, the experimenter explained and demonstrated the task to the participant. Participants initially stood with their back against a wall in front of the experimental area. Before starting the experiments, subjects were allowed to perform practice trials for a few minutes to get used to the VR system, the VE, and the task. At the end of the experiment, subjects filled a post-questionnaire to indicate their preferred selection method.

To assess 3D pointing performance and similar to Kopper et al.'s study [21], we used a variation of the ISO 9241-411 task [17]. We chose this work as a reference to highlight potential different outcomes for selection techniques. In our version of the task, two pairs of targets were placed along the lateral and longitudinal axes, i.e., targets appeared as



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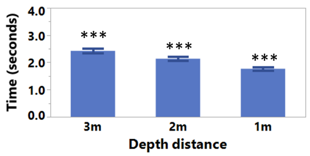
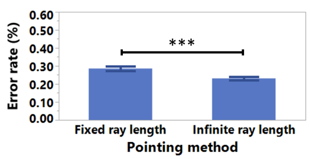


(b)

Figure 4: Time results for (a) pointing method and (b) depth distance condition. Please refer to Table 1 for further information.



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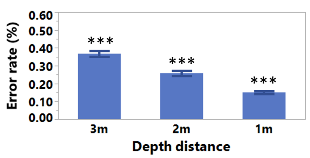


(b)

Figure 5: Error rate results for (a) pointing method and (b) depth distance condition. Please refer to Table 1 for further information.

North and South, or East and West relative to the vertical to the user. Targets were visible one at a time, i.e., when a selection occurred (regardless if successful or not), the current target disappeared and the other one appeared. Participants were asked to select these targets as fast and precisely as possible.

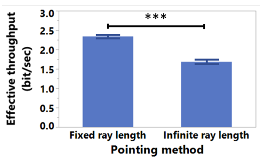
In the VE, subjects were placed in an empty room with depth cues (Figure 3). We used two **pointing methods**. In the *infinite ray length* condition, a virtual line, i.e., a ray, was drawn between the the controller origin and the intersection point of the ray with the scene, which is also where we showed the cursor (yellow sphere). The second condition used a *fixed ray length*, where the cursor was placed at a pre-determined distance away from the user.

Targets were placed 1, 2, or 3 meters away from the user in front aligned with each participant's individual eye-level. Since we varied the target depth distance, we also changed the ray length for each fixed ray length condition accordingly. To accommodate an ergonomic posture, the distance between the cursor and the controller was 30 cm less than the depth distance condition in each specific depth condition, e.g., the fixed ray length was 1.7 meters for targets at 2 meters. Before the experiment, we verified that each participant could easily reach all targets and position the cursor inside targets.

In the infinite ray length condition, and when the user placed the yellow (sphere) cursor "on" the target, we changed the color of the object to green to provide visual feedback (Figure 3(a)). In the fixed ray length condition, when the yellow (sphere) cursor was placed "inside" the target, we also changed the color of the object to green (Figure 3(b)). To activate the selection and to mitigate the "Heisenberg effect", subjects then needed to pull the trigger of the controller held in their non-dominant hand. If the cursor was inside the target for the fixed ray length or if the cursor was on the target for the infinite ray length while the subject pulled the trigger, a successful 'hit' was recorded. If the cursor was out of the target when subject pulled the trigger, we called it a "miss". In this case, we played a error sound in the HMD speakers and changed the color of the target to red for visual feedback.

Experimental Design
The twelve participants selected 13 consecutive targets in 6 experimental conditions: two Pointing Methods (PM_2: fixed ray length and infinite ray length) and three Depth Distance (DD_3: 1, 2 and 3 meters), in a PM_2 x DD_3 within-subject design. To avoid potential learning affects, the three different depth distances DD_3 and two pointing methods PM_2 were counterbalanced between subjects through a Latin Square design. We used movement time (seconds), error rate (%), and effective throughput (bits/s) based on ISO 9241-400:2012 [17] to measure users' 3D pointing performance. For the fixed ray length, we used the 3D distance between the cursor and target position, but used the 2D planar distance between the "touch" point of the cursor on the target sphere and the target center after projection into the target plane for the infinite ray length condition [36]. To vary ID, we used three Target Distances (TD_3: 0.2758, 0.8274, and 1.379 m) and four Target Sizes (TS_4: 17.65, 35.3, 52.95 and 70.6 mm) and evaluated 11 unique ID's between 2.21 and 6.31 with Equation 1. Each subject performed 936 trials (PM_2 x DD_3 x TD_3 x TS_4 x 13 trials). Overall, we collected 11232 data points.

Data Analysis
We analyzed results using 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 [16, 25], considered the data as normally dis-



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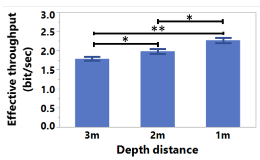
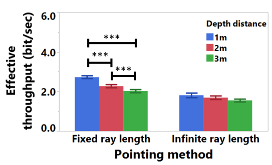


(b)

Figure 6: Effective throughput for (a) pointing method and (b) depth distance conditions. Please refer to Table 1 for further information.



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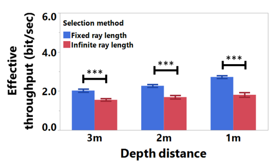

(b)

Figure 7: Throughput interaction results for (a) pointing method and (b) depth distance conditions.

tributed when Skewness and Kurtosis values were within ± 1.5. Before analyzing the data with RM ANOVA, we found that throughput (Skewness (S) = 0.421, Kurtosis (K) = -0.788) and the error rate (S = 1.141, K = 0.4789) had a normal distribution and that time (S = 0.359, K = -0.321) was normal after log-transform. Results are shown with *** for p $<$ 0.001, ** p $<$ 0.01, * p $<$ 0.05, and n.s. for non-significant results. We used the Sidak method for post-hoc analyses.

One-way RM ANOVA Results

For the **depth distance**, Mauchly's sphericity test was violated for throughput ($\chi^2(2)$ = 8.399, $p < 0.05$), but not for time ($\chi^2(2)$ = 1.418, $n.s.$) and error rate ($\chi^2(2)$ = 0.47, $n.s.$). For the **ID**, Mauchly's sphericity test was violated for time ($\chi^2(54)$ = 117.252, $p < 0.001$), but not for error rate ($\chi^2(54)$ = 75.387, n.s.) and throughput ($\chi^2(54)$ = 72.340, n.s.). For the RM analysis, we used Huynn-Feldt correction, since $\epsilon = 0.426 < 0.75$ for time and $\epsilon = 0.684 < 0.75$ for throughput. The one-way ANOVA results are shown in Table 1.

Table 1: RM ANOVA results

	Pointing method	Depth Distance	ID
Movement time	F(1,11)= 45.75 $p < 0.001$, $\eta^2 = 0.806$	F(2, 22)= 45.60 $p < 0.001$, $\eta^2 = 0.086$	F(4.262,46.880)=202.05 $p < 0.001, \eta^2 = 0.948$
Error rate	F(1,11)= 9.3 $p = 0.011, \eta^2 = 0.458$	F(2,22)= 109.736 $p < 0.001, \eta^2 = 0.909$	F(10,110)= 10.73 $p < 0.001, \eta^2 = 0.909$
Effective throughput	F(1,11)= 85.11 $p < 0.001, \eta^2 = 0.865$	F(1.37,15.05)= 13.691 $p < 0.001, \eta^2 = 0.554$	F(10,110)=23.91 $p < 0.001, \eta^2 = 0.760$

According to the results in Table 1, Figure 4(a) and Figure 5(a), subjects were faster and made fewer errors with the infinite ray length. However, subjects' throughput increased with the fixed ray condition compared to the infinite ray condition as shown in 6(a). When we look at the **depth distance** condition results in Table 1, we can see that subject were faster 4(b), made fewer errors (5(b) and their throughput increased (6(b) when target was closer to the user.

Two-way RM ANOVA Results

Two-way RM ANOVA results identify only a significant interaction between **pointing method** and **depth distance** for throughput F(2,22) = 5.45, p $<$ 0.05 (the sphericity assumption was not violated ($\chi^2(2)$ = 3.79, n.s.) According to the results in Figure 7(a), throughput performance of subjects increased when targets were closer to the user for the fixed ray length, but not for the infinite ray length. Moreover, subjects throughput increased at each target distance when they used a fixed ray length, as shown in Figure 7(b).

Subjective results

All participants preferred the infinite ray length to select objects. They stated that, "it is easy to use" and "requires less movement [in depth]". We also asked about the difficulty of interaction with infinite and fixed ray lengths using a 7-point Likert scale. For selection, none of the subjects rated the infinite ray length as difficult to interact with. However, for the fixed ray length condition, two of the subjects choose "somewhat easy" to select targets, while the rest said it was difficult. Also, subject thought they were faster and more accurate with the infinite ray length. From the ANOVA results we can see that their perceptions are correct in terms of time (Figure 4(a)) but not for accuracy (Figure 6(a)).

Fitts' law

When we use Fitts' law to model the movement time for the whole experiment in Figure 8(a), we can identify the following coefficients: a=-0.66 and b=0.66 with R^2 = 0.9. When we split the data by pointing methods in Figure 8(b), we found a=-1.04 and b=0.85 with R^2 = 0.91 for the fixed ray length, and a=-0.28 and b=0.47 with R^2 = 0.88 for the infinite ray length. According to these results, the movement time difference between fixed and infinite ray lengths de-

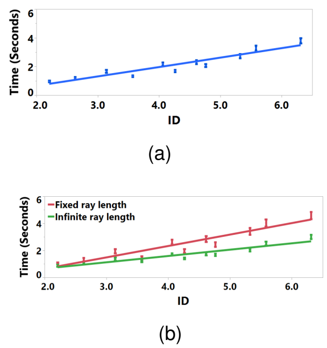

Figure 8: Fitts' law model for (a) whole study and (b) different selection methods.

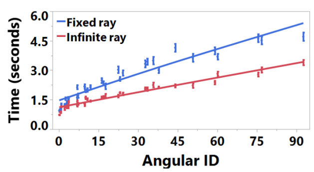

Figure 9: Angular Fitts' Law analysis. Here, ID is calculated as $(log_2((\alpha)/(\omega^k) + 1))^2$ with k=3, as in Kopper et al. study.

creases for smaller IDs. When Kopper et al.'s model [21] is used, the infinite ray is modeled as MT=1.19+0.02*ID, R^2 = 0.94, $AIC = -26$ and the fixed one as MT=1.5 + 0.042*ID, R^2 = 0.9. $AIC = 30$ (Figure 9). Both R^2 and AIC [1] values decrease for the fixed ray length condition. Using Burnham et al.'s [11] criterion, the difference in AIC scores is significant between the two conditions.

Discussion

In this study, we analyzed user performance with a 3D pointing task with a fixed and infinite ray length. Even though we had 12 subjects in this study, all the effect sizes were larger than $\eta^2 > 0.14$, which indicates large effects.

The time, error rate, and throughput differences between fixed and infinite ray length can be attributed to the interaction style for these methods. In the fixed ray length condition, subjects have to use the depth cues and stereo vision to move the cursor inside the target. Compared to the infinite ray length, this adds one more DoF to the selection process, which also supports our hypothesis. Previous work showed that decreasing or controlling DoFs one at a time improves user performance [27, 28, 34]. A similar result can also be observed here since the execution time and error rate decreases with the infinite ray length. Yet, effective throughput was less with the (simpler to control) infinite ray length. We believe that this might be caused by two effects: The first one is the difference in distances between the infinite and fixed ray lengths while the user positions the cursor on/in the target. With the infinite ray length, the cursor always stays on the surface of the target which faces the user [2]. Thus, the user does not try to place the cursor near the center of the target in the infinite ray length condition and the cursor cannot get closer to the center of the target than the corresponding 3D angular selection point [26, 39], which also affects the throughput calculation. To account for this, we calculated throughput with selection points *projected* into the 2D target plane for the infinite ray length [36]. Interestingly, the extra DoF provided by the fixed ray length improved user performance in this work. The slightly higher task execution time still improved user performance: while participants were positioning the cursor a bit more slowly with the fixed ray length, their throughput still increased, due to the speed-accuracy trade-off.

The differences between the fixed and infinite ray length conditions show that these two interaction techniques should be treated separately by practitioners, developers, and designers. For instance, since the Fitts' law results in Figure 8 and Figure 9 are different, Kopper et al.'s [21] findings for 3D distal pointing, including the proposed 3D angular equation, do not apply to fixed ray length performance assessments. This also poses the following question: Can we use the outcomes of other distal pointing studies, such as [7, 19], for both infinite and fixed ray length, even the two selection methods are different and user performance is not the same? This question will be subject to future work.

Conclusion and Future Work

We explored how fixed and infinite ray length pointing affects user performance in a 3D selection task. Results showed that user performance is not the same for these two distal methods: subjects were faster and made fewer errors when they used an infinite ray length. However, their throughput increased with the fixed ray length. We believe that these differences in the outcomes are inherent to the design of both techniques. In the future, we are going to the analyze how jitter affects user performance with both selection methods and plan to extend our work to other ray-based selection techniques, such as cone selection.

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