A Kinematic Evaluation of Linear and Parabolic Pointing in Virtual Reality

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We present the results of a study investigating the influence of task and effector constraints on the kinematics of pointing movements performed in immersive virtual environments. We compared the effect of target width, as a task constraint, to the effect of movement distance, as an effector constraint, in terms of overall effect on movement time in a pointing task. We also compared a linear ray-cast pointing technique to a parabolic pointing technique to understand how interaction style may be understood in the context of task and effector constraints. The effect of target width as an information constraint on pointing performance was amplified in VR. Pointing technique acted as an effector constraint, with linear ray-cast pointing resulting in faster performance than parabolic pointers.

INTRODUCTION

Human-computer interaction (HCI) frequently involves pointing and clicking actions on the part of the user. Appropriately, Fitts' law (Fitts, 1954; Fitts & Peterson, 1964), which models performance in pointing tasks, has become a standard for evaluating elements of the interface and control device (e.g., MacKenzie, 1992). Performance of pointing and target selection techniques in 3D interaction for virtual reality (VR) remains an area of investigation that can benefit from both an analysis in terms of Fitts' law and application of methods from human movement science. The emergence of consumer level VR has transformed this technology into a domain for everyday users. As a result, it is as important as ever to investigate human performance in VR.

Fitts' law is concerned with the effects of task scale (movement distance, D, and target width, W) on the duration of pointing movements, and is expressed by the relationship between an index of difficulty (ID), which incorporates the effects of D and W, and movement time (MT), where MT = a + b(ID) with a and b representing experimentally determined coefficients and ID = $\log_2(2D/W)$ in units of bits.

Performance in the Fitts' task is typically evaluated in terms of MT and throughput. However, other work has identified the value in using kinematic analyses in the evaluation of performance (e.g., Bootsma, et al., 2004; Deng, et al., 2019; Slocum, et al., 2005). Using kinematic analyses of movement velocity and acceleration, pointing movements can be subdivided into two phases. Movements begin with a high-velocity primary phase that is followed by a low velocity secondary phase, which is marked by the appearance of zero-crossings in the acceleration graph after peak velocity has occurred (Meyer, et al. 1988), and represents the onset of feedback-driven corrections (Elliot et al., 2010).

Of interest to performance evaluation in HCI are the factors that may separately influence the primary and secondary phases. Here we summarize these multiple findings (e.g., Bootsma et al., 2004; Buchanan et al., 2006; Fernandez & Bootsma, 2004; Huys et al., 2010; Mottet & Bootsma, 1999; Thompson et al., 2007). Increasing ID by decreasing W tends to selectively affect the secondary phase, changing the shape and symmetry of the velocity profile. Increasing ID by increasing D instead rescales the entire velocity profile, resulting in the expected increase in MT without changing the symmetry of the velocity curve. These two key findings have led researchers to classify target width as a task constraint that reflects the information processing load of the task in the form of reliance on feedback-driven corrections at the end of the movement (Huys et al., 2010; Sleimen-Malkoun et al., 2012), while movement distance is classified as an effector constraint that determines the dynamic and kinematic scale of the task.

Taken together, these results can predict Fitts' law. First, movement distance is the main determinant of the duration of the primary phase, and target width is the main determinant of the duration of the secondary phase, which has also been demonstrated empirically (Bohan et al., 2010; McConnell, 2019). Thus, total MT in the Fitts' task represents the combined effects of the two constraints.

These variables have been studied in a variety of both real-world and 2D computer-based pointing tasks, and while it is known that they exhibit similar effects in VR pointing (Deng et al., 2019), a systematic study of the relative effects of task and effector constraints in VR has yet to be undertaken.

We note that pointing performance in VR is not always identical to real-world or computer-based tasks. For example, a number of studies of virtual pointing have found that MT is slower in VR compared to the real world, and in particular have identified elongation of the secondary phase as the reason (Lin et al., 2015; Lin & Woldegiorgis, 2018; Liu et al., 2009; Nieuwenhuizen et al., 2009), suggesting that the effects of task constraints are magnified in VR. Further, practice with the pointing task results in increased speed and accuracy of the primary phase but not the secondary phase (Nieuwenhuizen, et al., 2009). Previous authors have speculated that impaired distance perception in VR (e.g., Stuerzlinger & Teather, 2014; Thompson et al., 2011) might explain these findings, however, studies that have attempted to improve distance information in displays have failed to demonstrate improvements in pointing performance (e.g., Lin et al., 2019; Lin & Woldegiorgis, 2017; Teather & Stuerzlinger, 2014).

Further, in real-world pointing, manipulation of D leads to larger effects on MT compared to manipulations of W (e.g., Heath et al., 2011; Temprado et al., 2013). A theoretical explanation for this finding has yet to be elucidated, and it remains possible that that this finding may not hold in VR pointing due to the aforementioned amplification of task constraints. If such was the case, then such a finding may contribute to a theoretical understanding of the differential effects of D and W manipulations.

Further, Deng et al. (2019) found that, in an object-placing task, increasing movement distance increased the duration of both the primary and secondary phases. This is inconsistent with studies of real world pointing with distance tending to only affect the primary phase. It remains unclear then, to what extent D and W act as effector and task constraints, respectively, in VR pointing. It is also not clear whether the effect of D on MT is stronger than the effect of W in VR, as it is in real-world performance.

Current Study

The goal of the current work is to compare directly the effects of D and W on MT, as well as the durations of the primary and secondary phases of pointing movements in VR. We will further investigate the effects of these constraints using two interaction techniques, linear and parabolic ray-cast pointing. The benefit of this is twofold. First, we can demonstrate the robustness and the findings vs. whether they are unique to a particular interaction technique. Second, we can evaluate these interaction techniques to determine how they affect performance and whether interaction technique can be categorized as either a task or effector constraint.

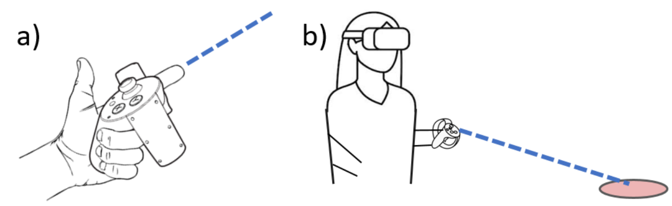
Interaction technique is here defined as the way in which user-target interaction is depicted in the virtual pointing task. Interaction styles differ across many studies, with few directly examining these techniques. In some studies, the hand or controller is used to guide a free-floating cursor toward the target (e.g., Babu, et al., 2020; Lin et al., 2015), while in others, a virtual ray is cast from the controller to the target (e.g., Deng et al., 2019; Wilson et al., 2020). It is thus unknown whether interaction techniques represent task or effector constraints. While multiple studies have compared the nature of the pointing device used in VR and 3D pointing studies (e.g., Babu et al., 2020; Hansen et al., 2014; Pham & Stuerzlinger, 2019) fewer have compared the interaction style of the visible pointer/cursor. The closest relevant work comes from studies of point-and-teleport interactions. Funk et al. (2019) reported that both the linear and parabolic ray-casting interaction styles were associated with fewer errors and faster performance compared to angular and other curved pointing rays.

The linear ray-cast pointer (Figure 1) allows a user to press a button to cast a straight ray from the virtual hand to a target. While some studies have demonstrated the effectiveness of linear ray-casting with a tracked hand in both remote and virtual pointing tasks (Deng et al., 2019; Jota et al., 2009; Vogel & Balakrishnan, 2005), others have reported that ray-casting was associated with markedly longer MT compared to a mouse-controlled cursor and a virtual stylus (Teather & Stuerzlinger, 2011).

The non-linear parabolic pointing technique (Figure 2) traces the parabola of a projectile from the controller using the formula for a basic parabolic trajectory. There are variables to set the initial velocity and acceleration of the cast particle, which adjusts the length of the parabola. Simulated gravity constantly guides the particle downward below the controller. This technique acts like a standard parabola as the user changes the orientation of the controller. The equation to calculate the parabolic path is $D = sin(2\theta)\ v^2/g$, where g is the acceleration due to gravity, v is the initial particle speed, and θ is the angle of the controller.

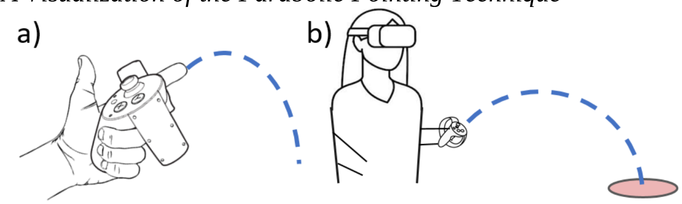
We propose two hypotheses regarding pointing performance in VR. First, the effect of target width as a task constraint is amplified in VR. If true, this would predict that manipulation of ID by W would exhibit effects comparable to, if not larger than, the effect of manipulating ID by D, in terms of slope differences in ID-MT regressions. Second, the interaction technique implemented in the VR task (e.g., linear ray-cast vs. parabolic pointer) represents a virtual effector and manipulations of the technique should reveal effects consistent with effector constraints, i.e., affecting the duration of the primary but not secondary movement phase.

Figure 1
A Visualization of the Linear Ray-Cast Pointing Technique.



Note. A straight ray shoots out from the controller to point to the target in the virtual environment.

Figure 2
A Visualization of the Parabolic Pointing Technique



Note. A non-linear ray shoots out from the controller and follows a parabolic path (see text) to point to a target in the virtual environment.

METHOD

Participants

Thirty-two right-handed participants (19 = Female; Median age = 26.5), recruited from a large southeastern US university, volunteered to participate in the study. All had normal or corrected-to-normal visual acuity and reported no other motor or sensory deficits. All protocols were approved by the university IRB. Participants consented to the protocols and were treated in accord with the ethical guidelines of the American Psychological Association and the Declaration of Helsinki.

Materials and Design

Participants stood and viewed the virtual environment using an Oculus Rift CV1 HMD and controlled the ray-cast using an Oculus Touch controller with their right-hand. The virtual environment was a 12×6×12m room with dark gray walls and floor (Figure 3). The hand appeared as a black avatar of the participant that was tracked via the Touch controller. The pointer extended from the virtual index finger as either a linear ray-cast or non-linear parabolic arc. This was presented as a between-subjects variable. A starting position was defined as a light blue 2D circle with a diameter of 0.25m appearing on the floor 3.91m away and 39.81 deg to the left. Targets appeared on the floor as red circles to the right of the starting position. The distance and diameter of the target varied as a function of condition. In the first condition, the distance between the starting position and target was held constant at either of two values while the target diameter was manipulated. In the second condition, the target diameter was held constant at either of two values while the distance was manipulated. Table 1 provides the target distances, sizes, and IDs.

Table 1

The Target Task Values Across the 4 Blocks of the Experiment

	D(m)	W(m)	ID (bits)
Block 1			
	2.4	0.6	3
	2.4	0.3	4
	2.4	0.15	5
	2.4	0.075	6
	2.4	0.0375	7
Block 2			
	4.8	0.6	4
	4.8	0.3	5
	4.8	0.15	6
	4.8	0.075	7
	4.8	0.0375	8
Block 3			
	3.6	0.05625	7
	1.8	0.05625	6
	0.9	0.05625	5
	0.45	0.05625	4
	0.225	0.05625	3
Block 4			
	3.6	0.1125	6
	1.8	0.1125	5
	0.9	0.1125	4
	0.45	0.1125	3
	0.225	0.1125	2

Dependent Variables

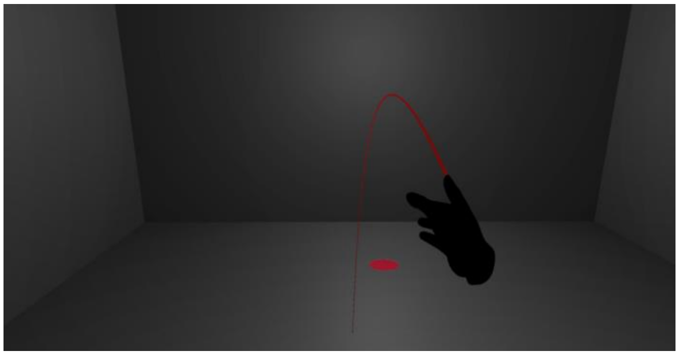
We captured the following data for analysis: pointer position, velocity, and acceleration. The movement sequence was smoothed with a box filter and parsed into primary and secondary phases using approaches by previous investigators (Meyer et al., 1988; Thompson et al., 2007). We then measured mean MT, as well as mean duration of the primary (PT) and secondary (ST) phases.

Procedure

Upon arrival, participants were instructed how to use the controller to point and click on targets in the virtual environment. Participants were told to move as quickly as possible while still being accurate. Upon confirming that the pointer was within the target boundaries, the participants pressed a button on the controller to end the trial. The target then disappeared, and the participant returned the pointer to the starting position and awaited the next trial. Conditions were presented in four blocks (Table 1), each with five conditions that were repeated five times in random order. There were 100 total trials. The duration of the session was approximately 15 minutes.

Figure 3

A visualization of the virtual environment used in the pointing task. This specific image depicts the parabolic pointer technique.



RESULTS

Analysis was performed on the mean dependent measures calculated per condition, averaged across trials and across the 16 participants in each of the two interaction conditions. 361 of the total 3200 trials were deemed outliers and removed. First, all trials with a movement endpoint outside their condition's effective target width were removed. After this, trials with a total movement time greater than 2 SDs from that condition's mean movement time were removed.

As shown in Figures 4 and 5, all conditions followed Fitts' law. For the linear ray-cast technique, multiple regression, $F(3,19) = 57.4$, $p < .001$, $R^2 = .92$, revealed that ID predicted MT, $t = 2.7$, $p = .02$. For the linear ray cast technique, the slope for the distance manipulation (b = .108) was only slightly larger than the slope for the target width manipulation (b = .095), which was not significant in the multiple regression, $t = .7$, $p = .48$, nor was there an intercept difference, $t = 1.8$, $p = .10$. For the parabolic pointer, multiple regression, $F(3,19) = 25.2$, $p < .001$, $R^2 = .83$, revealed ID was not a significant predictor, $t = 1.9$, $p = .08$. There was no slope difference between the distance manipulation (b = .155) and the width manipulation (b = .132), t = .6, p = .53, and there was no intercept difference, $t = .9$, $p = .38$.

In terms of the manipulation of pointing technique, the parabola exhibited longer MT ($M = 1.02$s, $SD = .27$) compared to the linear ray-cast technique ($M = .86$s, $SD = .20$), $t(39) = 2.16$, $p = .04$, $d = .68$. This effect was localized to the primary phase, with mean PT for the parabolic ($M = 0.69$s, $SD = .21$) greater than mean PT for the linear ray-cast (M = .56, $SD = .16$), $t(39) = 2.27$, $p = .03$, $d = .71$. There was no difference in ST between the parabola ($M = .33$, $SD = .12$) and linear ray-cast ($M = .30$, $SD = .09$), $t(39) = .80$, $p = .43$.

Figure 4
ID regressed against MT for the linear ray cast pointing technique.

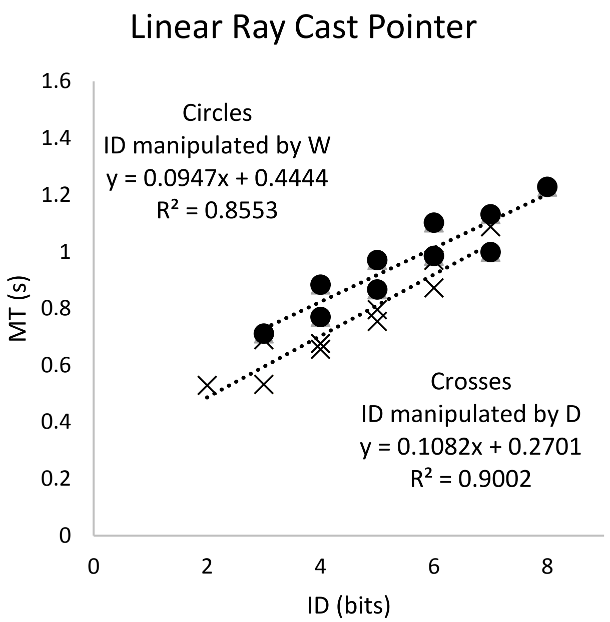
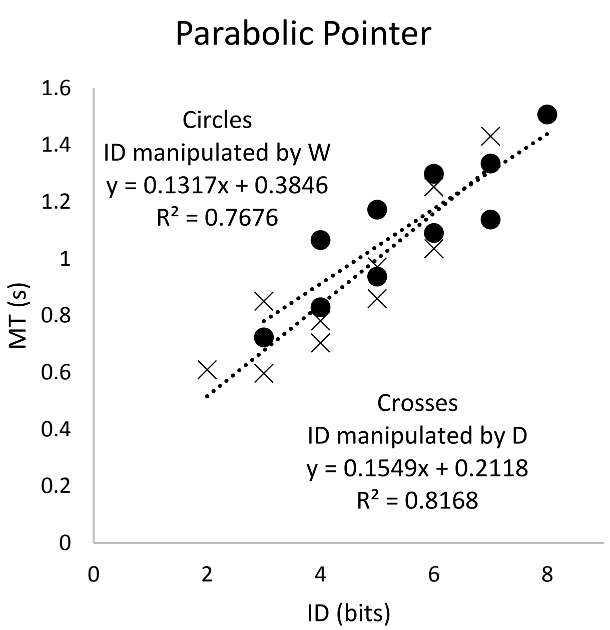


Figure 5
ID regressed against MT for the parabolic pointing technique.



DISCUSSION

We report evidence supporting both of our hypotheses. First, the effect of target size as a task constraint was magnified in virtual pointing compared to distance as an effector constraint. In real world pointing studies, manipulations of D result in steeper ID-MT slopes compared to manipulations of W (Heath et al., 2011; Sleimen-Malkoun et al., 2012), yet we found comparable slopes in these conditions. We take this to mean that the usual difference has been dampened due to the increased difficulty in processing visual feedback for small targets. Such a conclusion must be tempered by the possibility that the difficulty usually associated with distance manipulations is ameliorated in virtual pointing – especially given that the physical aspect of the task involved mainly rotations about the wrist rather than elbow. As a result, the inertial characteristics of the effector were minimized, which may have lessened the role of the effector at the longer distances (see also Bohan et al., 2003). Because we did not directly compare real and virtual pointing in the current work, it is difficult to resolve these two explanations. Nevertheless, given that previous work has also reported effects specific to feedback processing in VR (Lin & Woldegiorgis, 2018; Liu et al., 2009; Nieuwenhuizen et al., 2009), we argue that these findings support the first hypothesis.

It remains to be determined precisely why visual feedback processing is impaired in virtual environments. That the display quality does not match actual reality is one possibility, and future work should examine pointing performance across multiple HMDs varying in parameters such display resolution, size of the field of view, pixel response time, lag, and refresh rate. While VR display quality issues have been studied in the context of visual perception (see Thompson, et al., 2011 for a review), there has yet to be a systematic investigation of the effects of these variables on fast and accurate visually-guided actions.

In terms of the interaction techniques of linear ray-cast and parabolic pointing, our second hypothesis predicted that the pointers would act as virtual effectors, and this manipulation would mimic manipulations of effector constraints. We observed this to be the case, with the differences in performance localized to the primary phase of the movements. We did not predict which pointing technique would result in better performance, yet our findings point to the linear ray-cast technique in this regard. Anecdotally, we observed participants in the parabolic condition pulling back on the controller when reaching to longer distance targets, which we dubbed the fishing rod effect, as the movement resembled an angler jerking up on a fishing rod. We suspect that participants did not expect the depth variation that accompanied the angling movement of the controller, and had some difficulty locating and controlling the pointer subsequently. As a result, participants struggled to control the depth of the pointer. This behavior is consistent with psychological research on naive physics knowledge (McCloskey & Kohl, 1983), but it has yet to be determined whether these errors can be overcome with training and experience. The relationship between physics knowledge and successful use of parabolic pointers is potentially a fruitful avenue of research.

Pointing performance in VR is constrained in many of the same ways as real-world pointing. There are task constraints that affect the informational load of the task, the effect of which appear to be magnified in VR. The underlying causal factors for this effect warrant future research. There are effector constraints that affect the dynamic scale of the task, the effect of which may depend on the nature of the controller and pointing technique. Parabolic pointing is particularly constrained by the confusing relationship between controller angle and the length of the parabola. The current work has potentially only scratched the surface in terms of the number of interaction techniques that may be implemented in 3D pointing, not to mention the variety of controllers available. Future studies on the effects of learning, adaptation, and expertise with regard to both task constraints and pointing techniques are warranted.

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