Differences in Performance Characteristics for Head-Turn Selection of Receding and Approaching Moving Targets in 3D Virtual Space

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Abstract

Selecting moving targets by head rotation is a common operation in virtual reality (VR). However, moving targets include both receding and approaching motions, and determining the differences in temporal characteristics between these two types of operations is of significant importance for designing efficient user interfaces. This study selected 17 participants to quickly and accurately place a spherical cursor into a horizontally moving spherical target in VR through head rotation, while varying initial distance, target tolerance, and target speed. Total time results showed that operations for receding motion were more difficult, the effects of initial distance and target tolerance on receding and approaching motions were similar, while the effect of target speed on the two types of motion was opposite. Furthermore, by dividing the cursor movement process into acceleration, deceleration, and adjustment phases, results revealed that acceleration and deceleration times for receding motion were greater than those for approaching motion, but adjustment times for the two types of motion were similar, and only the effect of target tolerance on the two types of motion was consistent. Finally, a functional model of total time with respect to the three factors was constructed, which successfully explained the operational temporal characteristics of the two types of motion. This study demonstrates that receding and approaching motions have different operational temporal characteristics, providing important reference for independent interaction design for the two types of motion.

Full Text

The Different Characteristics of Human Performance in Selecting Receding and Approaching Targets by Head Rotation in 3D Virtual Environments

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Abstract

Selecting moving targets by rotating the head is a common operation in virtual reality (VR). Moving targets involve two fundamental directions: receding motion (moving away from the user) and approaching motion (moving toward the user). Understanding the temporal characteristics of these two movement types is crucial for designing efficient user interfaces. This study recruited 17 participants to perform a task in VR where they used head rotation to quickly and accurately place a spherical cursor inside a horizontally moving spherical target, while manipulating initial distance, target tolerance, and target velocity. Total time results revealed that receding motion was more difficult to operate than approaching motion. Initial distance and target tolerance had similar effects on both movement types, while target velocity exerted opposite effects. Further analysis divided the cursor movement into acceleration, deceleration, and correction phases. Results showed that receding motion required longer acceleration and deceleration times than approaching motion, but the correction times were comparable between the two. Only target tolerance had consistent effects on both movement types across all phases. Finally, we constructed a functional model relating total time to the three factors, successfully explaining the temporal characteristics of both movements. This study demonstrates that receding and approaching motions have distinct operational time characteristics, providing important reference for independent interaction design for each movement type.

Keywords: moving target, head rotation control, movement trajectory, human performance modeling, human-computer interaction
Classification Code: B849

Introduction

Head rotation interaction has become an important interaction method in VR. On one hand, it serves as the primary interaction mode for many portable VR and AR devices that do not provide handheld controllers, such as Samsung GearVR, Google Cardboard, and Microsoft HoloLens [?, ?]. On the other hand, head rotation interaction functions as the main interaction method when both hands are occupied in many VR applications, such as interacting with displays through head rotation during virtual surgical training [?]. Numerous applications based on head rotation interaction involve selecting moving targets, such as pedestrians and vehicles. To design efficient user interfaces, it is essential to understand the key factors affecting head rotation-based selection of moving targets and establish functional relationships between operation time and these influencing factors.

Previous research has thoroughly investigated the operational time characteristics of selecting static targets through head rotation in VR [?, ?, ?, ?]. These studies found that movement time (MT) conforms to Fitts' Law with respect to initial distance (A) and target width (W):

$$\mathrm{MT} = a + b\log_2\left(\frac{2A}{W}\right)$$

where a and b are fitted constants. However, this model cannot explain the operational characteristics of selecting moving targets because operation time is also affected by target velocity. Moreover, moving targets have directionality, with receding and approaching motions being two common movement patterns. The processes of selecting receding targets (receding motion) and approaching targets (approaching motion) differ fundamentally. In receding motion, operators must pursue the target at a speed greater than the target' s speed, whereas in approaching motion, operators must intercept the target. If interception fails, the subsequent operation transforms into a pursuit of a receding target [?, ?, ?]. Therefore, receding and approaching motions may exhibit different operational time characteristics.

No studies have been found that investigate head rotation for selecting moving targets in three-dimensional space. However, a few researchers have examined the operational time characteristics of selecting moving targets using hand control on two-dimensional screens, though the differences between receding and approaching motions remain uncertain. The operational time characteristics of receding motion are relatively straightforward: decreasing target size or increasing target velocity both increase operation time [?, ?, ?]. In contrast, the operational time characteristics of approaching motion are more complex.

Some studies have found that approaching motion shares similar operational time characteristics with receding motion, where decreasing target width or increasing target velocity increases the difficulty of selecting approaching targets [?, ?]. These studies have also proposed functional models to quantify the operational time characteristics of approaching motion. For instance, Jagacinski et al. (1980) had participants use a joystick to control a vertical line (cursor) to place it within a target composed of two vertical lines that gradually approached.

They found that movement time was affected by initial distance (A), target width (W), and target velocity (V), and established the following model to describe the functional relationship between operation time and the three factors [?]:

$$\mathrm{MT} = c + d\frac{A}{V} + e\frac{W}{V}$$

where c, d, and e are fitted constants. Later, Hoffmann proposed a two-stage model for approaching motion based on Fitts' Law:

$$\mathrm{MT} = a + b\frac{A}{V} + c\frac{W}{V} + K\frac{1}{V}$$

where a, b, c, and K are fitted constants. Hoffmann argued that $\frac{A}{V}+\frac{W}{V}$ primarily reflects the movement distance coverage stage, while $\frac{1}{V}$ reflects the correction stage [?].

On the other hand, a few studies have found that increasing target velocity reduces the difficulty of selecting approaching targets, contrary to the results for receding motion. In Ilich' s (2009) master' s thesis, participants used a mouse to capture a ring moving horizontally on a computer screen, which would bounce off screen edges and reverse direction. He classified the selection process into receding and approaching motions based on the relative positions of the cursor and target at task onset and completion. He found that when targets were medium to large in size, operation time showed a decreasing-then-increasing trend as target velocity increased [?]. These results suggest that the operation time of approaching motion may be interactively influenced by target size and target velocity. Additionally, the difference in operational difficulty between receding and approaching motions remains controversial. Ilich (2009) showed that the difference in operational difficulty between the two movements was jointly affected by target size and target velocity. When targets moved slowly or quickly, operation times for receding and approaching motions were very similar. However, when targets moved at medium speed and were smallest in size, approaching motion took longer than receding motion; in other cases, receding motion took longer [?]. In a later similar study using the same target velocities and even smaller target sizes, researchers failed to replicate these findings. The new study showed that when targets moved horizontally, receding motion took longer than approaching motion across all target sizes [?]. The discrepancy between these two studies may be due to incomplete separation of receding and approaching motion processes in their tasks, meaning their results cannot fully reflect the independent operational time characteristics of each movement type.

Recent studies have explored other aspects of selecting moving targets, such as the effects of different factors on endpoint distributions for receding and approaching motions [?, ?] and the effects of different factors on predicting target arrival at designated areas [?]. However, these studies did not examine temporal variations in operation time, which is the most commonly used metric in user interface design. While some studies have focused on operation time, such as the effects of visual feedback and delay [?, ?] and methods for improving the efficiency of selecting moving targets [?, ?, ?, ?], these studies did not fix target movement direction and thus did not separate receding and approaching motions.

To date, the differences in operational time characteristics between receding and approaching motions remain unclear. First, both initial distance and target size are important factors affecting target selection. Decreasing target size and increasing initial distance both increase the difficulty of receding and approaching motions, but whether these factors differentially affect the two movement types is unknown. Second, while it has been established that increasing target velocity increases the difficulty of selecting receding targets, there is no consensus on how target velocity affects performance in selecting approaching targets. The process of selecting static targets comprises two stages: a ballistic stage and a correction stage. In the ballistic stage, the cursor moves rapidly from the starting point to the vicinity of the target, primarily related to initial distance. The correction stage involves real-time adjustment of cursor position and alignment with the target based on visual feedback, influenced by both target size and initial distance [?, ?, ?, ?]. Some studies also support that selecting moving targets involves two stages [?, ?], with target velocity affecting both stages. Increasing target velocity increases the actual movement distance for receding motion but decreases it for approaching motion, while also increasing the difficulty of aligning with the target.

Based on these differences in operational processes between receding and approaching motions, we propose the following hypotheses. **Hypothesis 1**: In the ballistic stage, approaching motion should have shorter operation time than receding motion because the actual movement distance is shorter. In the correction stage, approaching motion should also have shorter correction time than receding motion because the target is closer, making adjustment less difficult. Based on these two-stage results, approaching motion should have lower total time. **Hypothesis 2**: As target velocity increases, the total time for approaching motion should show a U-shaped trend, first decreasing then increasing. Increasing target velocity reduces ballistic stage time but increases correction stage time. Previous research shows that head rotation interaction has the characteristics of slow movement speed and high stability [?, ?]. We therefore hypothesize that small increases in target velocity provide greater benefit to the ballistic stage, leading to decreased total operation time. However, further increases in target velocity cause correction time to increase rapidly, exceeding the time saved in the ballistic stage, causing total time to begin rising. **Hypothesis 3**: The inflection point velocity of the U-shaped curve for approaching motion is also affected by target size; smaller targets have higher adjustment difficulty and thus lower inflection point velocity.

The purpose of this study is to explore the differences in operational time characteristics between selecting receding and approaching targets through head rotation in VR. We employed a common placement task in VR, where participants position a spherical cursor into a designated spherical target [?, ?, ?]. Since placement task research shows that operation time is systematically affected by target tolerance (the size difference between cursor and target) rather than target size itself [?, ?, ?], we manipulated different levels of target tolerance. Additionally, we varied initial distance (the straight-line distance between cursor and target center) and target movement velocity. Deng et al. (2019) used head rotation to complete a static target placement task in VR and divided the cursor movement process into acceleration, deceleration, and correction phases, where the sum of acceleration and deceleration phases represented the ballistic stage [?]. In this study, we adopted Deng et al.' s method to divide cursor movement into three phases and systematically analyze how the three factors differentially affect receding and approaching motions. Finally, we propose a functional model describing the relationship between total operation time and the three factors for both receding and approaching motions. Our findings will provide important assistance for interaction design in VR.

Methodology

Participants

We used G*Power 3.1 software to estimate sample size, setting alpha level at 0.05 and statistical power at 0.95. Based on effect sizes from relevant literature ($\eta^2 > 0.2$) [?], we calculated that a minimum of 12 participants were needed. Referencing similar studies that primarily used 15-20 participants, we recruited 17 university students (7 males; age: 22.5 ± 2.5 years; height: 165.8 ± 6.4 cm). All participants were right-handed, healthy, had normal or corrected-to-normal vision, and no neck movement disorders. All participants signed informed consent forms approved by the university' s academic ethics committee before the experiment and received appropriate compensation afterward.

Apparatus and Materials

This study used an Oculus Rift CV1 immersive VR headset (monocular resolution: 1080$×$1200; refresh rate: 90 Hz; maximum field of view: 110°). The headset included an inertial measurement unit (IMU)-based rotation sensor and an infrared optical position sensor, capable of real-time acquisition of 6-degree-of-freedom spatial position (x, y, z, yaw, pitch, roll) (Figure 1a). The experimental program was developed using Unity3D and C# and run on a Dell Alienware Area computer (operating system: Windows 8.1; CPU: Intel Core i7; graphics card: NVIDIA GeForce GTX TITAN) to ensure the program ran at the headset' s maximum refresh rate.

Figure 1. Schematic diagram of experimental design. (a) Experimental setup and participant operation diagram, showing a participant wearing a VR headset

while seated at a computer; (b) Experimental stimulus scene, with a yellow ball as the cursor and a white semi-transparent large ball as the target; (c) Schematic diagram of parameters and operation process for selecting a receding target, including initial distance (angular size corresponding to the straight-line distance between cursor and target center), target tolerance (angular size difference between cursor and target), and target velocity, with cursor size fixed at 4° and target moving horizontally away from the cursor; (d) Operation process diagram for selecting an approaching target, with target moving horizontally toward the cursor.

The experimental scene and stimuli are shown in Figure 1. In a virtual space, a gray plane measuring 2000 m × 2000 m was placed vertically as a background. In front of the plane, a yellow ball served as the cursor and a white semi-transparent ball served as the target. The cursor and target appeared randomly on the left (right) and right (left) sides of the participant' s forward view at eye height. The target moved at a constant velocity in the horizontal direction either away from or toward the cursor.

To determine parameter ranges, we conducted a pilot experiment. Results showed that cursor size and head rotation direction had no significant effects on operation time or accuracy, so they were not included as experimental factors. Considering the maximum target value and cursor visibility in receding motion, we fixed the cursor diameter at 4°. To ensure effective task completion (error rate below 30%), the maximum target velocity was set at 2 m/s, target tolerance was no less than 4°, and the maximum initial distance was 40°. The minimum target velocity was set at 0.5 m/s to allow quick recognition of target motion. In approaching motion, to ensure high probability of successful interception at maximum velocity, the minimum initial distance was set at 20°. Additionally, the maximum target tolerance was set at 8°, as target selection difficulty was already low. Considering total trial count, fatigue levels, and the importance of target velocity, we set 4 levels of target velocity, 3 levels of target tolerance, and 2 levels of initial distance, equally spaced between maximum and minimum values.

In summary, this experiment employed a 2 (target movement direction: receding, approaching) × 4 (target velocity: 0.5 m/s, 1 m/s, 1.5 m/s, 2 m/s) × 2 (initial distance: 20°, 40°) × 3 (target tolerance: 4°, 6°, 8°) four-factor within-subjects repeated measures design. The cursor diameter was approximately 0.22 m (4°). The linear sizes of target tolerance were approximately 0.22 m, 0.33 m, and 0.43 m. Target size was the sum of target tolerance and cursor size, with diameters of 8° (0.43 m), 10° (0.54 m), and 12° (0.65 m). The linear distances for initial distance were 1.06 m and 2.18 m. This study used angular measurements for parameters because angular measures in three-dimensional space incorporate the effect of depth on operation time [**?**, **?**, **?**].

Procedure

The experiment consisted of 23 blocks, with each block containing all 48 experimental condition combinations, presented in random order within blocks. To avoid visual fatigue, neck fatigue, and dizziness from prolonged VR headset use—related research recommends continuous VR use of less than 1 hour [?]—the experiment was conducted over two days. The first day was practice, completing 8 blocks; the second day was the formal experiment, completing the remaining 15 blocks. Practice and formal testing each lasted approximately 1 hour. Participants rested for 1 minute between blocks. Since individuals differ in their susceptibility to VR-induced dizziness, participants could rest at any time between trials if they felt discomfort to ensure data quality was not affected.

As shown in Figure 1a, participants sat in a fixed chair, wore the VR headset, and held a controller. In the virtual scene, participants saw two spheres: a yellow ball on the left (right) side of the view served as the cursor, and a white semi-transparent large ball on the right (left) side served as the target (Figure 1b). A green dot in the center of the participant' s view represented head orientation. When participants turned their head to look at the cursor in the scene and pressed a button on the controller, the cursor color changed from yellow to red, and cursor movement was controlled by head rotation. Simultaneously, the target began moving at the set velocity in the horizontal direction either away from or toward the cursor. Participants then turned their head to place the cursor completely inside the target as quickly and accurately as possible, pressing the controller button to confirm task completion. If the cursor was not completely inside the target sphere, the task failed and the program played an error sound. The experimental program recorded completion time, cursor movement trajectory, and error rate for each task, with a trajectory sampling rate of 90 Hz.

Data Analysis

Based on testing experience, under normal operation, total task completion time ranged between 300 ms and 2500 ms. Completion times greater than 2500 ms likely resulted from program lag, while times less than 300 ms likely resulted from participant errors such as double-clicking. Therefore, we excluded trials with total completion times greater than 2500 ms or less than 300 ms, deleting 25 trials (0.20% of total trials).

We processed cursor velocity trajectories. First, we applied a 10 Hz low-pass filter to trajectory data to reduce noise effects [?, ?]. Second, we divided cursor velocity trajectories into three phases: acceleration, deceleration, and correction. The phase segmentation method was modified from static target selection methods to accommodate moving target selection [?]. The boundary between acceleration and deceleration phases was the point of maximum cursor velocity. The boundary between deceleration and correction phases was the first point satisfying any of the following three criteria, with velocity less than the midpoint between target velocity and maximum cursor velocity (for receding motion) or less than half of maximum cursor velocity (for approaching motion) (Figure 2):

1. **Receding motion:** The first point where cursor velocity changes from greater than target velocity to less than target velocity. **Approaching motion:** The first point where the direction of cursor velocity changes.
2. The first point where cursor velocity is less than 10% of maximum velocity.
3. The point where cursor acceleration remains negative but its absolute value is less than 0.1 times the maximum acceleration value.

The boundary between deceleration and correction phases must consider positive and negative velocity values. Since target movement was horizontal, we used the direction of cursor velocity in the horizontal dimension to represent overall velocity direction [**?**].

We conducted ANOVA on the total average completion time across 15 blocks to examine practice or fatigue effects. Results showed that although the main effect of block order was significant ($F(3.10, 49.59) = 6.12, p = 0.001, \eta^2 = 0.28$, Greenhouse-Geisser corrected), completion time did not continuously decrease or increase with block order. Bonferroni post-hoc tests on block order revealed that only Block 1 completion time (984 ± 161 ms) was significantly higher than Block 12 (857 ± 121 ms, $p = 0.005$) and Block 13 (842 ± 101 ms, $p = 0.030$); no significant differences existed between other blocks. This result indicates no practice or fatigue effects, so we used the average of all 15 blocks for subsequent analyses.

This study used SPSS Statistics 21.0 for multi-factor repeated measures ANOVA, applying Greenhouse-Geisser correction for results violating sphericity assumptions. Time analysis used only correct trials.

Figure 2. Example of cursor velocity trajectory and three-phase segmentation for one participant selecting a receding target (a) and an approaching target (b).

Results

Error Rate

Figure 3. Error rates for task completion. Error rates for selecting receding and approaching targets as functions of initial distance (a), target tolerance (b), and target velocity (c). Error bars represent standard error.

As shown in Figure 3, maximum error rates for receding and approaching motions were below 30%, with average error rates of only $7.38 \pm 3.31\%$ and $5.85 \pm 3.24\%$, respectively, indicating participants could perform the task well. A four-factor (target movement direction, target velocity, initial distance, target tolerance) repeated measures ANOVA on error rates revealed significant main effects of target velocity ($F(1.62, 25.88) = 40.13, p < 0.001, \eta^2 = 0.72$) and target tolerance ($F(1.19, 19.05) = 71.23, p < 0.001, \eta^2 = 0.82$). Error rates for both movements increased with target velocity and decreased with target tolerance. Initial distance had opposite effects on the two movements, with a significant interaction between initial distance and target movement direction ($F(1, 16) = 21.92, p < 0.001, \eta^2 = 0.58$). Simple effects analysis showed that for receding motion, error rate at 40° initial distance was higher than at 20° ($p = 0.013$), while for approaching motion, error rate at 20° was higher than at 40° ($p < 0.001$). The main effect of target movement direction was significant ($F(1, 16) = 8.01, p = 0.012, \eta^2 = 0.33$), with receding motion showing significantly higher average error rate than approaching motion, though the difference decreased as target tolerance increased, evidenced by a significant interaction between target movement direction and target tolerance ($F(1.31, 21.01) = 7.19, p = 0.009, \eta^2 = 0.31$). Additionally, a significant three-way interaction existed among target movement direction, initial distance, and target velocity ($F(1.57, 25.15) = 11.94, p = 0.001, \eta^2 = 0.43$). When initial distance was 20°, error rates for receding and approaching motions became increasingly similar as target velocity increased; particularly at 2 m/s, approaching motion error rate exceeded receding motion. Conversely, when initial distance increased to 40°, the difference in error rates between the two motions increased with target velocity. No other interaction effects were significant.

Total Movement Time

Figure 4. Total movement time for task completion. Total operation time for selecting receding and approaching targets as functions of initial distance (a), target tolerance (b), and target velocity (c).

Repeated measures ANOVA on total completion time for correct trials examined differential effects of the three factors on receding and approaching motions. Results are shown in Figure 4. The main effect of target movement direction was significant ($F(1, 16) = 99.64, p < 0.001, \eta^2 = 0.86$), with receding motion average total completion time (986 ± 120 ms) significantly higher than approaching motion (784 ± 124 ms), indicating greater difficulty in selecting receding targets. Main effects of initial distance ($F(1, 16) = 221.85, p < 0.001, \eta^2 = 0.93$) and target tolerance ($F(1.04, 16.61) = 69.94, p < 0.001, \eta^2 = 0.81$) were significant, with both factors having similar effects on the two movements: completion time increased with initial distance and decreased with target tolerance. However, a significant interaction existed between target movement direction and initial distance ($F(1, 16) = 8.59, p = 0.01, \eta^2 = 0.35$), with approaching motion time increasing slightly faster than receding motion, indicating a greater effect of initial distance on approaching motion. The interaction between target movement direction and target tolerance was not significant ($F(1.13, 18.07) = 1.60, p = 0.225$), suggesting consistent effects of target tolerance on both movements.

In contrast to the first two factors, target velocity had opposite effects on receding and approaching motions, with a significant interaction between target velocity and target movement direction ($F(1.44, 22.96) = 60.74, p < 0.001, \eta^2 = 0.79$). Separate ANOVAs for each movement showed that receding motion operation time increased rapidly with target velocity ($F(1.38, 22.11) = 48.49, p < 0.001, \eta^2 = 0.75$), while approaching motion operation time decreased rapidly ($F(1.16, 18.59) = 12.43, p = 0.002, \eta^2 = 0.44$). As target velocity decreased, moving targets gradually became static targets, making the difficulty of receding and approaching motions increasingly similar; at 0.5 m/s, no significant difference existed between the two movements ($p = 0.996$). Additionally, a significant three-way interaction existed among target movement direction, target velocity, and initial distance ($F(1.86, 29.82) = 4.03, p = 0.031, \eta^2 = 0.20$). Separate analyses for each movement revealed a significant interaction between initial distance and target velocity for approaching motion ($F(1.79, 28.57) = 3.72, p = 0.041, \eta^2 = 0.19$). When initial distance was 20°, approaching motion showed a weak U-shaped curve: operation time decreased rapidly then increased slowly as target velocity increased from 0.5 m/s to 1.5 m/s to 2 m/s, supporting Hypothesis 2 (Figure 4c). However, we found no evidence that the inflection point velocity of the U-shaped curve was affected by target tolerance, as the interaction between target tolerance and target velocity was not significant ($F(3.07, 49.13) = 0.70, p = 0.563$), rejecting Hypothesis 3. No other interaction effects were significant.

Three-Phase Movement Times

Figure 5. Three-phase movement time results. Acceleration phase time (a), deceleration phase time (b), and correction phase time (c) as functions of initial distance (top), target tolerance (middle), and target velocity (bottom).

We further compared differences between receding and approaching motions across the three phases. Results are shown in Figure 5. In the acceleration phase, the main effect of target movement direction was significant ($F(1, 16) = 162.32, p < 0.001, \eta^2 = 0.91$), with receding motion acceleration time (386 ± 58 ms) greater than approaching motion (255 ± 33 ms), indicating receding motion required more time to reach peak velocity. Initial distance had opposite effects on the two movements, with a significant interaction between target movement direction and initial distance ($F(1, 16) = 179.00, p < 0.001, \eta^2 = 0.92$). Separate ANOVAs showed that increased initial distance decreased receding motion acceleration time ($F(1, 16) = 50.26, p < 0.001, \eta^2 = 0.76$) but increased approaching motion acceleration time ($F(1, 16) = 90.03, p < 0.001, \eta^2 = 0.85$). Target velocity also had opposite effects, consistent with total time results, with a significant interaction between target movement direction and target velocity ($F(1.46, 23.42) = 55.82, p < 0.001, \eta^2 = 0.78$). Additionally, a significant three-way interaction existed among target movement direction, target velocity, and initial distance ($F(2.08, 33.29) = 28.26, p < 0.001, \eta^2 = 0.64$), with slightly different patterns of time differences between 20° and 40° initial distances for receding and approaching motions. Target tolerance main effect was not significant

($F(2, 32) = 0.04, p = 0.962$), and the interaction between target tolerance and target movement direction was not significant ($F(1.30, 20.86) = 0.80, p = 0.41$), indicating acceleration time was unaffected by target tolerance. However, a significant three-way interaction existed among target movement direction, initial distance, and target tolerance ($F(2, 32) = 3.94, p = 0.029, \eta^2 = 0.20$), with slightly different effects of initial distance on receding and approaching motions across target tolerance levels. No other interaction effects were significant (Figure 5a).

In the deceleration phase, receding motion deceleration time (342 ± 29 ms) remained greater than approaching motion (272 ± 33 ms), with a significant main effect of target movement direction ($F(1, 16) = 119.31, p < 0.001, \eta^2 = 0.88$). Main effects of target velocity ($F(1.75, 28.07) = 97.85, p < 0.001, \eta^2 = 0.86$) and initial distance ($F(1, 16) = 335.25, p < 0.001, \eta^2 = 0.95$) were significant, with significant interactions between target movement direction and target velocity ($F(1.95, 31.11) = 67.77, p < 0.001, \eta^2 = 0.81$) and between target movement direction and initial distance ($F(1, 16) = 38.03, p < 0.001, \eta^2 = 0.70$), indicating different effects of initial distance and target velocity on the two movements. Unlike the acceleration phase, initial distance had similar effects on both receding ($F(1, 16) = 128.83, p < 0.001, \eta^2 = 0.89$) and approaching ($F(1, 16) = 309.80, p < 0.001, \eta^2 = 0.95$) motions, increasing deceleration time, though approaching motion time increased faster. Increasing target velocity rapidly decreased approaching motion correction time ($F(1.76, 28.20) = 195.38, p < 0.001, \eta^2 = 0.92$) but only slightly affected receding motion ($F(1.73, 27.66) = 11.28, p < 0.001, \eta^2 = 0.41$). Additionally, a significant three-way interaction existed among target movement direction, initial distance, and target velocity ($F(3, 48) = 4.37, p = 0.008, \eta^2 = 0.21$), with slightly different patterns of time differences between 20° and 40° initial distances for receding and approaching motions. Although the main effect of target tolerance was significant ($F(2, 32) = 7.65, p = 0.002, \eta^2 = 0.32$) and the interaction between target tolerance and target movement direction was significant ($F(2, 32) = 6.36, p = 0.005, \eta^2 = 0.28$), the maximum average difference in deceleration time between receding and approaching motions was very small (18 ms and 2 ms, respectively), indicating minimal practical effect of target tolerance on deceleration time. No other interaction effects were significant (Figure 5b).

In the correction phase, unlike the previous two phases, the main effect of target movement direction was not significant ($F(1, 16) = 0.001, p = 0.974$), with nearly identical average correction times for receding (258 ± 107 ms) and approaching (259 ± 132 ms) motions. However, the two movements still showed differences at specific levels of initial distance and target velocity, with significant interactions between target movement direction and initial distance ($F(1, 16) = 31.22, p < 0.001, \eta^2 = 0.66$) and between target movement direction and target velocity ($F(1.69, 26.97) = 8.34, p = 0.002, \eta^2 = 0.34$). Separate analyses showed that receding motion correction time was related to both initial distance ($F(1, 16) = 129.81, p < 0.001, \eta^2 = 0.89$) and target velocity ($F(1.30, 20.73) = 25.32, p < 0.001, \eta^2 = 0.61$), while approaching motion correction time was unaffected by initial distance ($F(1, 16) = 0.14, p = 0.711$). Although approaching motion correction time increased slowly with target velocity, the effect was not significant ($F(1.35, 21.66) = 0.63, p = 0.48$). Additionally, the main effect of target tolerance was significant ($F(1.08, 17.25) = 55.46, p < 0.001, \eta^2 = 0.78$), with correction times for both movements decreasing rapidly as target tolerance increased, and the interaction between target tolerance and target movement direction was not significant ($F(1.32, 21.18) = 0.20, p = 0.728$), indicating consistent effects of target tolerance on adjustment difficulty for both movements. No other interaction effects were significant (Figure 5c).

Model Fitting

Operation time (MT) for receding and approaching motions was affected by initial distance (A), target tolerance (TT), and target velocity (V). We established a functional relationship between operation time and the three influencing factors to quantify the operational time characteristics of both movements. We used data from correct trials and averaged data across all participants for identical conditions. To maintain consistency with target velocity units (m/s), we converted angular measurements of initial distance and target tolerance to linear units. Previous studies have proposed formulas to quantify approaching motion operation time characteristics (Equations 2 and 3). We substituted target tolerance for target width and fitted our data to these equations. Results showed neither equation adequately explained our approaching motion (Equation 2: $R^2 = 0.449$; Equation 3: $R^2 = 0.628$) or receding motion (Equation 2: $R^2 = 0.900$; Equation 3: $R^2 = 0.610$) data, necessitating a new functional model.

Since initial distance and target tolerance affect operation time for moving target selection similarly to static target selection, we modified Fitts' Law (Equation 1) by adding a target velocity parameter. As receding motion completion time increased linearly with target velocity while approaching motion completion time decreased with target velocity, and target velocity showed no strong interaction with initial distance or target tolerance, we included target velocity as an independent parameter in the new model. We propose the following model:

$$\mathrm{MT} = a + b \cdot \mathrm{ID} + c \cdot V^k$$

where a, b, and c are fitted constants, ID is task difficulty, and k is an exponent. When $k = 1$, Equation 4 represents the receding motion model; when $k = -1$, it represents the approaching motion model.

Model fitting results are shown in Figure 6a. Equation 4 fit the receding motion data well ($R^2 = 0.971, p < 0.001$). Using stepwise regression (entry $F \leq 0.05$, removal $F \geq 0.1$) to determine each factor' s contribution, we found V explained 37.1% of variance, while $\log_2\left(\frac{2A}{TT}\right)$ explained the remaining 60.0%. Model coefficients were $k = 1$, $a = 366.1$ (95% CI = [315.1, 417]), $b = 126.5$ (95% CI = [110.5, 142.5]), and $c = 1.1$ (95% CI = [0.93, 1.3]).

Equation 4 also explained 95.2% of variance in approaching motion data ($R^2 = 0.952, p < 0.001$) (Figure 6b). Stepwise regression showed that $1/V$ and $\log_2\left(\frac{2A}{TT}\right)$ explained 31.2% and 63.9% of variance, respectively. Model coefficients were $k = -1$, $a = 122.0$ (95% CI = [50.4, 193.6]), $b = 124.5$ (95% CI = [102.3, 146.7]), and $c = 1.3$ (95% CI = [1.0, 1.6]).

To validate model stability, we randomly split participant data into training and test sets. The training set comprised data from 2/3 of participants (11 people) randomly selected, and we fitted Equation 4 to the training set to predict data from the remaining 1/3 (6 people). We repeated this process 1000 times, obtaining distributions of model fit R^2 for training sets and prediction R^2 for test sets (Figure 6c). Average test set R^2 values were 0.940 for approaching motion and 0.966 for receding motion, very close to the fit results using all data (approaching: $R^2 = 0.952$; receding: $R^2 = 0.971$). For receding motion, all model prediction R^2 values exceeded 0.8, with a mean of 0.941. Although approaching motion model predictions were lower than receding motion, 75% of prediction R^2 values exceeded 0.82, with a mean of 0.855. These results demonstrate that our proposed model is stable and can effectively predict data.

Figure 6. Fitting results of Equation 4 for receding and approaching motion data. (a) Fit to all receding motion data: $\mathrm{MT} = 366.1 + 126.5 \cdot \log_2\left(\frac{2A}{TT}\right) + 1.1 \cdot V$; (b) Fit to all approaching motion data: $\mathrm{MT} = 122.0 + 124.5 \cdot \log_2\left(\frac{2A}{TT}\right) + 1.3 \cdot \frac{1}{V}$; (c) Box plots of model fit R^2 for training sets and prediction R^2 for test sets. Training sets comprised data from randomly selected 2/3 of participants (11 people), and test sets comprised data from remaining 1/3 (6 people). "Train 11" shows R^2 results from 1000 fits to training sets; "Predict 6"shows R^2 results from 1000 predictions to test sets using models from training sets. Top and bottom lines represent maximum and minimum values; box top and bottom represent upper and lower quartiles; horizontal line inside box represents median.

Discussion

Selecting receding and approaching targets through head rotation is common in VR, yet the differences in operational time characteristics between these movements remain unclear. This study analyzed total operation time and further divided cursor movement into acceleration, deceleration, and correction phases to systematically explore differential effects of initial distance, target tolerance, and target velocity on the two movement types. Our results demonstrate that receding and approaching motions share some operational time characteristics while also exhibiting distinct differences. On one hand, target tolerance had consistent effects on both movements, affecting only the correction phase without influencing acceleration or deceleration times. This indicates that participants did not consider target size during rapid cursor movement toward the target, consistent with segmentation results for static target selection [**?**, **?**]. On the other hand, initial distance had different effects on receding and approaching motions. Although total times for the two movements were similar across initial distance levels, significant differences emerged in three-phase operation times.

Initial distance affected all three phases of receding motion but only the acceleration and deceleration phases of approaching motion. Approaching motion correction time was unaffected by initial distance, possibly because during the correction phase, the target appeared near the operator, resulting in consistent cursor alignment difficulty.

Furthermore, target velocity had different effects on receding and approaching motions. In receding motion, increased target velocity lengthened acceleration and correction phases, increasing total operation time, supporting previous research [?, ?, ?]. In approaching motion, increased target velocity shortened acceleration and deceleration phases while lengthening the correction phase. Since time saved in the first two phases exceeded time added in the correction phase, total time for approaching motion decreased. However, our results differ from previous studies that found operation time generally increased rapidly with target velocity [?, ?, ?]. Two factors may explain these discrepancies. First, different tasks may yield different results. For instance, in Ilich (2009) and Hajri et al. (2011), receding and approaching motions were not completely separated, whereas our study used completely independent movements [?, ?]. Second, different interaction methods have different operational characteristics, which may also lead to different results. Previous studies primarily used mouse or joystick interaction, but head rotation interaction shows significantly different completion times compared to joystick and mouse operations [?, ?, ?]. Head rotation interaction may have better stability than joystick and mouse, making correction time less susceptible to target velocity effects. Additionally, we found a U-shaped relationship between approaching motion operation time and target velocity when initial distance was 20°. When target velocity was within a certain range, time saved in acceleration and deceleration phases exceeded added correction time; beyond a threshold, this advantage disappeared. Figure 5 shows that when target velocity increased from 1.5 m/s to 2 m/s, acceleration and deceleration times decreased by only 4 ms and 14 ms, respectively, while correction time increased by 66 ms. This result supports Hypothesis 2 and previous findings [?]. However, we found no evidence that the U-shaped curve’ s inflection point velocity was affected by target tolerance, rejecting Hypothesis 3, possibly because target tolerance was not small enough to create high correction difficulty.

This study also revealed differences in operational difficulty between receding and approaching motions. In terms of total time, selecting receding targets took longer, indicating higher difficulty. However, examining the three phases showed that time differences between the two movements primarily occurred in acceleration and deceleration phases, while correction times were nearly identical. This partially supports Hypothesis 1, which predicted longer operation times for receding motion in all three phases. First, acceleration and deceleration times are determined by actual movement distance. Since receding motion has a longer actual movement distance, it requires more time in these phases, and faster target velocity increases the distance difference between the two movements, amplifying time differences—supporting Hypothesis 1. Second, in the correction phase, receding targets are farther away than approaching targets, suggesting greater alignment difficulty, yet correction times were very similar, contradicting Hypothesis 1. This may be due to the good stability of head-controlled interaction [?, ?], making correction time less susceptible to influence. However, our results show that when target velocity exceeded 1.5 m/s, receding motion correction time began to exceed approaching motion correction time, suggesting that with further velocity increases, the difference may become significant.

This study established a functional model relating total operation time to the three factors to describe operational time characteristics of receding and approaching motions. We used data from correct trials because error rates were low (receding: 7.61±3.38%; approaching: 5.96±3.26%), similar to related studies [?, ?]. However, in static target selection, some researchers have considered error trials, using effective target width (W_e) instead of actual target width in model fitting. Effective target width is calculated from the distribution of all cursor endpoint positions under identical conditions:

$$W_e = 2 \times 4.133 \times \sigma$$

where σ represents the standard deviation of all endpoint positions. Researchers argue that effective target width more accurately reflects the speed-accuracy trade-off in operation [?, ?]. We calculated effective target tolerance (TT_e) and substituted it into Equation 4, obtaining model fits of $R^2 = 0.799$ for receding motion and $R^2 = 0.858$ for approaching motion, lower than fits using actual target tolerance from correct trials (receding: $R^2 = 0.971$; approaching: $R^2 = 0.952$). This suggests that effective target size may not be suitable for functional models of moving target selection; when error rates are low, using correct trials with actual target tolerance more accurately describes operational time characteristics.

Our findings have multiple applications. First, the distinct operational time characteristics of receding and approaching motions suggest that 3D interaction designers should consider separate user interface designs for each movement type to improve operation efficiency and user experience. Second, since multiple factors significantly affect moving target selection difficulty, our functional model quantifies task difficulty, helping designers effectively select parameter ranges. Third, results can help understand real-world processes of selecting moving targets through other means, such as athletes hitting flying discs, providing reference for related sports training. Finally, our model may have applications in preliminary detection of neck rotation-related disorders, such as comparing performance differences between healthy individuals and those with neck pain [?, ?], providing reference for disease prevention.

This study has limitations. First, we only considered horizontal target movement and did not verify results for vertical or depth movements. When targets move in different dimensions, head rotation directions differ, and research shows performance differences exist for head rotations in different directions [?, ?], potentially yielding different results. Second, although angular parameters for initial distance and target size incorporate depth effects on performance [?, ?, ?], our target velocity was linear. Whether linear target velocity has the same differential effect on receding and approaching motions at different depths remains unverified. Therefore, our conclusions currently apply only to a depth of 3 m; future research will explore different depths to extend our findings.

Conclusion

This study systematically analyzed the effects of initial distance, target tolerance, and target velocity on selecting receding versus approaching targets through head rotation in VR using total operation time and three-phase operation times (acceleration, deceleration, and correction). Results demonstrated that initial distance and target velocity had different effects on receding and approaching motions, while target tolerance had consistent effects. Additionally, receding motion was more difficult, but difficulty differences primarily occurred in acceleration and deceleration phases. Based on these operational time characteristics, we proposed a new model to explain operation time for both movements, providing a method to quantify and evaluate human performance characteristics in selecting moving targets through head rotation.

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Note: Figure translations are in progress. See original paper for figures.