Landing Windows Method as Soft Visual Constraints for Mid-Air Interactions

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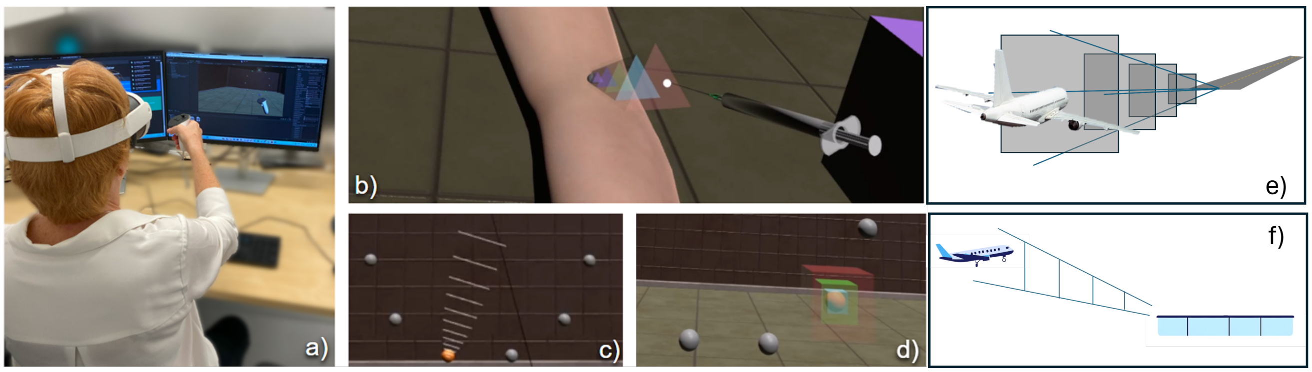

Figure 1: a) A participant performing TASK-1 using the virtual hand interaction method. b) An example scene from the catheter insertion task (TASK-3) with the LANDING WINDOWS METHOD in Virtual Reality. c) An example scene from the ray cast interaction method using the LANDING WINDOWS METHOD in TASK-2. d) An example scene from the virtual hand interaction method using the LANDING WINDOWS METHOD in TASK-1. e) Landing windows in ILS. When the plane approaches the runway, the windows decrease in size. The plane is aligned to pass through these windows for a safe landing. f) A side view of landing windows in ILSs.

ABSTRACT

Accurate object interaction has been a longstanding research topic for 3D mid-air interactions. In this paper, we propose an approach inspired by landing systems used in aircrafts while approaching the runway, called *landing windows*, to increase user accuracy in mid-air interactions. In the virtual environment, we created soft visual constraints that get smaller as the controller gets closer to the targets, called LANDING WINDOWS METHOD. We evaluated this method with 18 participants across three tasks in Virtual Reality (VR): virtual hand interaction, ray casting interaction, and a medical catheter insertion application, as well as a post-user study in Augmented Reality (AR). The results showed that LANDING WINDOWS METHOD increases user accuracy for virtual hand and ray casting interaction methods, as well as for medical catheter insertion in VR and AR. Participants also preferred the proposed method for complex tasks. We hope that our findings can be used by practitioners, developers, and researchers to improve user performance in tasks requiring accuracy.

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CCS CONCEPTS

• **Human-centered computing → Graphics input devices**; **Interactive systems and tools**; **Pointing**.

KEYWORDS

Mid-Air, Fitts' law, Ray Casting, Virtual Hand, Interaction Accuracy

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1 INTRODUCTION

Accurate object interaction in mid-air presents several challenges due to the complexity required to effectively manipulate virtual objects. One major challenge is the absence of physical feedback [44], which in real-world tasks conveys vital cues like texture, resistance, and object boundaries [2]. Moreover, depth perception in head-mounted displays (HMDs) is less accurate than in the real world, making it harder to judge distances and spatial relationships, often leading to pointing and selection errors [8]. In addition, prolonged mid-air interactions cause ergonomic issues like "gorilla arm fatigue," leading to discomfort and reduced precision as muscles tire [24]. All such hardware, software, and cognitive limitations might negatively affect user accuracy during mid-air interactions.

Accurate pointing in VR and AR environments is essential for applications where even small positional deviations can have significant consequences. For example, in medical surgical planning, accurate placement of surgical screws during spine procedures is critical to avoid damaging surrounding nerves, blood vessels, or spinal structures, directly impacting patient safety and surgical outcomes [69, 74]. In industrial assembly training, workers must learn to align components within tight tolerances to ensure product reliability and safety [50]. In aerospace and automotive maintenance, technicians often operate within constrained spaces where accuracy determines both efficiency and operational integrity [42]. From a human–computer interaction perspective, accuracy in 3D interaction also shapes the user's sense of agency, control, and immersion, e.g., errors in object placement or selection accuracy can lead to frustration, reduced task confidence, and disengagement, especially in skill-critical scenarios [3].

An approach to increase user accuracy is visual guides that highlight target positions, which can improve spatial understanding and increase accuracy in mid-air tasks [2, 43]. However, designing effective visual cues in mid-air is challenging, as users need intuitive guidance without physical constraints [27, 43]. One possible solution is **soft visual constraints**, which are designed as subtle cues that encourage desired behaviour without enforcing strict rules [55]. These cues can include highlighting target areas, colour gradients, or visual boundaries to encourage intuitive adjustments in user actions without imposing rigid restrictions, enabling seamless and flexible interactions.

In this paper, we propose and evaluate a soft visual constraint method, called "Landing Windows Method", to improve user accuracy in mid-air interactions. Inspired by aviation's Instrument Landing Systems (ILS), which is defined as a specific time period and spatial zone during landing that helps ensure the aircraft follows the correct trajectory for a precise landing [19, 28], our method uses shrinking virtual objects to visually guide users toward the target. These visual windows act as soft constraints, narrowing as users approach the target. As the guides visually get smaller, users slow down to go through a narrow path, leading to slower movements and higher accuracy, i.e., speed-accuracy trade-off.

The spatial and temporal soft visual constraints of Landing Windows Method can be applied to different interaction techniques and tasks. Thus, in this paper, we evaluated Landing Windows Method with three different tasks. In the first two user tasks, we designed soft visual constraints for the two most common interaction techniques, virtual hand and ray casting methods [1, 44], and evaluated them with an ISO-9241-411 multidirectional selection task [36]. We selected this task as it is commonly used to compare different interaction techniques and provides a benchmark metric to compare accuracy [1]. To show the generalizability of the method, we implemented Landing Windows Method to catheter insertion in the third task. We chose this task as it is a real-world medical simulation task that requires high accuracy [7]. As there are differences in designs for the first two user tasks and the final task, we do not recommend comparing the results across tasks, and compared only between interaction techniques. Our contributions are:

- Designing soft visual constraints based on Landing Windows Method to increase user accuracy for virtual hand and ray casting methods.
- Developing soft visual constraints based on Landing Windows Method to improve accuracy in catheter insertion tasks in Virtual Reality (VR).
- Demonstrating that using Landing Windows Method significantly increases user accuracy in mid-air interactions.
- Demonstrating that the Landing Windows Method improves user experience for pointing tasks.

2 PREVIOUS WORK

2.1 Virtual Hand and Ray Casting Interaction

For objects in peri-personal space, interaction often involves moving the hand near the target [52]. A common approach is the virtual hand method, e.g., a hand-held controller maps to a virtual hand, enabling intuitive interaction [32, 75]. However, limited depth cues in VR can reduce the accuracy and effectiveness of this technique [8, 32].

When virtual objects are beyond immediate reach, interaction is referred to as distant object manipulation [52]. A common distant interaction technique is ray casting, which projects a virtual ray from the user's hand or controller [21, 44]. Some other distant interaction techniques include Go-Go [59], which extends the user's virtual arm, and HOMER [21], which combines ray casting with hand-based manipulation by attaching the virtual hand to the selected object.

Manipulating distant objects in virtual environments is challenging due to the lack of exact depth cues that are naturally available in the real world [10, 32, 71]. Since HMDs rely mainly on visual cues, replicating real-world depth and perspective remains difficult, making perception of objects in the correct position challenging [8, 54]. Additionally, HMD tracking can introduce limitations, such as jitter, disrupting fine motor control and reducing interaction accuracy [14, 15]. These limitations can significantly impact user accuracy when interacting with distant targets.

Since virtual hand and ray casting are among the most widely used interaction techniques [1, 44], we implemented and evaluated Landing Windows Method with both to assess its impact on user accuracy in virtual environments.

2.2 Speed and Accuracy in Mid-air Interactions

The speed-accuracy trade-off refers to the inverse relationship between the speed of a response or action and its accuracy, e.g., faster actions often reduce accuracy, while slower actions tend to increase it [47]. Researchers have explored the speed-accuracy trade-off using methods like predictive modelling [25], assistive technologies [5], and haptic feedback [57].

Prior studies have explored ways to enhance accuracy with virtual hand and ray casting techniques. For instance, Malekmakan et al. [48] reported higher task completion time but lower error rates with virtual hand compared to ray casting. Gerig et al. [32] showed that virtual hand interaction with an HMD improves performance in depth-related tasks over 2D displays. Yu et al. [75] found that both ray casting and virtual hand (via grabbing gesture) were faster and more accurate than hand extension techniques. Finally, Mifsud et al. [51] found that ray casting performed better than a pointing gesture and touchpad in AR in terms of error rate and throughput.

Optimizing speed and accuracy is key to improving user engagement and performance. Most studies focused on dynamic speed adjustment algorithms that slow down movement for accuracy [22, 31, 38, 53, 64]. In this study, we also aimed to improve user accuracy through the speed-accuracy trade-off, acknowledging that this may impact task execution time. As participants focus on visual guides to increase accuracy, they may slow down, potentially increasing accuracy at the cost of longer completion times.

2.3 Visual Guides

Visual guides have been widely explored in virtual environments for navigation, tracking, and spatial awareness. For example, SeeingVR enhanced object edges and added directional cues to support low-vision users in VR games [77]. Speicher et al. [66] used coloured markers, arrows, and highlights to guide attention in 360°videos. Other studies have applied visual feedback to support proprioception by providing spatial references to virtual targets [26, 41, 68, 76], though these often focused on avatar representations. Schneider et al. [63] used visual guides to assist with the placement of a ventricular drain in AR for neurosurgical procedures. In contrast, our work introduced *soft visual constraints* that guide users toward targets by visually indicating target positions in the environment.

2.4 Fitts' Law and ISO 9241:411

Fitts' law is a mathematical formula to model the rapid movement time between alternating targets [30]. Equation 1 shows the Shannon's capacity formulation for Fitts' law [45].

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

In Equation 1, A represents the target distance and W represents the width of a target. The coefficients a and b are determined empirically through regression analysis. The logarithmic term in the equation represents the Index of Difficulty (ID), which indicates the task complexity. In this paper, we also used throughput (based on effective measures), as defined in the ISO 9241-411:2012 standard [36] to measure user performance, as in Equation 2.

$$\text{Throughput} = \frac{ID_e}{MT}, \quad ID_e = \log_2\left(\frac{A_e}{W_e}{+}1\right) \quad (2)$$

In Equation 2, ID_e is the effective index of difficulty, measuring the precision of the user [36]. A_e is the effective distance and W_e is the effective target width. W_e is calculated as W_e = 4.133 * SD_x [36]. SD_x is the standard deviation of the selection coordinates along the task axis and is used to evaluate the accuracy of the participants. The notation SD_x is in line with the notation from ISO documents [36]. Here, we define accuracy as the *"closeness of agreement between a measured quantity value and a true quantity value"* [36], and error as any unintended action, decision, or outcome. We focus on human errors in selection tasks, and do not focus on tracking errors. In this paper, the measurement quantity is the cursor position, and the true quantity is the target position.

Previous studies used Fitts' law to evaluate user motor performance for different interaction methods [8, 13, 67]. In this paper, we also used the same approach to evaluate user performance for the Landing Windows Method with virtual hand and raycasting.

3 LANDING WINDOWS METHOD

3.1 Landing Windows in Aviation

In the autopilot systems, a "landing window" refers to the spatial and temporal zone where the aircraft must align correctly to safely land using Instrument Landing Systems (ILS) [19], as shown in Figure 1(e). The ILS provides two key signals: the localizer for lateral alignment and the glide slope for vertical descent [58]. These signals define a landing window that widens with distance from the runway [28], as shown in Figure 1(f). During an ILS approach, the autopilot continuously adjusts the aircraft's trajectory to stay within this window, ensuring accurate alignment within the glide path.

The landing window is especially critical during the final approach, where *accurate* positioning within the narrow ILS boundaries is essential for a safe landing, e.g., any significant deviation may trigger a missed approach. To ensure safety, the landing window includes built-in margins that help maintain a stabilized approach and reduce landing risks, thus allowing for a high degree of accuracy and reliability during approach and landing. In this paper, we also implemented a similar approach used in ILS to improve the accuracy of the user interaction in mid-air by visualizing virtual boundaries that get smaller as they get closer to the target.

In this paper, we draw an analogy between the landing window technique used in aviation for accurate navigation and user interaction in virtual environments. In aviation, ILS guides aircraft through a series of *"windows"* which are defined by signals from instruments on the runway. These *"windows"* narrow as the aircraft approaches the runway, ensuring accurate alignment. In the meantime, the plane also gets slower to accurately navigate through *"windows"*. Similarly, we use these windows as soft visual constraints in a virtual environment: as the cursor (aircraft) moves toward the target (runway), the guides become tighter, promoting higher accuracy.

3.2 Motivation & Hypotheses

Given that landing windows increase spatial accuracy in 3D space, we propose adapting and evaluating this methodology for a virtual environment. We think that a similar approach can significantly improve user accuracy during task execution. Therefore, this paper investigates the following hypotheses:

H1. *The Landing Windows Method improves user accuracy when interacting with objects in a virtual environment compared to without it.* Just as landing windows narrow as an aircraft nears the runway, using progressively smaller visual guides can aid spatial alignment and enhance pointing accuracy.

H2. *Participants prefer using the Landing Windows Method in virtual environments.* Since this method aims to improve accuracy, participants may perceive performance benefits and favour it during mid-air interactions.

4 USER STUDY

4.1 Participants

We recruited 18 participants (7 female, 9 male, and 2 identifying with other genders), with an average age of 29.67 ± 11.1. Seventeen participants were right-handed, and one was left-handed. All had either normal (n = 9) or corrected-to-normal vision (n = 9). Regarding VR experience, 10 participants reported using VR 0–2 times, 3 reported 2–4 times, 1 reported 8–10 times, 3 reported 10+ times, and 1 preferred not to answer.

4.2 Apparatus

The experiment was conducted on a desktop PC equipped with a 12^{th} Gen Intel(R) Core(TM) i7-12700F processor running at 2.1GHz, 16 GB RAM, and an NVIDIA GeForce RTX 3060 Ti graphics card. We used Meta Quest 3 as the HMD. Visual guides for the Landing Windows Method were designed in Blender 4.0, and the virtual environment was developed using Unity 2021.3.5f1..

4.3 Procedure

Before the experiment, participants completed a consent and demographic form. They were then shown a demo of each task and given time to practice and familiarize themselves with the system. During the experiment, participants sat at a desk and wore an HMD connected to a PC (Figure 1(a)). In the virtual environment, they were placed in an empty room designed to provide monocular depth cues, such as linear perspective, texture gradients, and depth contrast. After each task, participants were asked which visual guides they preferred. Throughout, they were instructed to be as fast and accurate as possible and aim for the centre of the target.

Landing Windows Method is a spatial and temporal visual constraint independent from the task. Thus, to increase the validity, we evaluated Landing Windows Method with 3 different tasks. Task-1 focused on peri-personal space, where targets were within arm's reach. Task-2 evaluated distal pointing performance using ray casting for far-distance targets. As these tasks involve distinct interaction zones, we conducted separate user studies and designed task-specific visual guides. Task-3 explored a medical training application of Landing Windows Method to assess its relevance in real-world VR scenarios.

4.3.1 Task-1, Virtual Hand. In Task-1, we used the virtual hand interaction technique with the ISO 9241-411 [36] multidirectional task to evaluate the Landing Windows Method. The virtual hand interaction method was selected because it is the most commonly used technique in VR studies [2] and 36% of XR studies use ISO 9241:411 to assess virtual hand interaction [1]. In Task-1, we implemented the ISO 9241-411 multidirectional selection task, using 11 spheres arranged in a circular layout 0.44 m from the user—based on prior work [11, 17]. For the virtual hand interaction, participants held the controller in their dominant hand using a power grip, i.e., fingers wrapped around the controller with the palm in contact and the thumb applying counter pressure [13], as shown in Figure 1(a). During the task, the target sphere appeared orange while the others remained grey. Participants moved the virtual controller to intersect the target, which turned blue on collision (Figure 3(b)). To avoid the "Heisenberg effect of spatial interaction", selection was triggered by pressing the space bar [20, 73].

When a target was selected, it turned green if the cursor was within its bounds; otherwise, it turned red, and an error sound at Middle C (C4) played [18]. Upon selection, the next target sphere turned orange, as shown in Figure 3(a). Each sphere served as the target only once, and once all were selected, a new set was instantiated. This process was repeated nine times, using three target sizes (0.01 m, 0.015 m, 0.02 m) and three target distances (0.25 m, 0.3 m, 0.35 m). Based on Equation 1, these combinations resulted in ID values ranging from 3.75 to 5.16.

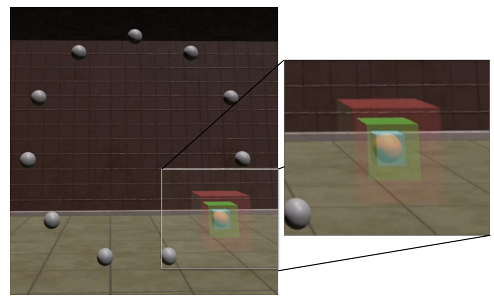
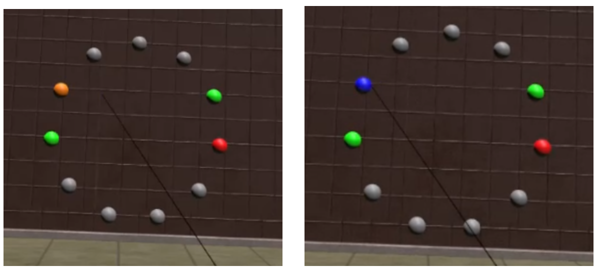


Figure 2: ISO 9241:411 multidirectional selection task and Landing Windows Method on the target for Task-1.

In Task-1, participants performed the ISO 9241-411 multidirectional selection task both with and without the Landing Windows Method. When enabled, the target was surrounded by three nested visual guide cubes, based on the target in 3D, of varying colours and transparency levels: a large red cube (8.62% transparency), a medium green cube (14.9%), and a small blue cube (41.96%), as shown in Figure 2. These transparency levels were determined by pilot studies based on the task, number of spheres, and their sizes, and ensured clear visibility despite overlapping geometry. The dimensions of the visual guide cubes were relative to the size of the targets and were chosen so that the visual guides did not overlap with the neighbouring targets. We chose cubes as 3D visual guides to differentiate from target spheres. As the participant's cursor entered each visual guide cube, that cube disappeared, allowing focus to shift to the next. Once the cursor reached the target sphere, all cubes disappeared, and the target turned blue. When the Landing Windows Method was not activated, the procedure was the same, but without visual guide cubes.

4.3.2 Task-2, Ray casting. In Task-2, we used the same setup as Task-1 but positioned the target spheres at 1.33 m from the participant, based on previous work [11, 17], and evaluated the Landing Windows Method using the ray casting interaction technique (Figure 3). Ray casting was selected because it is the second most commonly used technique in VR studies [2] and 36% of XR studies use ISO 9241:411 to assess ray casting [1]. Participants held the controller in their dominant hand using a precision grip, involving only the fingertips with minimal palm contact. This grip enables fine motor control through coordinated pressure from the thumb, index, and middle fingers [13].

In Task-2, we used the angular target sizes and distances from Task-1 to compute the Euclidean values. This allowed us to position targets at different depths while maintaining consistent visual perception of size and distance across both tasks [11]. As in Task-1, participants selected the target by moving the cursor into the sphere and pressing the space bar; however, in Task-2, the cursor was attached to the tip of a ray projected from the controller.



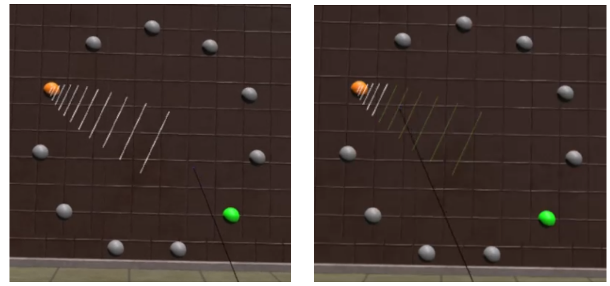
(a) (b)

Figure 3: The orange sphere indicates the target, the green spheres indicate targets that were selected correctly, and the red sphere indicates a target that was not selected correctly. The grey spheres have not yet been targets. (a) The target is orange before the cursor at the tip of the ray is inside it. (b) The target turns blue when the cursor is inside it.

When the Landing Windows Method was enabled in Task-2, 12 visual guide lines were placed along the path from the center of the sphere circle to the target (Figure 4(a)). We used lines for our design to illustrate the landing window from a side view. The number of these visual guides and their positions were determined by pilot studies based on the target sizes and target distances. As the cursor got closer, we placed the guides more frequently so that the participant could accurately "land" on the center of the target. The length of each line and the spacing between them decreased as they approached the target. When the ray cursor collided with a line, it turned green to indicate a successful pass (Figure 4(b)). Participants were instructed to pass through as many visual guides as possible before reaching the target. If a guide was missed, they continued the task without backtracking, as returning would affect task time. Collisions were not recorded, so missing a guide had no penalty. When the Landing Windows Method was disabled, the task remained identical, but the visual guides were not shown.

4.3.3 Task-3, Catheter Insertion. In Task-3, we evaluated the Landing Windows Method within a medical catheter insertion task in VR, replicating previous studies [56, 60]. Unlike training studies [56, 60], our focus was on improving user accuracy during the approach phase with speed-accuracy trade-off, as in the pointing stage in 3D user interfaces. Thus, we did not aim to assess training effectiveness or learning outcomes. Instead, the goal was to explore whether the Landing Windows Method could be applied to a real-world VR simulator application to increase accuracy.

In Task-3, the virtual controller was replaced with a syringe model, held in the participant's dominant hand using a precision grip to mimic how nurses typically handle syringes (Figure 5(a)).



(a) (b)

Figure 4: Landing Windows Method for Task-2. (a) Guides are white before the cursor collides with them. (b) Guides turn green once the cursor collides.

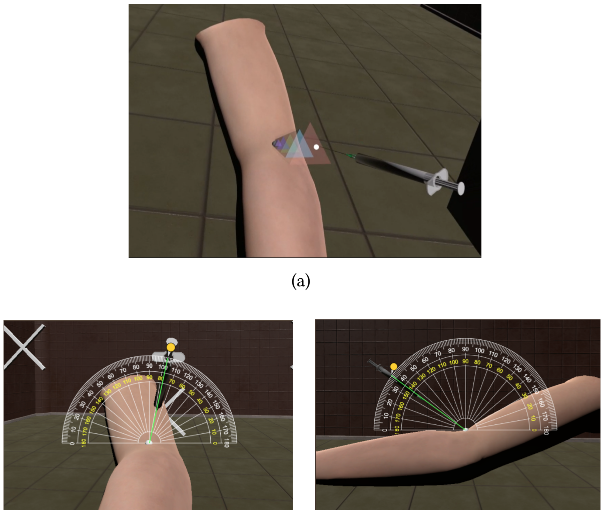
A purple cube was placed beside the dominant hand and served as a trigger to start or reset the experiment. When the syringe tip (indicated by a white sphere cursor) entered the purple cube, a virtual arm appeared in a fixed position and angle, with a target sphere located at the cubital fossa to mark the syringe insertion point [4]. When the cursor collided with the target sphere, it turned blue, consistent with the feedback used in Task-1 and Task-2.

Participants aimed to insert the syringe tip into the target at an angle of $102.15° \pm 3.12$ on the axial plane and $36° \pm 6.80$ on the sagittal plane [7], as shown in Figure 5. These angles were recommended by Barzegari et al. [7]. Participants used the space bar to record task completion, and they repeated 10 insertions per round.

After each selection, the virtual arm disappeared, and participants were required to re-insert the syringe into the purple cube to re-instantiate the arm. This ensured that participants reset their position between trials rather than maintaining the same insertion angle. The purple cube was positioned to mimic the natural action of picking up a syringe from a tray or table. After completing each repetition, all objects were placed at the same location and angle. For repetition without Landing Windows Method, we did not render any visual guides to replicate Barzegari et al. [7] study.

The visual guides of Landing Windows Method in Task-3 consisted of five nested prisms aligned at 36° on the sagittal plane and 102.15° on the axial plane. These prisms decreased in size as they neared the target. The largest was red (8.62% transparency), followed by baby blue (41.96%), green (14.9%), dark blue (37.65%), and the smallest, lavender (7.84%). These transparency values were selected with pilot studies to ensure all nested prisms remained visible, though they can be adjusted for different tasks. As participants inserted the syringe, each prism disappeared sequentially until the target sphere was reached. We chose to use a prism as we expected an easier location of the center of a triangle than a square. In the condition without Landing Windows Method, the task remained the same, but without visual guides. The virtual arm was positioned relative to the HMD.

At the end of Task-3, participants filled a NASA TLX [34] and a System Usability Scale Questionnaire (SUS) [37] after completing a task with or without Landing Windows Method.



(a)

(b) (c)

Figure 5: (a) Example of Task-3 showing the visual guides activated. (b) Axial view of the arm with the syringe at a 102.15°angle. (c) Sagittal view of the arm with a syringe at a 36°angle [7].

4.4 Experimental Design

The user study involved three distinct tasks. For each task, participants completed the experiment under two visual guide (VG_2) conditions: with Landing Windows Method and without Landing Windows Method.

For Task-1 and Task-2, participants performed each task with three different target sizes (TS_3) and three different target distances (TD_3), resulting in a total of $TS_3 \times TD_3 = 9$ Index of Difficulties (ID_9). Participants repeated each (ID) 11 times. In total, each participant completed $VG_2 \times ID_9 \times 11$ repetitions for each task. For Task-1 and Task-2, we collected and analyzed data on time, error rate, throughput, SD_x, and ID_e, as in previous work [8, 15].

In Task-3, participants completed the experiment under two visual guide conditions (VG_2). We recorded task time, error rate, and continuous accuracy along the x- and y-axes. Task time was measured from the moment the controller tip exited the purple cube until it collided with the target on the arm. Error rate was defined by whether the cursor was within the target area at the time of selection. Continuous accuracy on the x-axis and y-axis was calculated as the angular deviation from the recommended insertion angle on the referenced plane, both based on Berzegari et al. [7].

Since the tasks and the design of the visual guides differed, a full-factorial design across tasks and visual guides was not feasible. Instead, we employed a Latin square design to ensure counterbalancing, applying it separately to the tasks and visual guides.

Participants were given the opportunity to take breaks between tasks and during the experiment while the task reset, as often as needed. On average, the entire experiment took 45 minutes.

5 RESULTS

The data was analyzed using Repeated Measures (RM) ANOVA on SPSS 24. The data was considered normally distributed if Skewness (S) and Kurtosis (K) were within [-1, +1] [33, 49]. Otherwise, if the log-transform still did not yield a normal distribution, we performed the Aligned Rank Transform on the original data [72] before performing RM-ANOVA. For post-hoc analyses, we used the Bonferroni method and applied Huynh-Feldt correction when $\epsilon <$ 0.75. The figures display the mean values, with error bars indicating the standard error of the mean. After analyzing the outcomes of each task separately, we proceeded to Fitts' law analysis, followed by an analysis of the user experience results. For *brevity*, we only focused on significant results. For the ISO 9241:411 multidirectional selection task, we used mean-of-means to analyze the data [65].

5.1 Task-1 Results

In Task-1, we asked participants to select a target with a virtual hand interaction technique. While time and throughput data had a normal distribution (S = 0.96, K = 0.98, and S = 0.27 and K = 0.98, respectively), the error rate, SD_x, and ID_e did not exhibit a normal distribution, even after log-transformation. Thus, we used ART [72] before data analysis. The results are shown in Table 1 and Figure 6.

Table 1: Virtual Hand Results

	Visual Guide	ID	Visual Guide x ID
Time	**F(1,17)=10.275, p <0.001**, η^2 = 0.377	**F(4.36,74.13)=26.74, p <0.05**, η^2 = 0.611	F(8,136)=1.752, p = 0.05, η^2 = 0.093
Error rate	**F(1,17)=9.664, p <0.01**, η^2 = 0.362	**F(8,136)=6.818, p <0.001**, η^2 = 0.286	F(8,136)=0.928, p = 0.928, η^2 = 0.052
Throughput	**F(1,17)=7.103, p <0.05**, η^2 = 0.295	**F(8, 136)=9.622, p <0.001**, η^2 = 0.361	**F(8,136)=4.346, p <0.001**, η^2 = 0.204
SDx	**F(1,17)=48.425, p <0.001**, η^2 = 0.74	**F(8, 136)=7.491, p <0.001**, η^2 = 0.306	**F(8, 136)=11.504, p <0.001**, η^2 = 0.404
IDe	F(1,17)=1.901, p = 0.186, η^2 = 0.101	**F(8, 136)=17.114, p <0.001**, η^2 = 0.502	F(8, 136)=1.364, p = 0.21, η^2 = 0.074

As illustrated in Table 1 and Figure 6, we observed a significant difference in visual guides for time, error rate, throughput, and SD_x. According to these results, participants were faster, made fewer errors, and had a higher throughput performance without visual guides. On the other hand, we observed a higher accuracy when using Landing Windows Method.

In Task-1, participants used the virtual hand interaction technique. Results showed that while the visual guides improved discrete accuracy, participants were slower, made more errors, and had reduced throughput. This aligns with speed-accuracy expectations, as the guides were designed to prioritize accuracy. Prior work has shown that increased accuracy often leads to slower movements [47], and visualizations can introduce a speed-precision trade-off that affects overall performance time [9].

5.2 Task-2 Results

In Task-2, we asked participants to perform an ISO 9241-411 multidirectional selection task using the ray casting interaction technique. While throughput data had a normal distribution (S = 0.45, K = -0.66), time had a normal distribution after log transform (S = 0.43, K = 0.007). The error rate, SD_x, and ID_e did not exhibit normal

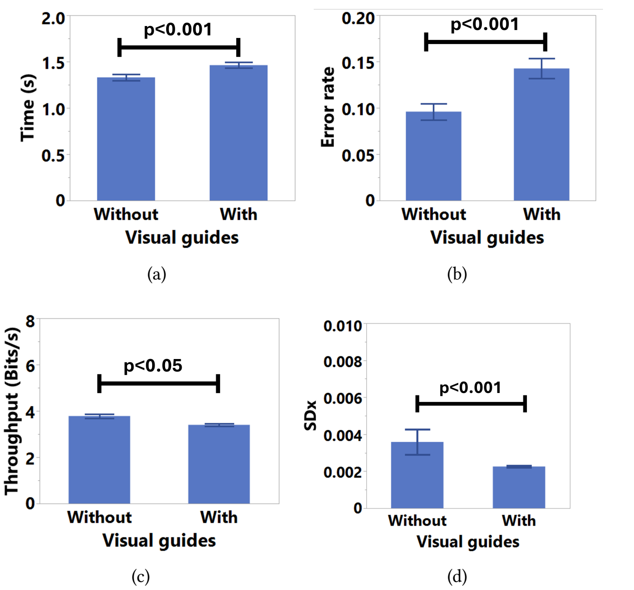


Figure 6: Task-1 results for (a) time, (b) error rate, (c) Throughput, and (d) SD_x. For brevity, we report significant results.

Table 2: Ray Casting Results

	Visual Guide	ID	Visual Guide x ID
Time	**F(1,17)=15.871, p <0.001**, η^2 = 0.483	**F(1, 17)=58.898, p <0.001**, η^2 = 0.775	F(8,136)=1.726, p = 0.98, η^2 = 0.092
Error rate	F(1,17)=0.06, p <0.809, η^2 = 0.04	**F(8,136)=13.850, p <0.001**, η^2 = 0.449	F(8,136)=0.684, p = 0.705, η^2 = 0.039
Throughput	**F(1,17)=15.602, p <0.01**, η^2 = 0.479	**F(8, 136)=11.063, p <0.001**, η^2 = 0.394	F(8,136)=0.894, p = 0.523, η^2 = 0.05
SDx	**F(1,17)=56.128, p <0.001**, η^2 = 0.768	**F(8, 136)=13.147, p <0.001**, η^2 = 0.436	**F(8, 136)=6.606, p <0.001**, η^2 = 0.280
IDe	F(1,17)=.124, p = 0.729, η^2 = 0.007	**F(8, 136)=5.133, p <0.001**, η^2 = 0.232	F(8, 136)=1.628, p = 0.122, η^2 = 0.087

distribution even after log-transformation, so we used ART [72]. The results are shown in Table 2 and Figure 7. According to the results, participants were faster and had a higher throughput performance without visual guides. On the other hand, their accuracy significantly increased when using Landing Windows Method.

In Task-2, participants used the ray casting interaction method with and without the Landing Windows Method. This design was inspired by the side view of ILS landing windows, as shown in Figure 1(f). The results showed improved accuracy with the visual guides, but –– as with the virtual hand –– participants were slower and had reduced throughput. This likely occurred because participants were instructed to pass through as many visual guidelines as possible before reaching the target, encouraging them to focus on moving through the guides that were getting smaller as they got closer to the target. This also led to a speed-accuracy trade-off.

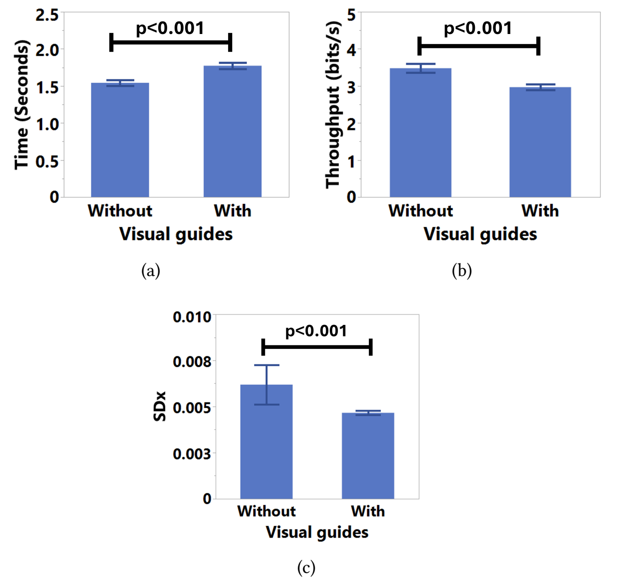


Figure 7: Task-2 results for (a) time, (b) Throughput, and (c) SD_x. For brevity, we report significant results.

5.3 Fitts' Law Results

We also analyzed the results using Fitts' law formulation [30] in Figure 8. For Task-1, MT can be formulated as MT =-0.74 + 0.46× ID , R^2 = 0.92 for without visual guide condition and MT = -0.19 + 0.37×ID , R^2 = 0.89 for Landing Windows Method. For Task-2, MT can be formulated as MT =-17.87 + 10.08×ID , R^2 = 0.89 for without visual guide condition and MT =-10.46 + 9.55×ID , R^2 = 0.91 for Landing Windows Method.

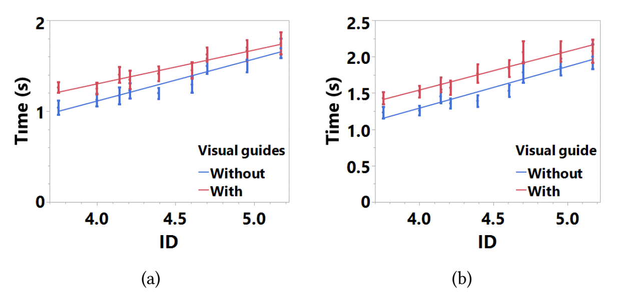


Figure 8: Fitts' law results for (a) virtual hand (Task-1) and (b) ray casting (Task-2) interaction methods.

5.4 Task-3 Results

In Task-3, we had one factor: visual guides, VG_2. Since we collected fewer than 50 data points, we used the Anderson-Darling test to determine whether the data exhibited a normal distribution. The results indicated that none of the dependent variables had a normal distribution (p < 0.05*). Therefore, we used the Wilcoxon signed-rank test to analyze the data.

Table 3: Task-3 (Catheter Insertion Task) Results

	Statistical Analysis
Time	**Z=-2.461, p<0.05**
Error Rate	$Z = 0.794, p = 0.428$
Accuracy X	**Z=-2.635, p<0.001**
Accuracy Y	$Z = -0.328, p = 0.744$

According to Table 3, participants had a higher discrete accuracy in the x-axis with Landing Windows Method (-1.15° ±7.6) compared to without visual guides (-5.76° ±3.5). However, participants were slower with Landing Windows Method (3.65 s ±1.19) compared to those without visual guides (2.98 s ±1.2).

In Task-3, participants performed a catheter insertion task in VR. While the controller differed in size and weight from an actual catheter, prior research has shown that small variations in lightweight tools do not significantly affect motor performance [23]. Participants demonstrated higher continuous accuracy on the x-axis (sagittal plane) when the visual guides were enabled, aligning more closely with the expected 36° insertion angle. This outcome was anticipated, as the Landing Windows Method was designed to support continuous accuracy while slowing down participants. Without these guides, participants lacked real-time feedback on their angle, making it harder to reach the correct orientation despite being shown the target angle during the task demonstration.

5.4.1 User Experience Results. The SUS results showed that with Landing Windows Method, the system received a score of 85 ± 14, while without visual guides, it received a score of 73 ± 14. According to these results, the system with visual guides received an A grade (Best Imaginable), whereas without visual guides, it received a C grade (Good) [6]. Within the SUS questionnaires, we only found a significant difference for "I found the various functions in this system were well integrated" (Z = -1.98, p <0.05). Based on the question results, the participant thought that various functions of Landing Windows Method were better integrated (4.4 ± 0.6) compared to those without visual guides (3.88 ± 1.23). For NASA TLX results, we did not observe any significant differences between any of the subscales.

5.5 User Preferences

After completing Task-1, Task-2, and Task-3, participants were asked to indicate their preferred method for each interaction type. In Task-1, 61.1% of participants (11 participants) preferred using the virtual hand without the Landing Windows Method, and 38.9% (7 participants) preferred the Landing Windows Method.In Task-2, the preference was split equally, with 50% (9 participants) preferring to use the ray casting method with Landing Windows Method and the rest preferring without Landing Windows Method. In Task-3, 72.2% (13 participants) of participants preferred using the syringe with the Landing Windows Method and 27.8% (5 participants) without. These results showed that as the task difficulty increases, participants preferred to use Landing Windows Method.

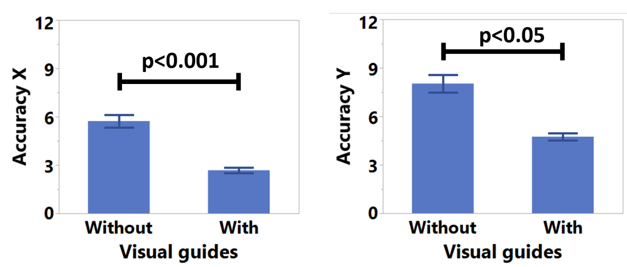
6 POST USER STUDY IN AR

Following the main study, we conducted a short post-user study using the same methodology as Task-3, but in a video see-through AR environment (Figure 9(a)). A pencil was attached to the end of the controller to simulate the catheter tip, and a virtual arm was superimposed onto the experimenter's real arm with a 4-point calibration method (Figure 9(b)). This alignment ensured consistent data collection between participants. As participants pushed the controller toward the experimenter's arm, the pencil lead retracted, providing a basic haptic sensation of catheter insertion. A new group of 18 participants (6 female, 9 male, 3 with other gender identities; M= 27 ± 4.7) took part in this AR post-user study.

(a) (b)

Figure 9: (a) Catheter insertion task with a video see-through AR. (b) Landing Windows Method as seen from HMD.

Results did not show a significant result for time and error rate, yet participants were significantly more accurate along both the x-axis (t(17) = -2.77, p < 0.001) and y-axis (t(17) = -2.44, p < 0.05) as shown in Figure 10. In terms of user preference, 14 out of 18 participants preferred the Landing Windows Method, and 16 reported feeling more accurate while using it.



(a) (b)

Figure 10: Results for Post User Study in AR. (a) Accuracy along the x-axis and (b) accuracy along the y-axis.

7 DISCUSSION

In this paper, we implemented soft visual constraints as visual guides inspired by aircraft ILS, called Landing Windows Method, to increase user accuracy in mid-air interactions. We evaluated our approach with three different tasks varying in interaction type and methods to evaluate the effectiveness of our approach.

In this paper, we define accuracy as the *closeness of agreement between a measured quantity value and a true quantity value* [36], and Landing Windows Method aims to improve this accuracy. For Task-1 and Task-2, we measured the accuracy as the standard deviation of the selection coordinates along the task axis, using the SD_x notation as in [36]. However, we computed these coordinates in 3D for Task-1 and in 2D for Task-2, following prior work [8, 11]. In Task-3, accuracy was measured as the angular deviation between the reference and actual catheter insertion angles, as recommended by [40]. Using multiple accuracy metrics allowed us to demonstrate the applicability of the Landing Windows Method across different task types and measurement approaches.

We also evaluated the Landing Windows Method with a post-user study using a see-through AR system. While the 3 main tasks were in VR, the aim of post user-study was to show the effectiveness of the Landing Windows Method in AR. Results showed that the visual guides improved continuous accuracy on both the X and Y axes without significantly affecting task time or error rate.

In all tasks, enabling Landing Windows Method increased participant accuracy, enhancing spatial perception as they approached the target while reducing speed, i.e., speed-accuracy trade-off. These findings support our hypothesis **H1**: the Landing Windows Method improves user accuracy when interacting with objects in a virtual environment compared to without it.

We observed a higher error rate in Task-1, which is different from accuracy [36]. Since the target sizes were small in the experiment, even if selections fall outside the target, the accuracy metrics may still appear high, which could explain the increased error rate. For instance, we used transparent cubes as visual guides, allowing participants to approach from either the front or the side. However, the smallest cube was positioned around the target sphere, and its disappearance did not guarantee that the cursor was inside the sphere, potentially contributing to higher error rates. While the Landing Windows Method improved spatial accuracy, participants may have focused on the visual guides and target alignment without adequately accounting for depth during selection. In contrast, Task-2 used ray casting, which does not require depth-based hand movement, supporting this speculation.

The ISO 9241-411 multidirectional selection task offers a standardized framework for assessing interaction performance [46] and has been widely used to evaluate various input/output devices and interaction techniques [12, 61, 62, 70]. It is also used for speed-accuracy trade-off analysis [47]. By using the ISO 9241:411 task, we not only evaluated the efficiency of Landing Windows Method but also improved its comparability with other user studies [1].

Although participants preferred the system without the Landing Windows Method in Task-1 and Task-2, they preferred it in Task-3 and the post-user study. Additionally, the visual guides improved the SUS score in Task-3. These findings suggest that the landing window approach is better suited for more complex tasks and offers greater usability. This partially supports our hypothesis **H2**, indicating that participants prefer the Landing Windows Method in virtual environments. We believe that refining the visual guide design for Task-1 and Task-2 could further increase user preference in future studies.

The Landing Windows Method is a soft visual constraint, guiding user interaction through visual cues without imposing strict requirements. *They are spatial and temporal zones, independent of the task.* It enhances accuracy by encouraging users to adjust their movements while slowing down, i.e., speed-accuracy trade-off, but also allows flexibility in how tasks are completed, e.g., participants were not required to pass through every guide. The participant who followed the visual cues tended to slow down, control gross motor movement, and focus on fine adjustments—leading to a natural speed-accuracy trade-off. Since this behaviour was not enforced, we cannot guarantee that all users consistently adopted it. Future work should explore hard visual constraints, where users must pass through each guide, to further investigate these effects.

In this paper, we designed three variations of the Landing Windows Method, each tailored to the specific requirements of its task. In Task-1, we used transparent nested cubes, allowing participants to approach the target from the front or side. Since virtual hand interaction technique allows users to move their hands in 3D space, we decided to use a 3D object. Since the spheres are used for targets, we used cubes for guides. In Task-2, the guides were implemented using ray casting, effectively reducing the dimensional complexity and scene clutter. Since the ray casting allows users to move in 2D, we choose guides as 2D objects. For Task-3 and the post-user study, we adapted the method based on the approach by Barzegari et al. [7]. While the visual designs differed across tasks, they followed a shared principle: the guiding window narrowed as the user approached the target. Due to these design differences, we do not recommend directly comparing results across tasks; instead, comparisons should be made between interaction techniques.

The proposed Landing Windows Method is not an interaction technique itself, but a soft visual constraint that can be integrated into existing techniques and applied in real-world scenarios. Given the widespread use of virtual hand and ray casting in VR [1], these visual guides have the potential for broad applicability. For example, as shown in our AR post-study, the guides can be anchored to a controller or reference point—such as an ultrasound probe—for bimanual tasks in medical contexts. This allows users to align tools like needles or catheters with high precision in 3D space. A relevant application is Hu et al.'s [35] work on medical training. Another example is the precise placement of surgical screws during spine procedures [74]. Beyond medicine, Landing Windows Method can support training systems, such as assembly tasks, where objects must be placed accurately onto predefined targets. Similarly, this method can be used with systems requiring hand tracking.

Overall, to apply the Landing Windows Method to any interaction technique or application, we recommend introducing soft visual constraints as spatial and temporal zones. These zones should progressively shrink as the user approaches the target. To reinforce the interaction, visual feedback should be provided when the user successfully passes through each guide, helping them stay focused and aligned with the target. Navigating through increasingly smaller guides naturally encourages users to slow down, creating a speed-accuracy trade-off that increases accuracy. These visual guides can be tailored to task-specific requirements and adapted for use with various interaction techniques, e.g., the number of visual guides, colours, their sizes, and positions. The values can be found with pilot studies.

8 LIMITATIONS & FUTURE WORK

In this paper, we evaluated the Landing Windows Method in three methods: virtual hand, ray casting, and catheter insertion. However, the methodology of virtual windows shrinking as they near the target should be implemented and tested with other interaction techniques, particularly in scenarios requiring *high accuracy*. Here, we choose virtual hand and ray casting since they are most commonly used interaction techniques in XR [1, 2, 44]. Likewise, varying window sizes should be explored across different virtual objects and task types to better understand their impact on accuracy and usability. Here, we selected these sizes based on our tasks.

We acknowledge that the ergonomics and biomechanical constraints differed across tasks. Participants used a power grip for the virtual hand interaction and a precision grip for the catheter insertion task. Since grip style significantly influences performance [13], directly comparing results between these tasks may lead to misleading conclusions, so we did not analyze them here.

We did not conduct a detailed analysis of ID effects in this study, as these have been extensively examined in prior ISO 9241-411 research [13, 15, 16]. Our findings are consistent with those studies, i.e., higher ID values correspond to increased task difficulty.

In Task-1 and Task-2, we used the same angular target sizes and distances, resulting in an ID range between 3.75 and 5.16. This relatively high ID indicates that the tasks were challenging—appropriate given that the Landing Windows Method was designed to support accurate interaction. In lower ID conditions (i.e., easier tasks), the method may offer limited benefit. Prior work shows that most XR studies focus on ID values between 2.5 and 5 [1], which largely overlaps with our range. Although we used angular parameters consistent with earlier ISO 9241-411 studies [11, 17], we recommend future work to extend the ID range to further evaluate the robustness of the Landing Windows Method.

Here, we had 18 participants, which aligns with the average sample size used in XR ISO 9241-411 studies [1], increasing the comparability of our findings. A priori power analysis was conducted using G*Power [29], and results indicated the required sample size to achieve $\eta^2 > 0.14$ at $\alpha = 0.05$ was N = 18. The significant results in this paper also indicate a high effect size, meaning that our results are robust and likely have a considerable real-world impact.

Furthermore, our participants were part of the general population. Different expertise, task requirements, task execution strategies, and other factors might affect the performance of the Landing Windows Method [39].

We also evaluated the Landing Windows Method in a VR and AR catheter insertion task. While this study does not specifically examine the impact of visual guides on learning, it demonstrates the potential of the Landing Windows Method as a soft visual constraint to enhance accuracy in eye-hand coordination tasks. We also did not evaluate the method with medical experts, since our aim was not to design a training simulator. Future longitudinal studies should explore its effects on learning and assess its integration into training systems, particularly in medical contexts [40].

9 CONCLUSION

In this paper, we introduced and evaluated the Landing Windows Method as a soft visual constraint inspired by aviation to enhance user accuracy in virtual environments. This method refers to spatial and temporal zones independent of the task. We evaluated this method across three tasks: the ISO 9241-411 multidirectional selection task using virtual hand and ray casting techniques, and a catheter insertion task commonly used in medical procedures. We also used a catheter insertion task to replicate the experiment with a see-through augmented reality (AR). Results showed that the Landing Windows Method improved user accuracy across all tasks and was preferred by participants for the catheter insertion task in both VR and AR. Additionally, it increased perceived usability in the VR catheter scenario. These findings suggest that progressively narrowing visual cues can effectively enhance accuracy, offering potential benefits for future VR and AR applications.

REFERENCES

[1] Mohammadreza Amini, Wolfgang Stuerzlinger, Robert J Teather, and Anil Ufuk Batmaz. 2025. A Systematic Review of Fitts' Law in 3D Extended Reality. In *Conference on Human Factors in Computing Systems (CHI '25)*. 25 pages. doi:10.1145//3706598.3713623 To appear.

[2] Ferran Argelaguet and Carlos Andujar. 2013. A Survey of 3D Object Selection Techniques for Virtual Environments. *Computers & Graphics* 37, 3 (2013), 121–136.

[3] Daniel Bachmann, Frank Weichert, and Gerhard Rinkenauer. 2018. Review of three-dimensional human-computer interaction with focus on the leap motion controller. *Sensors* 18, 7 (2018), 2194.

[4] Kanwal Naveen S. Bains and Sarah L. Lappin. 2023. *Anatomy, Shoulder and Upper Limb, Elbow Cubital Fossa*. StatPearls Publishing, Treasure Island (FL). http://europepmc.org/books/NBK459250

[5] Marc Baloup, Thomas Pietrzak, and Géry Casiez. 2019. RayCursor: A 3D Pointing Facilitation Technique based on Raycasting. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–12. doi:10.1145/3290605.3300331

[6] Aaron Bangor, Philip Kortum, and James Miller. 2009. Determining what individual SUS scores mean: Adding an adjective rating scale. *Journal of usability studies* 4, 3 (2009), 114–123.

[7] Hassan Barzegari, Arash Forouzan, Mohammad Ali Fahimi, Behzad Zohrevandi, and Mandana Ghanavati. 2016. Proper angle of sono-guided central venous line insertion. *Emergency* 4, 3 (2016), 155.

[8] Anil Ufuk Batmaz, Mayra Donaji Barrera Machuca, Junwei Sun, and Wolfgang Stuerzlinger. 2022. The Effect of the Vergence-Accommodation Conflict on Virtual Hand Pointing in Immersive Displays. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 633, 15 pages. doi:10.1145/3491102.3502067

[9] Anil Ufuk Batmaz, Michel de Mathelin, and Birgitta Dresp-Langley. 2016. Getting nowhere fast: Trade-off between speed and precision in training to execute image-guided hand-tool movements. *BMC psychology* 4 (2016), 1–19.

[10] Anil Ufuk Batmaz, Mayra Donaji Barrera Machuca, Duc Minh Pham, and Wolfgang Stuerzlinger. 2019. Do Head-Mounted Display Stereo Deficiencies Affect 3D Pointing Tasks in AR and VR?. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. 585–592. doi:10.1109/VR.2019.8797975

[11] Anil Ufuk Batmaz, Moaaz Hudhud Mughribi, Mine Sarac, Mayra Barrera Machuca, and Wolfgang Stuerzlinger. 2023. Measuring the effect of stereo deficiencies on peripersonal space pointing. In *2023 IEEE Conference Virtual Reality and 3D User Interfaces (VR)*. IEEE, 1–11.

[12] Anil Ufuk Batmaz, Aunnoy K Mutasim, Morteza Malekmakan, Elham Sadr, and Wolfgang Stuerzlinger. 2020. Touch the wall: Comparison of virtual and augmented reality with conventional 2D screen eye-hand coordination training systems. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, 184–193.

[13] Anil Ufuk Batmaz, Aunnoy K Mutasim, and Wolfgang Stuerzlinger. 2020. Precision vs. power grip: A comparison of pen grip styles for selection in virtual reality. In *2020 IEEE conference on virtual reality and 3D user interfaces abstracts and workshops (VRW)*. IEEE, 23–28.

[14] Anil Ufuk Batmaz, Mohammad Rajabi Seraji, Johanna Kneifel, and Wolfgang Stuerzlinger. 2021. No Jitter Please: Effects of Rotational and Positional Jitter on 3D Mid-Air Interaction. In *Proceedings of the Future Technologies Conference (FTC) 2020, Volume 2*, Kohei Arai, Supriya Kapoor, and Rahul Bhatia (Eds.). Springer International Publishing, Cham, 792–808.

[15] Anil Ufuk Batmaz and Wolfgang Stuerzlinger. 2019. The Effect of Rotational Jitter on 3D Pointing Tasks. In *Extended Abstracts of the 2019 CHI Conference on*

Human Factors in Computing Systems. 1–6.

[16] Anil Ufuk Batmaz and Wolfgang Stuerzlinger. 2020. Effect of Fixed and Infinite Ray Length on Distal 3D Pointing in Virtual Reality. Extended Abstract, 10 pages. doi:10.1145/3334480.3382796

[17] Anil Ufuk Batmaz, Rumeysa Turkmen, Mine Sarac, Mayra Donaji Barrera Machuca, and Wolfgang Stuerzlinger. 2023. Re-investigating the Effect of the Vergence-Accommodation Conflict on 3D Pointing. In *Proceedings of the 29th ACM Symposium on Virtual Reality Software and Technology* (Christchurch, New Zealand) *(VRST '23)*. Association for Computing Machinery, New York, NY, USA, Article 8, 10 pages. doi:10.1145/3611659.3615686

[18] Anil Ufuk Batmaz, Kangyou Yu, Hai-Ning Liang, and Wolfgang Stuerzlinger. 2022. Improving effective throughput performance using auditory feedback in virtual reality. In *Proceedings of the 2022 ACM Symposium on Spatial User Interaction*. 1–11.

[19] Robert J Bleeg, Henry F Tisdale, Robert M Vircks, and BOEING CO SEATTLE WA. 1972. Inertially Augmented Automatic Landing System: Autopilot Performance with Imperfect ILS Beams. *FAA Final Rep. No. FAA-RD-72-22. Federal Aviation Admin., Washington, DC* (1972).

[20] Doug Bowman, Chadwick Wingrave, Joshua Campbell, and Vinh Ly. 2001. Using pinch gloves (tm) for both natural and abstract interaction techniques in virtual environments. (2001).

[21] Doug A Bowman and Larry F Hodges. 1997. An Evaluation of Techniques for Grabbing and Manipulating Remote Objects in Immersive Virtual Environments. In *Proceedings of the 1997 symposium on Interactive 3D graphics*. 35–ff.

[22] Hugo Brument, Anne-Hélène Olivier, Maud Marchal, and Ferran Argelaguet. 2020. Does the Control Law Matter? Characterization and Evaluation of Control Laws for Virtual Steering Navigation. In *ICAT-EGVE 2020-International Conference on Artificial Reality and Telexistence & Eurographics Symposium on Virtual Environments*. 1–10.

[23] Julien Cauquis, Etienne Peillard, Lionel Dominjon, Thierry Duval, and Guillaume Moreau. 2024. Investigating Whether the Mass of a Tool Replica Influences Virtual Training Learning Outcomes. *Transactions on Visualization & Computer Graphics (TVCG)* (2024).

[24] Noshaba Cheema, Laura A. Frey-Law, Kourosh Naderi, Jaakko Lehtinen, Philipp Slusallek, and Perttu Hämäläinen. 2020. Predicting Mid-Air Interaction Movements and Fatigue Using Deep Reinforcement Learning. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA,) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–13. doi:10.1145/3313831.3376701

[25] Logan D Clark, Aakash B Bhagat, and Sara L Riggs. 2020. Extending Fitts' law in three-dimensional virtual environments with current low-cost virtual reality technology. *International Journal of Human-Computer Studies* 139 (2020), 102413.

[26] Diane Dewez, Ludovic Hoyet, Anatole Lécuyer, and Ferran Argelaguet. 2022. Do you need another hand? investigating dual body representations during anisomorphic 3d manipulation. *IEEE Transactions on Visualization and Computer Graphics* 28, 5 (2022), 2047–2057.

[27] Brygida Dzidek, William Frier, Adam Harwood, and Richard Hayden. 2018. Design and evaluation of mid-air haptic interactions in an augmented reality environment. In *Haptics: Science, Technology, and Applications: 11th International Conference, EuroHaptics 2018, Pisa, Italy, June 13-16, 2018, Proceedings, Part II 11*. Springer, Springer International Publishing, Cham, 489–499.

[28] John D Ellis. 2003. A review and analysis of precision approach and landing system (PALS) certification procedures. (2003).

[29] Franz Faul, Edgar Erdfelder, Albert-Georg Lang, and Axel Buchner. 2007. G* Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior research methods* 39, 2 (2007), 175–191.

[30] Paul M Fitts. 1954. The information capacity of the human motor system in controlling the amplitude of movement. *Journal of experimental psychology* 47, 6 (1954), 381.

[31] Mucahit Gemici, Wolfgang Stuerzlinger, and Anil Ufuk Batmaz. 2024. Object Speed Control with a Signed Distance Field for Distant Mid-Air Object Manipulation in Virtual Reality. In *2024 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. IEEE, 465–474.

[32] Nicolas Gerig, Johnathan Mayo, Kilian Baur, Frieder Wittmann, Robert Riener, and Peter Wolf. 2018. Missing Depth Cues in Virtual Reality Limit Performance and Quality of Three Dimensional Reaching Movements. *PLoS one* 13, 1 (2018), e0189275.

[33] Joseph F Hair Jr, William C Black, Barry J Babin, and Rolph E. Anderson. 2014. Multivariate Data Analysis.

[34] Sandra G Hart. 1986. NASA task load index (TLX). (1986).

[35] Yingjie Hu, Jing Xiao, Xiao He, Tingting Qin, Li Wan, and Wenlong Yao. 2022. Comparison of the Learning Curves of Ultrasound-Guided In-Plane Needle Placement Among Four Different Puncture Modes: A Randomized, Crossover, Simulation Study. *Anesthesia & Analgesia* (2022), 10–1213.

[36] ISO. 2015. ISO 9241-400:2015 Ergonomics of human-system interaction - Part 411: Evaluation methods for the design of physical input devices.

[37] Patrick W Jordan, Bruce Thomas, Ian Lyall McClelland, and Bernard Weerdmeester. 1996. *Usability evaluation in industry*. CRC Press.

[38] Jari Kangas, Sriram Kishore Kumar, Helena Mehtonen, Jorma Järnstedt, and Roope Raisamo. 2022. Trade-off between task accuracy, task completion time and naturalness for direct object manipulation in virtual reality. *Multimodal Technologies and Interaction* 6, 1 (2022), 6.

[39] Talha Khan, Toby S Zhu, Thomas Downes, Lucille Cheng, Nicolás M Kass, Edward G Andrews, and Jacob T Biehl. 2023. Understanding effects of visual feedback delay in ar on fine motor surgical tasks. *IEEE Transactions on Visualization and Computer Graphics* 29, 11 (2023), 4697–4707.

[40] Inki Kim, Scarlett R Miller, and Andris Freivalds. 2014. Motion analysis as an evaluation framework for eye-hand coordination: A case study in ultrasound-guided catheter insertion. In *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, Vol. 46285. American Society of Mechanical Engineers, V01AT02A076.

[41] Jinwook Kim, Seonghyeon Kim, and Jeongmi Lee. 2022. The effect of multisensory pseudo-haptic feedback on perception of virtual weight. *IEEE Access* 10 (2022), 5129–5140.

[42] Peter Korba, Patrik Šváb, Michal Vereš, and Ján Lukáč. 2023. Optimizing aviation maintenance through algorithmic approach of real-life data. *Applied Sciences* 13, 6 (2023), 3824.

[43] Panayiotis Koutsabasis and Panagiotis Vogiatzidakis. 2019. Empirical research in mid-air interaction: A systematic review. *International Journal of Human–Computer Interaction* 35, 18 (2019), 1747–1768.

[44] Joseph J LaViola Jr, Ernst Kruijff, Ryan P McMahan, Doug Bowman, and Ivan P Poupyrev. 2017. *3D User Interfaces: Theory and Practice*. Addison-Wesley Professional.

[45] I Scott MacKenzie. 1992. Fitts' law as a research and design tool in human-computer interaction. *Human-computer interaction* 7, 1 (1992), 91–139.

[46] I Scott MacKenzie. 2018. Fitts' law. *The wiley handbook of human computer interaction* 1 (2018), 347–370.

[47] I. Scott MacKenzie and Poika Isokoski. 2008. Fitts' throughput and the speed-accuracy tradeoff. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Florence, Italy) *(CHI '08)*. Association for Computing Machinery, New York, NY, USA, 1633–1636. doi:10.1145/1357054.1357308

[48] Morteza Malekmakan, Wolfgang Stuerzlinger, and Bernhard Riecke. 2020. Analyzing the Trade-off between Selection and Navigation in VR. In *Proceedings of the 26th ACM Symposium on Virtual Reality Software and Technology* (Virtual Event, Canada) *(VRST '20)*. Association for Computing Machinery, New York, NY, USA, Article 42, 3 pages. doi:10.1145/3385956.3422123

[49] Paul Mallery and Darren George. 2003. *SPSS for Windows Step by Step: A Simple Guide and Reference*. Pearson.

[50] George Michalos, Sotiris Makris, Nikolaos Papakostas, Dimitris Mourtzis, and George Chryssolouris. 2010. Automotive assembly technologies review: challenges and outlook for a flexible and adaptive approach. *CIRP Journal of Manufacturing Science and Technology* 2, 2 (2010), 81–91.

[51] Domenick M Mifsud, Adam S Williams, Francisco Ortega, and Robert J Teather. 2022. Augmented reality fitts' law input comparison between touchpad, pointing gesture, and raycast. In *2022 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*. IEEE, 590–591.

[52] Mark R Mine. 1995. Virtual Environment Interaction Techniques. *UNC Chapel Hill CS Dept* (1995).

[53] Seyedkoosha Mirhosseini, Ievgeniia Gutenko, Sushant Ojal, Joseph Marino, and Arie E Kaufman. 2017. Automatic Speed and Direction Control Along Constrained Navigation Paths. In *2017 IEEE Virtual Reality (VR)*. IEEE, 29–36.

[54] Adrian K. T. Ng, Leith K. Y. Chan, and Henry Y. K. Lau. 2016. Depth Perception in Virtual Environment: The Effects of Immersive System and Freedom of Movement. In *Virtual, Augmented and Mixed Reality*, Stephanie Lackey and Randall Shumaker (Eds.). Springer International Publishing, Cham, 173–183.

[55] D Norman. 1988. Design Of Everyday Things.

[56] David Pepley, Mary Yovanoff, Katelin Mirkin, Scarlett Miller, David Han, and Jason Moore. 2016. A virtual reality haptic robotic simulator for central venous catheterization training. *Journal of medical devices* 10, 3 (2016), 030937.

[57] Max Pfeiffer and Wolfgang Stuerzlinger. 2015. 3D Virtual Hand Selection with EMS and Vibration Feedback. In *Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems* (Seoul, Republic of Korea,) *(CHI EA '15)*. Association for Computing Machinery, New York, NY, USA, 1361–1366. doi:10.1145/2702613.2732763

[58] MM Poulose, PR Mahapatra, and N Balakrishnan. 1985. Microwave Landing System—A Favoured Alternative to Current ILS. *IETE Technical Review* 2, 11 (1985), 375–382.

[59] Ivan Poupyrev, Mark Billinghurst, Suzanne Weghorst, and Tadao Ichikawa. 1996. The go-go interaction technique: non-linear mapping for direct manipulation in VR. In *Proceedings of the 9th annual ACM symposium on User interface software and technology*. 79–80.

[60] Jay B Prystowsky, Glenn Regehr, David A Rogers, J Peter Loan, Leslie L Hiemenz, and Kenneth M Smith. 1999. A virtual reality module for intravenous catheter placement. *The American journal of surgery* 177, 2 (1999), 171–175.

[61] Yuan Yuan Qian and Robert J. Teather. 2017. The eyes don't have it: an empirical comparison of head-based and eye-based selection in virtual reality. In *Proceedings*

of the 5th Symposium on Spatial User Interaction (Brighton, United Kingdom) *(SUI '17)*. Association for Computing Machinery, New York, NY, USA, 91–98. doi:10.1145/3131277.3132182

[62] Vijay Rajanna and Tracy Hammond. 2022. Can Gaze Beat Touch? A Fitts' Law Evaluation of Gaze, Touch, and Mouse Inputs. *arXiv preprint arXiv:2208.01248* (2022).

[63] Max Schneider, Christian Kunz, Andrej Pal'a, Christian Rainer Wirtz, Franziska Mathis-Ullrich, and Michal Hlaváč. 2021. Augmented reality–assisted ventriculostomy. *Neurosurgical focus* 50, 1 (2021), E16.

[64] Ajay Singh, Kapil Joshi, Mohammed Shuaib, Salil Bharany, Shadab Alam, and Sadaf Ahmad. 2022. Navigation and Speed Regulation Aimed at Travel through Immersive Virtual Environments: A Review. In *2022 IEEE International Conference on Current Development in Engineering and Technology (CCET)*. IEEE, 1–6.

[65] R William Soukoreff and I Scott MacKenzie. 2004. Towards a standard for pointing device evaluation, perspectives on 27 years of Fitts' law research in HCI. *International journal of human-computer studies* 61, 6 (2004), 751–789.

[66] Marco Speicher, Christoph Rosenberg, Donald Degraen, Florian Daiber, and Antonio Krúger. 2019. Exploring Visual Guidance in 360-degree Videos. In *Proceedings of the 2019 ACM International Conference on Interactive Experiences for TV and Online Video* (Salford (Manchester), United Kingdom) *(TVX '19)*. Association for Computing Machinery, New York, NY, USA, 1–12. doi:10.1145/3317697.3323350

[67] Robert J. Teather, Andriy Pavlovych, Wolfgang Stuerzlinger, and I. Scott MacKenzie. 2009. Effects of tracking technology, latency, and spatial jitter on object movement. In *2009 IEEE Symposium on 3D User Interfaces*. 43–50. doi:10.1109/3DUI.2009.4811204

[68] Yang Tian, Yuming Bai, Shengdong Zhao, Chi-Wing Fu, Tianpei Yang, and Pheng Ann Heng. 2020. Virtually-extended proprioception: Providing spatial reference in vr through an appended virtual limb. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–12.

[69] Rumeysa Turkmen, Laurent Voisard, Marta Kerten-Oertel, and Anil Ufuk Batmaz. 2025. Adaptive Hand Visibility for Accurate 3D User Interactions in Virtual Environments. In *2025 IEEE International Symposium on Mixed and Augmented Reality (ISMAR*. IEEE.

[70] A K M Amanat Ullah, William Delamare, and Khalad Hasan. 2023. Exploring Users Pointing Performance on Large Displays with Different Curvatures in Virtual Reality. *IEEE Transactions on Visualization and Computer Graphics* 29, 11 (2023), 4535–4545. doi:10.1109/TVCG.2023.3320242

[71] Cyril Vienne, Stephane Masfrand, Christophe Bourdin, and Jean-Louis Vercher. 2020. Depth Perception in Virtual Reality Systems: Effect of Screen Distance, Environment Richness and Display Factors. *IEEE Access* 8 (2020), 29099–29110.

[72] Jacob O. Wobbrock, Leah Findlater, Darren Gergle, and James J. Higgins. 2011. The aligned rank transform for nonparametric factorial analyses using only anova procedures. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Vancouver, BC, Canada) *(CHI '11)*. Association for Computing Machinery, New York, NY, USA, 143–146. doi:10.1145/1978942.1978963

[73] Dennis Wolf, Jan Gugenheimer, Marco Combosch, and Enrico Rukzio. 2020. Understanding the heisenberg effect of spatial interaction: A selection induced error for spatially tracked input devices. In *Proceedings of the 2020 CHI conference on human factors in computing systems*. 1–10.

[74] Baoquan Xin, Guanghui Chen, Yang Wang, Guangjian Bai, Xin Gao, Jianjun Chu, Jianru Xiao, and Tielong Liu. 2019. The efficacy of immersive virtual reality surgical simulator training for pedicle screw placement: a randomized double-blind controlled trial. *World neurosurgery* 124 (2019), e324–e330.

[75] Difeng Yu, Hai-Ning Liang, Feiyu Lu, Vijayakumar Nanjappan, Konstantinos Papangelis, Wei Wang, et al. 2018. Target Selection in Head-Mounted Display Virtual Reality Environments. *J. Univers. Comput. Sci.* 24, 9 (2018), 1217–1243.

[76] Xiaotian Zhang, Weiping He, Mark Billinghurst, Lingxiao Yang, Shuo Feng, and Daisong Liu. 2022. Design and Evaluation of Bare-Hand Interaction for Precise Manipulation of Distant Objects in AR. *International Journal of Human–Computer Interaction* (2022), 1–15.

[77] Yuhang Zhao, Edward Cutrell, Christian Holz, Meredith Ringel Morris, Eyal Ofek, and Andrew D. Wilson. 2019. SeeingVR: A Set of Tools to Make Virtual Reality More Accessible to People with Low Vision. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–14. doi:10.1145/3290605.3300341