Visual Perceptual Confidence: Exploring Discrepancies Between Self-reported and Actual Distance Perception In Virtual Reality

Yahya Hmaiti, Mykola Maslych, Amirpouya Ghasemaghaei, Ryan K Ghamandi, and Joseph J. LaViola Jr.

Abstract—Virtual Reality (VR) systems are widely used, and it is essential to know if spatial perception in virtual environments (VEs) is similar to reality. Research indicates that users tend to underestimate distances in VR. Prior work suggests that actual distance judgments in VR may not always match the users self-reported preference of where they think they most accurately estimated distances. However, no explicit investigation evaluated whether user preferences match actual performance in a spatial judgment task. We used blind walking to explore potential dissimilarities between actual distance estimates and user-selected preferences of visual complexities, VE conditions, and targets. Our findings show a gap between user preferences and actual performance when visual complexities were varied, which has implications for better visual perception understanding, VR applications design, and research in spatial perception, indicating the need to calibrate and align user preferences and true spatial perception abilities in VR.

Index Terms—Virtual reality, spatial perception, distance perception, visual complexity, understanding people

1 Introduction

Virtual Reality (VR) enables users to be immersed in new virtual environments (VE). This technology represents a potent tool that permits conducting research in spatial perception and cognition [7, 42, 74]. For example, distance estimation consists of a user's capability to correctly judge the depth of the scene, and estimate distances between objects, or between themselves and other VE elements [7, 14, 48, 82]. Misinterpretations in spatial judgments can reduce VR immersive experiences, and cause negative repercussions when performing in-VR activities [7, 20, 52, 68]. A large array of research on spatial perception indicates that judging distances is not a straightforward task. Prior findings suggest that distances tend to be underestimated while wearing head-mounted displays (HMD) [7, 9, 17, 32]. Various factors contribute to this phenomenon including VR system characteristics and VE attributes, such as HMD weight, field of view (FOV), camera height, avatar embodiment, and presence of depth cues, etc. [7, 9, 13, 32, 46, 50, 68]. These factors impact spatial judgments with their own unique mechanisms.

Several investigations identified solutions to distance underestimation in VR; some techniques that enhance distance estimation accuracy include introducing additional visual depth cues, enabling full avatar representations, increasing FOV size, and adding head-centric rest frames to the user [7, 24, 50, 55, 64, 68]. While research is abundant on distance perception and reducing its underestimation, a central question motivating our research is whether participants' perception of distal judgments in VR matches their actual accuracy in spatial judgment tasks. We break down this question into four sub-questions relevant to the audience interested in accurate spatial judgments, including human factors and immersive technology researchers, VR designers, and training simulation developers:

- **RQ.1:** Do users think they underestimated the distance to the target?
- **RQ.2:** Do users know where they were the most accurate at judging distances and where they weren't?
- **RQ.3:** What makes users think they perceive distances better in a specific VE condition?
- **RQ.4:** How does the user's own perceived performance in a distance judgment task compare to their actual performance?

We attempt to fill the literature gap on VR distance estimation coupled with a participant's subjective perception of their distance judgment performance. We assess participants' actual performance in estimating distances in VR across different VE settings, targets, and visual complexity levels, and compare the obtained results to participants' self-perceived efficacy. Our findings represent a valuable perspective on understanding participants' perception in VR and can be used to develop more effective VR training and education systems, contribute to a better understanding of cognitive biases, and inform the design of VR experiences where task performance is dependent on spatial perception.

We assess potential similarities and differences between participants' actual distance judgments compared to their self-reported preferences of VE conditions where they thought they accurately estimated distances. We were also interested in investigating the effect of varying visual complexity on distance perception in VR. We conducted a within-subject blind walking experiment [5, 13, 14, 43, 71] with 22 participants followed by a post-study self-assessment survey (see Sec. 3.6). The study factors were environment type (indoors/outdoors), visual complexity level (low, medium, and high), and target distance (3m, 4.5m, and 6m). We define *visual complexity* as the degree of detail and fidelity, density of objects, and VE clutter [66]. Low visual complexity is characterized by VE components simpler in shape and texture with some removed or omitted elements, whereas high visual complexity correlates to higher realism, fidelity, and visual richness. The findings from a survey and a blind walking task reveal a discrepancy between participants' perceived performance and actual results. Most participants believed they had a better grasp of gauging distances in high complexity indoors, particularly at the 3m target distance. While this perception aligns with the objective performance (environment type and target distance), the difference in objective performance between low and high visual complexities was not significant, contradicting participants' self-reported perception. Based on our study design and findings, we consider the following as our main contributions:

- A within-subject experiment that varies visual complexity, target distance, and environment variables and collects user-reported preferred conditions for distance judgment accuracy.
- Empirical evidence indicating the presence of a mismatch between

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participants' perceived performance and actual outcomes when judging distances in a blind-walking task in VR.

- A set of open-source VEs, each with different levels of varied visual complexity components, to enable conducting future experiments on factors impacting spatial perception.

2 Distance Perception and Visual Complexity

VEs are often perceived smaller than in reality with distances underestimated with different magnitudes [7, 8, 46, 68]. A review of 78 articles (1993 - 2012) on distance perception found an average distance perception at 74% of the actual modeled distance [68], and 82% average distance perception with recent HMDs [32].

Scale perception improved when viewing the real world before viewing a VE, with improvements in spatial judgments transitioning to new VEs [16, 26, 79]. However, these improvements might not be generalizable to other aspects of size and scale perception [7]. Moreover, viewer body cues, avatar embodiment, and eye height characteristics also impact spatial judgment accuracy. Distance perception was more accurate when participants were represented with an avatar, or when they were shown a full-body avatar with character animations [21, 53, 55]. Using some rest frames improves near and mid-field VR distance estimation (i.e. virtual nose, black metallic mesh, etc.) [23, 24]. For eye height, increasing the declination angle caused additional distance underestimation [2, 58]. Raising the virtual horizon or using floors different from the one the user is standing on also affects distance judgment [67, 81]. In realistic VEs with abundant familiar size cues, more sensitivity to changes in eye height was recorded [11]. Additionally, camera placement influences distance estimation [7, 28, 39] with higher camera positions increasing distance underestimation and lower positions causing overestimation [3].

The presence of more visual cues improves distance perception [7, 46, 49]. However, certain depth and visual cues efficiency decreased with distance [10]. Depth cue availability can improve in-VR performance resulting in mitigating negative repercussions of misperceived distance [7, 45, 59, 64]. Terrain design is related to visual cues, when it has missing information (gaps), distance estimates were less accurate compared to when it was continuous and homogeneous [72]. Less distance compression was recorded indoors compared to outdoors [7, 9, 50]. Other technological factors impacting spatial judgments include HMD weight, FOV, and display quality [7]. The HMD weight can impact the determination of the declination angle influencing distance estimation [7, 39, 40, 58]. Some experiments indicate that HMD weight increased distance underestimation [4, 78], whereas others showed contradicting results, relating distance misperception to display quality, size, and FOV [7, 31, 32, 50]. Some findings show more underestimation with smaller FOVs, compared to larger FOVs that promote accurate distal judgments [4, 7, 50]. Prior work also examined the effects of vertical FOV extension in VEs, finding that such extensions improve distance judgments and influence posture, and speculating that these improvements were related to the integration of textual details along the ground plane [29].

Several studies indicate that in high fidelity, immersion, and graphics quality, distance underestimation is less significant [26, 44, 63]. Moreover, texture gradients considerably reduced distance underestimation for short distances [25]. Other work suggests that graphics quality minimally impacts distance estimates [36, 47, 75, 77] and reducing visual realism does not significantly impact distance perception [38, 76, 77]. However, for verbal reports, texture and graphics quality increased distance estimates in contrast with blind walking where distance misperception was less significant [36, 75, 76]. Visual complexity significantly improved target detection, but worsened overall performance [66]. Other findings show distance underestimation in maximum and minimum visual cues VE compared to moderate environments, where overestimation was recorded [59].

Overall, some investigations suggest that changes in visual complexity might not have a clear direct impact on distance estimation, whereas others indicate distal judgment and task performance improvements in higher-complexity environments. The reviewed literature did not contain an experiment assessing distance judgments while simultaneously varying fidelity, object density, and clutter. Our study is an initial attempt to vary these factors and compare the results to the frequency of users' self-reported preferred conditions.

3 Procedure and Methodology

We explored potential discrepancies between participant preferences of where they accurately estimated distances and their objective performance. We also explored how different visual complexities in different VE settings impact distance judgments and user self-reported preferences. Since VR experiences often occur in complex VEs resembling the real world, participants performed blind walking in VEs designed with different visual complexities combinations and target distances.

3.1 Study and Experimental Design

Our investigation was within-subject ($2 \times 3 \times 3$), with distance estimation error and survey data (see Sec. 3.6) as dependent variables. Independent variables were environment type (2 levels: *indoors vs outdoors*), target distance (3 levels: *3m*, *4.5m*, and *6m*), and visual complexity (3 levels: *low*, *mid*, and *high*). Distance perception is an intricate mental process, often inaccessible directly, and its evaluation is abstract. Body motion showed more precise and direct distance estimates than other methods, leading to numerous evaluation approaches based on the direct action paradigm [7, 68]. Visually guided actions are most prevalent today [7, 13, 68]. Some of these methods include *blind walking*, *imagined time walking*, *blind throwing*, *triangulated blind walking*, etc. [7, 13, 18, 68]. We chose blind walking due to its popularity [7, 19, 50, 68], and as it has higher accuracy compared to several other techniques, despite its weaknesses [13]. We expand on blind walking mechanisms in our study procedure (see Sec. 3.5).

Research showed that distal estimates vary between indoors and outdoors [7, 9, 50, 68], thus, we included it as a variable in our experiment. To contrast our findings with prior work, we modified VEs used in the literature [24, 49, 50]. Before varying the three visual complexity levels (*low*, *mid*, *high*), our VEs differed in illumination, color gradients, objects, user location, etc. We discuss VE details and changes based on visual complexity levels in Sec. 3.2. We altered different components' complexities (model-related, visualization, and rendering factors), following methods by Ragan et al. [66]. We first designed the high complexity environments (see Fig. 3, and Fig. 6) with high object density, visual cues abundance, high fidelity, high realism, finer graphics and texturing, elaborate and detailed skyboxes. We reduced these features for the intermediate complexity level (see Fig. 2, and Fig. 5), and further reduced them for low complexity (see Fig. 1, and Fig. 4).

Target distance, the other independent factor, was marked by a $10cm \times 5cm$ red cylinder placed on the floor that cast and received shadows. Its color and size made it easily seen, and seamlessly integrated with its VE surroundings, not to obstruct the view of other scene depth cues nor for it to be perceived as an obstacle when blindly walking towards it. The target was located on the floor at one of three distances per trial: *3m*, *4.5m*, and *6m*. We selected these target distances as they fit within the physical constraints of our study room, are common in the literature [24, 32, 50, 70], and lie within action space, where blind walking was found to be an accurate measure of distance perception compared to other methods [7, 13, 35]. The user's physical starting position was constant across trials, while the in-VE starting and target positions were randomized within a safe walking area to ensure a different walking path for each trial.

To sum up, we had two VEs, three target distances, and three visual complexity levels. A combination of a single level from each condition was displayed per trial, resulting in 18 total conditions. Each participant experienced three repetitions of the 18 conditions (54 trials in total), where the order of conditions in each repetition was counterbalanced using a balanced Latin square. In each trial, the HMD position was continuously tracked, and the error distance was recorded by deducting the target's position from the participants' final position. Overall, when blind-walking, participants walked in a straight line to the target. However, since we allowed participants to walk naturally when moving to the target, we expected that in some trials they would veer off of the straight line between the trial's starting point and the target. This occurred for under 10% of total trials for 4 participants ($< 1.82\%$ of total experiment trials), and in those cases, participants' final trial position was projected onto the straight line between their start and target positions, and the error was the distance between the adjusted final position and the target. We grouped and averaged error distances by participant, trial, and condition. Averaging afforded preserving error direction (underestimation or overestimation) as recommended by prior work [24, 50, 51, 61].

3.2 Virtual Environment Design

The two VEs we used were modified using Unity3D and Blender. The indoor VE was a typical indoor house living room. This room was $10m \times 5m$ with a 3m height and featured different furniture and the illumination source was the external light coming through the windows (see Fig. 3). The outdoor VE was a street in a suburban area with a walking trail designated on the pavement. The VE featured vehicles, fences, houses, vegetation, etc. (see Fig. 6. At first, these VEs were modified to be of high visual complexity and realistic (See Fig. 3, and Fig. 6). Afterward, we derived their medium (See Fig. 2, and Fig. 5), and low (See Fig. 1, and Fig. 4) visual complexity versions by simplifying the advanced versions. Hence, every trio of the VE models had a consistent and comparable configuration and design. For indoors, the locations of the rooms, walls, doors, and windows remained the same. For outdoors, streets and sidewalk locations were the same. We modified the skybox, buildings, and the remaining VE components per each complexity level in each set of VEs. The modifications and differences represent a systematic simplification going from high to low complexity, and we summarize the details and differences between the visual complexities indoors (See Table. 1) and outdoors (See Table. 2). The original unmodified versions of the used VEs were obtained from Unity3D's asset store [1] [2]. The modified VEs and all models are made open-source for ease of replicability and to contribute to future research on spatial perception [3].

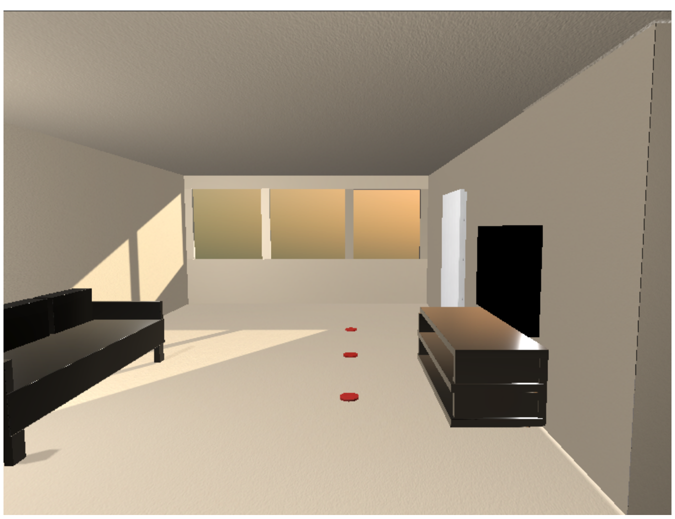

Fig. 1: Low complexity indoor environment with all target distances in the study (3m, 4.5m, and 6m).

3.3 Apparatus and User Study Location

We used a Pimax 5k+ headset with a large FOV ($170° \times 110°$) and a resolution of 2560×1440 pixels per eye. Since the FOV is not a factor in our experiment we kept it constant. The HMD had a 144hz refresh rate and weighed 500g including the head strap. We ensured that our VEs and in-VR experiment ran at consistent 80-90 frames per second

Fig. 2: Medium complexity indoor environment with all target distances in the study (3m, 4.5m, and 6m).

Fig. 3: High complexity indoor environment with all target distances in the study (3m, 4.5m, and 6m).

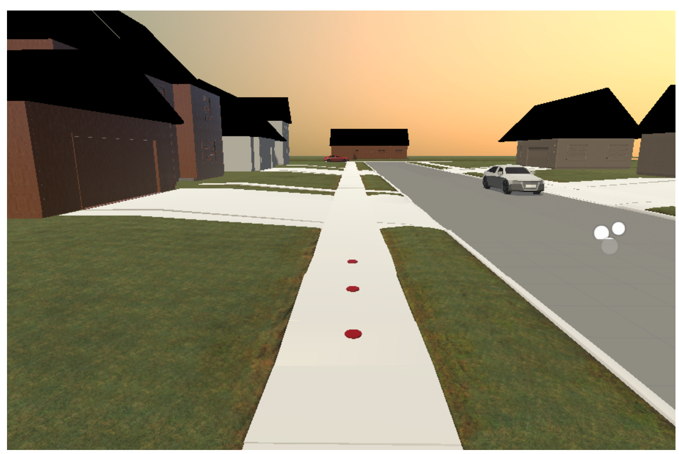

Fig. 4: Low complexity outdoor environment with all target distances in the study (3m, 4.5m, and 6m).

(FPS). We adjusted the HMD interpupillary distance (IPD) for each participant to match their measured IPD, ensuring optimized comfort and visual settings per individual. We used a portable backpack computer (HP Z VR backpack) since we wanted participants to walk freely to different targets at different VE locations. This battery-supported backpack has a GPU NVIDIA Quadro P5200, 32GB RAM, and an Intel 7820HQ processor. We added to the backpack wireless headphones to deliver verbal instructions to participants. This resulted in a final weight of 4.08kg. Moreover, we conducted our experiment in a closed

[1] Original outdoor VE; retrieved 2022-06-12
[2] Original indoor VE; retrieved 2022-06-12
[3] Open-source study environments

Table 1: Variations in visual complexity in the indoors environment.

Model Specifics	High Complexity	Medium Complexity	Low Complexity
Possible targets	3	3	3
Room length/width	$10m \times 5m$	$10m \times 5m$	$10m \times 5m$
Surroundings complexity	Intricate patterns Many objects Diverse designs Detailed interior architectures	Simple and intricate patterns Simplified interior architecture Fewer objects Fewer design details	Low poly textures Flat faced interior Minimal details Minimal object density
Number of objects	40	20	5
Skybox	Clear blue sky Many clouds Background skyscrapers	Clear blue texture Fewer clouds No skyscrapers	Ambient light yellow No clouds No Skyscrapers
Additional details	Many household interior features, tables, sofa, bookshelf, desk, books, vases, carpet, chairs, TV, lamps, windows, etc.	Fewer household interior features with reduced detail, windows, tables, TV, sofas, lamps, carpet, etc.	Minimal household features, sofas, TV, doors, table, etc.

Table 2: Variations in visual complexity in the outdoors environment.

Model Specifics	High Complexity	Medium Complexity	Low Complexity
Possible targets	3	3	3
Number of alleys	2	2	2
Surroundings complexity	Intricate patterns Many houses Diverse designs Detailed architectures	Simple and intricate patterns Simplified house architecture Fewer objects Fewer design details	Low poly textures Flat faced houses Minimal details Minimal object density
Number of houses	22	12	8
Number of vehicles	8	6	4
Skybox	Clear blue sky Many clouds	Clear blue texture Fewer clouds	Ambient light yellow No clouds
Additional details	Many neighborhood features, light poles, trees, plants, cars, house accessories, mailboxes, trash bins, road and sidewalk details, etc.	Fewer neighborhood features, electricity poles, plants, cars, house accessories, sidewalk details, etc.	No electricity poles, trees, plants, house accessories, sidewalk and road details, etc.

Fig. 5: Medium complexity outdoor environment with all target distances in the study (3m, 4.5m, and 6m).

Fig. 6: High complexity outdoor environment with all target distances in the study (3m, 4.5m, and 6m).

large laboratory room, where participants walked safely and naturally. The furthest target from the user was located 2m away from the study room's physical wall in front of the participant and 3m away on both sides from any non-study object. This was adequate for participant safety. The ceiling was 3.4m tall. We ensured that no real object was moved and that participants were not exposed to external noises until the in-VR experiment and data collection ended.

3.4 Participants

The minimum participant number was determined by G*Power [15]. We chose a medium effect size, 18 conditions measurements, and ANOVA repeated measures within-subjects. Our target sample size (N) was 14. We recruited 22 participants from our university (8 females, 14 males) of different ages ranging from 18 to 37 (M = 23.09, SD = 4.27), with different self-reported VR experience levels on a scale from 1 (never) to 5 (always) (M= 1.68, SD= 0.42), with "always" denoting the daily use of VR technology, while "never" indicates no use or minimal experience with VR (e.g., used once). All participants spoke and understood English, walked without assistance, were not color blind, and expressed no neuropathic, or physical disability. They had normal or corrected-to-normal vision. If a participant wore glasses or contact lenses, they kept them on.

3.5 Study Procedure

Our study procedure was similar to prior studies [24, 49, 50]. Upon arrival, participants received a consent form with all study information. Once read, we answered any questions they had, followed by getting their consent to conduct the experiment. Afterward, we conducted a vision acuity test using a Snellen chart to ensure participants had normal or corrected-to-normal vision. Then, we administered an Ishihara color test [27]. If the participant failed the vision acuity test or was color blind, they would be dismissed, however, we did not have such an occurrence. We then collected participant demographic data through a survey asking about their age, gender, and experience with VR.

Afterward, we explained the in-VR task to participants in detail, answering any questions. Next, we introduced and explained the study apparatus, and helped participants wear it, assisting them in the process. Once set up, we guided them toward the experiment's beginning point and helped them orient themselves toward the walking area. As a precaution to minimize light seeping through the space between the HMD and participant's face, we turned the lights off. Then, we logged their initial location, which they returned to after trial completion. Once the start position was logged, the in-VR task started directly, and no practice sessions were given. Until the participant informed the investigator of their readiness to start the assessment, the HMD screen remained dark. After saying "okay", the current trial scene was activated. Participants had ten seconds to detect the target and gauge its distance. Once the participant was ready to walk, they signaled by saying "okay". Then, the researcher disabled the VE display by pressing a button on a remote keyboard, and an audio that said "go" was played through headphones. When walking, participants were asked to keep their eyes closed till they walked the full distance they intended to walk, and the black screen ensured that the participant did not use any VE visual cues.

The walking phase ended once the participant said "okay" marking their reach to the target. Once hearing the participant's confirmation, the researcher clicked on a remote keyboard to log the participant's end position. This was followed by audio played through headphones that said "done", then a red arrow was shown on the floor near the participant's feet, which guided them back to the beginning position of the next trial. When the participant reached their intended destination and opened their eyes, no scene component was displayed through the HMD, thus, no feedback about location or performance was given at the end of the trial to prevent the influence of any training or corrective effects. The red arrow was always connected to the participant's feet and pointed toward the trial's start position. Once each trial concluded, the participant traced the red arrow (*guidance arrow*) until they saw a green one (*alignment arrow*). Participants needed to align themselves with the green arrow as we had it as a tool to help them stop at the start position for the next trial and face the correct direction in the room. To ensure position and orientation correctness, both red and green arrows needed to overlay until only the green arrow was visible before moving to the subsequent trial. During the returning phase nothing was displayed through the HMD except for the red arrow, and when returning, the participant had to go through a randomized circuitous path back to the starting position as we did not want the returning path to be a confounding variable or have an impact on the recorded distance estimates.

After reaching the start position, aligning with the walking area, the next trial started once the participant said "okay" followed by the experimenter clicking a button on a remote keyboard. We note that both the guidance and alignment arrows disappeared when the trial started. After the in-VR experiment, we administered a post-study survey (see Sec. 3.6). We adopted this methodology to limit direct engagement with participants and ensure that the experimenter did not inadvertently give hints that could impact participants' ability to perceive distances or determine their position within the study area. No participant expressed fatigue signs, and the study lasted ∼30 min.

3.6 Assessment of Self-Reported Performance

At the end of blind-walking, participants were directed to a desktop station and partook in a self-assessment survey. Participants ranked the VE conditions where they thought they were most accurate at judging distances. Before filling out the survey, participants read a summary of the in-VR study completed. By doing so, we ensured that participants based their responses on the same understanding of the experiment. Furthermore, the survey was administered at the end of the in-VR task as participants needed to experience all conditions before making judgments. Conversely, if we opted for post-condition surveys, the comparison baseline would be constantly changing with each newly experienced condition, and introducing intermediate ratings could cause consistency bias in participant responses. Also, our survey questions were based on ranking only and not rating, as we were not interested in quantifying improvement.

Participants selected the best choice amongst the available answer options for each question and the survey questions covered three main components: ***Environment Type Preference:*** Participants chose the environment type where they believed they were most accurate at judging distances (indoors or outdoors). **(Question 1):** *In which environment did you judge distance most accurately?* ***Target Distance Preference:*** Participants chose the target they thought they judged most precisely distance-wise (target 1 (3m), target 2 (4.5m), or target 3 (6m)). We also provided the measurements in feet. **(Question 2):** *Which target distance did you judge most accurately?* ***Visual Complexity Preference:*** Participants chose the visual complexity level where they were most accurate at judging distances (indoors low, indoors medium, indoors high, or outdoors low, outdoors medium, outdoors high). **(Question 3):** *In which of the following environments, characterized by different visual complexities, did you feel most accurate when judging distances to the targets?*

To help participants remember the VE conditions, we presented clear images of the VEs with captions corresponding to each condition and question. For every question, participants selected only one answer. Following each selection, participants shared ideas and reasons that motivated their selection choices in a text input field. We answered any questions participants asked during this process, and results from this survey provided introspective data, allowing us to compare their preferred choices against objective outcomes from the blind-walking VR task (see Sec. 4.2, and Fig. 9).

4 Results

Since we repeated every condition three times, we first averaged the three distance errors recorded per condition for each participant. Applying Shapiro-Wilks test showed our data was normally distributed ($W = 0.966$, $p = 0.619$). We conducted a within-subject study, where the factors were *Target Distance, Environment Type, and Visual Complexity Level*. Fig. 7 and Fig. 8 visualize the main and interaction effects and display the mean distance error and standard deviation for each target distance per visual complexity level (see Table 4). We performed RM-ANOVA, and reported main and interaction effects (see Table 3). Where Mauchly's sphericity test showed significance, we applied Greenhouse-Geisser correction, which offers an explanation of the degrees of freedom found. Moreover, we used pairwise t-tests comparisons with Bonferroni corrections unless we specified otherwise in-text. Since the interaction effects were not significant, we only summarized them in Table 3. We applied Cousineau's and Morey's corrections to remove between-subject variability [6, 56]. This ensured error bars provide meaningful data for within-subject comparisons.

4.1 Objective Performance Analysis

4.1.1 Visual Complexity

We found a significant main effect of visual complexity on distance estimates ($F_{1.458,30.624} = 4.825$, $p = .024$, $\eta_p^2 = .187$) (see Fig. 7-c). Distances were more underestimated at mid-field complexity (M=−68.80, SD=13.40) compared to low (M=−60.82, SD=13.60), and high (M=−58.60, SD=13.10) complexity levels. We found the following through post-hoc comparisons using pairwise t-tests: low vs high ($t_{21} = .605$, $p = .552$), low vs mid ($t_{21} = 1.962$, $p = .063$), and mid vs high ($t_{21} = 4.687$, $p < .001$).

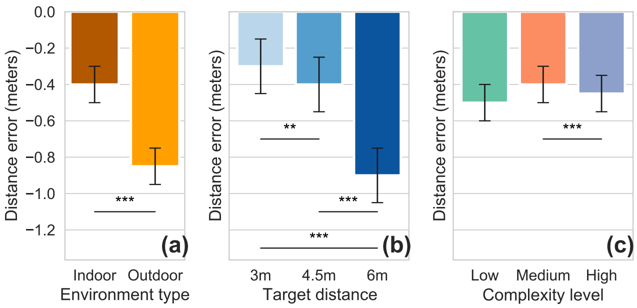

Fig. 7: Results of the user study (95% CI are Cousineau and Morey adjusted, and distance error on Y-axis). (a) Distance error by environment type; (b) Distance error by target distance; (c) Distance error by visual complexity level; ($p < .05 = *$, $p < .01 = **$, $p < .001 = ***$).

Table 3: RM-ANOVA effects for each factor and interactions. Strongest effects sizes are highlighted in bold. C: Visual Complexity Level, E: Environment Type, T: Target Distances. *(* = $p < .05$; ** = $p < .01$; *** = $p < .001$).*

Factor	F	df_{effect}	df_{error}	p	η_p^2	Sig
C	4.825	1.458	30.624	.024	**.187**	*
E	35.539	1.00	21.00	<.001	**.629**	***
T	19.075	1.411	29.63	<.001	**.476**	***
$C \times E$	2.880	2	42	.067	**.121**	no
$C \times T$	2.632	2.705	56.802	.064	**.111**	no
$E \times T$	1.183	2	42	.316	.053	no
$C \times E \times T$	1.595	4.00	84.00	.183	.071	no

4.1.2 Environment Type

We found a significant main effect of VE type ($F_{1,21} = 35.539$, $p < .001$, $\eta_p^2 = .629$) on distance estimation (see Fig. 7-a). Distance underestimation was lower indoors (M=−44.68, SD=14.00) than outdoors (M=−80.08, SD=13.10) by 55.8%.

4.1.3 Target Distance

We found a significant main effect of target distance on distance estimates ($F_{1.411,29.63} = 19.075$, $p < .001$, $\eta_p^2 = .476$) (see Fig. 7-b). Distances were more underestimated at the far-field (6m) (M=−88.40, SD=16.30) compared to (4.5m) (M=−60.60, SD=15.20), and (3m) (M=−39.10, SD=9.71). We found the following through post-hoc comparisons using pairwise t-tests: 6m vs 3m ($t_{21} = 4.811$, $p < .001$), 6m vs 4.5m ($t_{21} = 4.507$, $p < .001$), and 4.5m vs 3m ($t_{21} = 3.061$, $p = .006$).

4.2 Self-Reported Perceived Performance Survey

Participants reported their preferred study conditions where they thought they most accurately estimated distances. First, participants selected their preferred environment type (indoor vs. outdoor). Chi-Squared test on these responses (χ_1^2 (N = 22) = 4.96, p = 0.03) suggests that choices were not uniformly selected (see Fig. 9). 81.8% of participants picked indoors, whereas only 18.2% selected outdoors. Second, users selected their preferred target distance (3m, 4.5m, and 6m). Chi-Squared test on the responses (χ_2^2 (N = 22) = 12.81, p = 0.002) indicated that the choices were not uniformly picked (see Fig. 9). 81.8% of participants chose the 3m target, whereas 18.2% selected 6m, and no one picked 4.5m. Third, users selected their preferred visual complexity level (low, medium, and high) either indoors or outdoors. Chi-Squared test on these responses (χ_5^2 (N = 22) = 22.07, p < 0.001) showed that choices were not uniformly selected (see Fig. 9). We found that 81.8% of participants selected high complexity indoors, 13.6% picked medium complexity outdoors, and 4.5% chose high complexity outdoors. Without considering the environment type, 86.4% selected high complexity, and 13.6% selected mid complexity.

Table 4: Mean error and standard deviation by target by complexity level.

Target (meters)	Complexity Level	Error (centimeters)
3m	Low	M = -40.62, SD = 10.70
	Medium	M = -37.50, SD = 10.20
	High	M = -39.25, SD = 9.10
4.5m	Low	M = -55.22, SD = 16.40
	Medium	M = -69.04, SD = 14.60
	High	M = -57.18, SD = 15.80
6m	Low	M = -86.32, SD = 16.30
	Medium	M = -99.79, SD = 17.10
	High	M = -78.89, SD = 16.70

5 Discussion

Our study is an initial step toward evaluating if participants' self-reported preference of where they most accurately judged distances in a blind-walking task matches their objective distance estimates. Thus, some results were difficult to contrast with prior work. Our results provide insight into the existence of similarities and dissimilarities between user preferences and their actual performance.

5.1 Objective vs. Perceived Performance Discrepancies

The majority of participants thought they more accurately gauged distances to the 3m target in high-complexity indoors (see Fig. 9, and Sec. 4.2). However, their objective performance across visual complexities was only significantly different for mid-complexity (see Fig. 7-c, Fig. 8, and Sec. 4.1.1), yet with more underestimation. For target distance and VE type, participants' preferences aligned with objective findings, showing less underestimation indoors and at 3m (see Fig. 7-a, and Fig. 7-b). To analyze participants' justifications we conducted a thematic analysis. We extracted statements about various VE conditions, grouping and counting them when similar statements appeared multiple times. All participants comments had several statements, and the different participant statements did not contradict each other. We provide participant observations and percentages per common reason, grouped by study factors, below:

For **visual complexity**, participants preferred high visual complexity due to the following reasons: **(1)** *VE components being highly realistic and not ambiguous to interpret*($N = 20$, 90.9%); **(2)** *having more objects surrounding the target and participant allowing them to reference themselves compared to the target*($N = 18$, 81.8%);**(3)** *having objects in the VE similar to daily life and recalling real-life copies of objects* ($N = 16$, 72.7%); **(4)** *the walking path having consistent and continuous details surrounding it*($N = 8$, 36.4%). For **target distance**, participants preferred the 3m distance for the following reasons: **(1)** *the target requiring the least effort to get to*($N = 14$, 63.6%); **(2)** *the target having the least distractions surrounding it*($N = 11$, 50%); **(3)** *the closest target giving more confidence to participants in their ability to perform blind walking as far targets made them scared of hitting the wall or other objects*($N = 4$, 18.2%). For **environment type**, most participants preferred indoors due to: **(1)** *the availability of more objects as references within an enclosed area*($N = 20$, 90.9%); **(2)** *the presence of enough details on the VE floor indoors*($N = 11$, 50%); **(3)** *having walls that helped recall VE dimensions with respect to the physical study room*($N = 8$, 36.4%); **(4)** *having a VE similar to an area where a lot of walking is performed daily*($N = 6$, 27.3%).

We expected participants to select high visual complexity indoors as it provides an abundance of visual cues, reference points, and a more realistic appearance while being most familiar to participants, compared to outdoors. We also expected participants to select indoors and the 4.5m or 3m target as estimates are influenced by the actual distance to the target and the anticipated walking effort [65, 80]. Moreover, distance judgments are influenced by perceptions of walkability within the VE [41]. Thus, we think participants lean more toward a target distance choice that wouldn't require much traversal effort and without

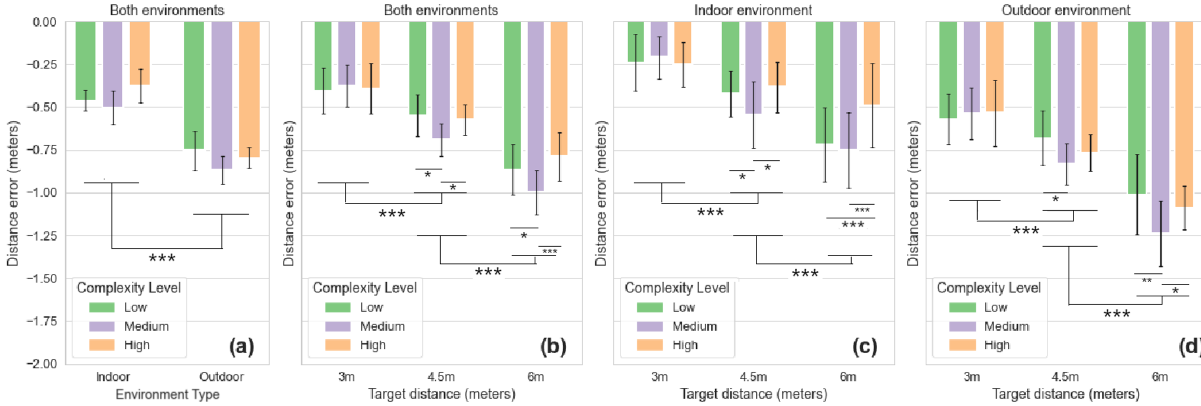

Fig. 8: Results of the user study (95% CI are Cousineau and Morey adjusted, and distance error on Y-axis). (a) Distance error by visual complexity level by environment type; (b) Distance error by visual complexity level by target distance; (c) Distance error by visual complexity level by target distance indoors; (d) Distance error by visual complexity level by target distance outdoors; We highlight the significance of the differences between conditions most central to our research ($p < .05 = *$, $p < .01 = **$, $p < .001 = ***$).

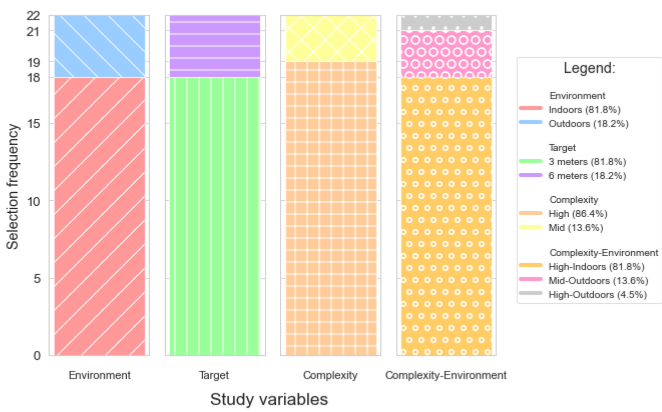

Fig. 9: Results of the post-study survey on self-reported preferences of where users thought they were more accurate at judging distances across different study conditions.

obstacles on the walking path. We observed that participants perceived the 3m target as having fewer distractions. This perception, reported by 50% of participants, is likely due to the proximity of the target reducing surrounding visual stimuli and perceived task complexity. Additionally, a few participants noted ease in focusing on the 3m target without too many distractions and reduced anxiety. Our findings show that using only self-reported preferences might be inaccurate, especially if the VE design and VR tasks focus on precise distance perception. Nevertheless, when the goal isn't strictly technical or objective, our results inform the design of human-centered immersive VR experiences, and guide the creation of applications where self-assessment of spatial preferences and performance is essential.

5.2 Depth Cues and VE Attributes in Distance Judgment

Our objective results suggest that participants were more accurate at judging distance indoors compared to outdoors (see Fig. 7-a) confirming prior work [9, 50]. This finding can be attributed to indoors having more reference points that act as memory anchors easily accessible and identifiable (i.e. furniture, walls, etc.) compared to outdoors, which has a wider horizon, different architectures, and topographies.

Relative size, occlusion, linear perspective, aerial perspective, shadows, and texture gradient are monocular static visual cues [10, 37] that we expected to improve distance judgment with increased visual complexity levels. Increasing the number of familiar size objects to participants affords comparing their relative size, and increases clutter, occlusion, and shadows serving as depth cues that improve spatial judgments [8, 10, 26, 68, 73]. With increased distance from the viewer, parallel lines appear to converge (*linear perspective*), and textures appear denser (*texture gradient*), providing additional relative depth cues that can help improve distance and depth estimations [7, 25, 37, 68]. In our study, rug and sidewalk tiles alongside grass and carpet textures provided texture gradient cues. Finally, aerial perspective scatters the light and makes distant objects appear less saturated, bluer with decreased contrast, and dimmer than close ones, helping with distance perception [10, 12, 37, 68].

Moreover, height relative to the horizon (*angle of declination*) is another depth cue, which automatically varied with changes to target distance. Below the horizon, objects low in the visual field are perceived as closer than those that are higher, with a reverse effect for objects above the horizon [7, 37, 54, 58, 68]. Without a horizon, the floor-wall boundary can serve as a virtual horizon maintaining the same depth cue effect [7, 67], which was the case in our indoor VE. Another depth cue is motion parallax which occurs when the observer moves relative to static objects, or when objects move relative to the static observer (or when both are moving), and motion parallax causes closer objects to seem like they're moving faster than distant ones [37]. This depth cue did not have an impact in our experiment as VEs were static when viewed by participants, and they had eyes closed when walking to the target. Furthermore, binocular disparity can provide a depth cue that is based on the ability to perceive depth from the slightly different images each eye sees [10, 60, 68]. We expected this depth cue to influence spatial perception in our experiment as it was present by default across all conditions.

Compared to prior work on VR spatial perception, which often isolates a single variable and evaluates its impact on spatial perception, our research explores the interplay of several visual complexity components in tandem. Our findings indicate that the impact of these depth cues when combined and varied on distance estimation is less pronounced than when each element is varied individually as shown in the literature. The significant effect of visual complexity comes from performance at the mid-complexity level being significantly different from low and high complexities, with more underestimation overall at mid-complexity (see Fig. 7-c, Fig. 8, and Sec. 4.1.1). This finding was surprising as we expected to see distance underestimation decrease gradually from low to high visual complexity as indicated in prior findings [25, 26, 44, 63]. This could be due to differences between our modern hardware compared to what exists in the literature, as newer devices have less distance underestimation [4, 7, 32–34], and it is plausible that combining the depth cues we implemented when using modern hardware with a large FOV reduces their effect on distance judgment. Our mid-visual complexity level had features pertinent to both low and high visual complexity levels, which we speculate caused confusion and ambiguity to participants, potentially not serving them in gauging distances. This can be supported by recent findings indicating that medium complexity visualizations led to the highest mental effort measurements compared to low and high complexity levels [1, 22]. However, additional work with different medium visual complexity VEs is needed to generalize this claim.

For low complexity, we suspect that the VE simplicity contributed to participants locating targets easily, yet needing to work harder to locate VE features to gauge distances to targets as minimal visual cues were available. Furthermore, the insignificant difference in estimating distances between low and high complexities (see Fig. 7-c, Fig. 8, and Sec. 4.1.1) aligns with some work indicating that visual complexity did not improve spatial perception [36, 59, 66, 76, 77]. Conversely, other work indicates that escalating depth cues from low to high visual complexity by increasing the variety and abundance of depth cues can reduce distance underestimation [7, 46, 49, 57]. Thus, additional spatial perception experiments with varied visual complexity levels could help establish a common ground to this contradiction in literature findings. To consolidate our analysis, we tested for potential learning effects and found that distance estimation improved with time even though no feedback was given at the trials' end. This resembles prior work showing a high initial distance judgment improvement, followed by performance stabilization and reduction of learning effect [24, 53, 62], and this is not a concern as each condition was repeated thrice following a counterbalanced order.

The blind-walking experiment and survey data enabled us to answer the introductory questions: **RQ.1 Answer:** Most participants acknowledged that they misperceived the distance to several targets in some conditions. **RQ.2 Answer:** Most participants correctly identified the target distance and environment type where they were accurate, but misidentified the visual complexity level. **RQ.3 Answer:** The summary of participant reasoning offers insights justifying their preferences of VE conditions where they thought they were most accurate (see subsection 5.1). **RQ.4 Answer:** Most participants thought of high complexity as the level where they were most accurate, differing from their objective blind-walking results.

5.3 Limitations

In our experiment, we explored and varied visual complexity attributes based on prior work, attempting to reduce subjectivity in design decisions. We acknowledge a limitation that some visual complexity operationalizations could be improved in the future. In our follow-up investigations, we plan to conduct a similar experiment extending our research to include a wider array of settings across different environments, beyond the initially investigated VEs and conditions to better align with the rich nature of real-world applications. Additionally, our experiment was in VR using a large FOV HMD equipped with a backpack, thus, conducting a similar evaluation with consumer HMDs and in other settings (AR/MR) would be valuable to increase our results' generalizability. Although our sample size exceeds the minimum required by a G*Power test for a medium effect size, we acknowledge its limitations and the potential impact of the gender imbalance in our participant pool. Our sample is male-dominated, preventing us from testing gender differences. Thus, to better generalize our results across different genders, in our future work we will ensure a more balanced gender representation and consider increasing sample sizes to further validate the findings. Since there isn't an established framework or guidelines for post-study assessment questionnaires for spatial perception tasks, we created our own post-study survey and improved it through several pilots. Moreover, while our study is an exploration that uncovered discrepancies between user preferences and objective performance in blind-walking, follow-up investigations should vary more factors in a similar study context. Eye height in most VR experiments remains unchanged (as it was in our study) unless explicitly introduced as a variable. Since prior work showed that increasing eye height shrinks participants' VE perception (similarly, reducing it leads to overestimation) [7, 39, 58], we plan to have follow-up experiments that include eye height as a variable with defined levels, exploring potential interactions between eye height, visual complexity, and target distance on spatial perception in VR.

Some prior work indicated that differences between distal judgment errors in real and virtual environments are limited in significance [16, 30, 33, 63]. Others show a significant and measurable mismatch in perception between those two, with less difference between the two recorded when using newer devices [7,8,32,69]. While we used modern VR hardware, and our research offers valuable insights to the research community for creating VEs that enhance distal judgment accuracy and user confidence in spatial judgment tasks, further validating our findings with a follow-up experiment replicating these conditions in the real world would be beneficial. This will help determine if the observed trends also occur in real-world settings, allowing for more generalization of our results. Moreover, our distances were appropriate to answer the research questions we posed, and even though it wasn't our experiment's focus, these targets are limited in revealing a global distance underestimation trend, requiring a follow-up experiment using larger target distances.

6 Conclusion and Future Work

In the future, we intend to explore the causes of the discrepancies found, which can pave the path for research bridging meta-cognition and spatial perception in VR. We are also interested in conducting future experiments to determine different feedback mechanisms to bridge the gap between perceived and actual performance in spatial perception tasks. Currently, we are testing various visual complexity and spatial perception aspects to train a model that predicts underestimation in VEs, using data from participant camera views.

Distance perception in VR is important in several VR tasks and applications relevant to several domains. Consequently, assessing users' ability to judge distances accurately in VR is crucial while also analyzing how their self-perceived efficacy aligns with their actual performance. Through this investigation, we explored differences between users' preference of where they most accurately judged distances and their actual task performance in a blind-walking task. This represents an initial step towards incorporating human feedback and preference in a spatial judgment task. We pave the path for research geared towards investigating potential cognitive discrepancies relevant to distal judgments in VR.

We observed a difference between user preferences of where they accurately estimated distances and the measurable outcomes from blind-walking. Most users think they performed better in high-complexity indoors for near-field distance (3m). Their actual performance matches their preferences for target distance and environment type. Conversely, the difference in objective performance between low and high complexities was insignificant, even though participants felt more accurate at judging distances in high visual complexity. This uncovers a valuable new perspective on user performance assessment in VR distance judgment tasks. Our findings suggest that relying solely on self-reported preferences in this context can be misleading if the VE design and VR tasks are centered on accurate distance judgment. This becomes more evident when misjudgments can cause critical errors or harm participants. Our research offers valuable insights that help develop immersive and engaging VR experiences, effective training and education systems, improve VR system calibration means and user feedback mechanisms, and inform the design of applications where self-evaluation of spatial judgment preferences and performance is crucial.

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