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Linear perspective cues have a greater effect on the perceptual rescaling of distant stimuli than textures in the virtual environment

Gizem Y. Yildiz[1,2], Richard Skarbez[3], Irene Sperandio[4], Sandra J. Chen[1], Indiana J. Mulder[1], Philippe A. Chouinard[1]

[1]Department of Psychology, Counselling, & Therapy, La Trobe University, Melbourne, Australia.

[2]Institute of Neuroscience and Medicine (INM-3), Forschungszentrum Jülich GmbH, Jülich, Germany

[3] Department of Computer Science and Information Technology, La Trobe University, Melbourne, Australia.

[4] Department of Psychology and Cognitive Science, University of Trento, Rovereto (TN), Italy.

Author Note

Corresponding Author: Philippe A. Chouinard.

Postal address: George Singer Building, Room 460, La Trobe University, 75 Kingsbury Drive, Bundoora, Victoria, 3086, Australia

E-mail: p.chouinard@latrobe.edu.au.

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Abstract

The presence of pictorial depth cues in virtual environments is important for minimising distortions driven by unnatural viewing conditions (e.g., vergence-accommodation conflict). Our aim was to determine how different pictorial depth cues affect size constancy in virtual environments under binocular and monocular viewing conditions. We systematically removed linear perspective cues and textures of a hallway in a virtual environment. The experiment was performed using the method of constant stimuli. The task required participants to compare the size of ‘far’ (10 m) and ‘near’ (5 m) circles displayed inside a virtual environment with either one or both or none of the pictorial depth cues. Participants performed the experiment under binocular and monocular viewing conditions while wearing a virtual reality headset. ANOVA revealed that size constancy was greater for both the far and near circles in the virtual environment with pictorial depth cues compared to the one without cues. Yet, the effect of linear perspective cues was stronger than textures, especially for the far circle. We found no difference between the binocular and monocular viewing conditions across the different virtual environments. We conclude that linear perspective cues exert a stronger effect than textures on the perceptual rescaling of far stimuli placed in the virtual environment and that this effect does not vary between binocular and monocular viewing conditions.

Keywords: visual perception, size constancy, virtual reality, pictorial depth cues, non-pictorial depth cues

1. Introduction

While we are driving, the image projected onto our retina by the car in front of us grows dramatically in size as we get closer to it. Yet, we do not perceive the car as changing in size but rather in distance. This phenomenon is known as size constancy (e.g., Holway & Boring, 1941). To maintain size constancy, the visual system perceptually rescales objects' retinal size with perceived distance (for a review, see Sperandio & Chouinard, 2015). Various pictorial (i.e., linear perspective cues, textures, and occlusion) and non-pictorial (i.e., binocular disparity, convergence, motion parallax, and accommodation) depth cues are used by the brain to estimate distance (e.g., Bruno & Cutting, 1988; Landy et al., 1995) and establish size constancy (e.g., Gregory, 1963; Holway & Boring, 1941; Sperandio & Chouinard, 2015, but also see Linton, 2020, 2021, 2023). The contributions of depth cues to size constancy differ depending on viewing distance and viewing conditions in real world environments (Feldstein, 2019). The contributions of these cues to size constancy might also differ in virtual reality (VR) environments in light of well-reported differences in perceived depth and size perception between real and virtual environments (Hoffman et al., 2008; Hornsey & Hibbard, 2021; Kelly et al., 2017; Naceri et al., 2015, for a review, see Creem-Regehr et al., 2023; Kelly, 2022; Renner et al., 2013). This VR study aims to evaluate the unique effects of linear perspective cues and textures on size constancy under binocular and monocular viewing conditions.

VR allows researchers to construct simulated environments that emulate reality while enabling precise stimulus control so that one can investigate the effects of pictorial depth cues on size and depth judgments (Chen et al., 2019; Glennerster et al., 2006; Hornsey & Hibbard, 2021; Hornsey et al., 2020; Loyola, 2018; Murgia & Sharkey, 2009; Scarfe & Glennerster, 2015, 20919; Svarverud et al., 2010). For example, Hornsey and Hibbard (2021) tested size constancy in virtual environments with and without pictorial depth cues by asking participants to adjust the size of a sphere placed at different viewing distances (3 to 11 m) until it would appear as having the same size as a football (22 cm). Their results revealed that the participants performed better in the size constancy task when the stimulus was presented in the virtual environment with pictorial depth cues (i.e., linear perspective cues and textures) compared to the one without cues. Yet, the effects of linear perspective cues were not separated from the effects of textures in their study.

Linear perspective cues and textures are widely utilized in virtual environments to enhance the perception of size and depth; however, the specific impacts of these two pictorial depth cues on size and depth judgments are still a matter of controversy. While numerous studies agree that the presence of linear perspective cues improves the accuracy of size and depth judgments, studies testing the effects of textures have yielded inconsistent results. For instance, both Witmer and Kline (1998), as well as Zhang et al. (2014), found that the inclusion of texture patterns on the floor had no discernible influence on depth judgments. In contrast, Sinai et al. (1999) demonstrated that the presence of a brick pattern, but not a grass pattern, on the floor of a hallway increased the accuracy of estimated depth. Several factors have been proposed to explain these discrepancies among studies, such as methodological differences, variations in depth levels, and differences in texture density.

Another potential reason for the inconsistent findings could be the lack of real graphical addition or subtraction of these two pictorial depth cues in previous virtual environments. In our previous studies, we tested the unique contributions of linear perspective cues and textures to perceptual rescaling mechanisms inside the corridor illusion using a systematic approach (Yildiz et al., 2019, 2021a, 2021b). We achieved this by employing real graphical addition or subtraction of these two pictorial depth cues in a 2D flat image. In the corridor illusion, two stimuli that are physically identical appear to differ from each other when placed at locations where pictorial depth cues signal varying depths. More precisely, the stimulus positioned in an area where the pictorial depth cues suggest a closer distance appears smaller than the one placed in an area where the cues suggest a greater depth. In our previous investigations of the corridor illusion, we obtained two significant findings. First, we established that both linear perspective cues and textures displayed in 2D flat images play crucial roles in influencing perceptual rescaling mechanisms. Second, we observed that the impact of these perceptual rescaling mechanisms on the perceived size of stimuli was more pronounced when the stimuli were presented at locations where pictorial depth cues indicated greater depth in 2D flat images (Yildiz et al., 2019, 2021a, 2021b, 2022). Although the corridor illusion has been explained by real-world size constancy mechanisms (Gregory, 1963, 1998), it is unknown whether or not our findings accurately reflect the variations in size constancy for stimuli placed within a corridor, with linear perspective cues and/or textures, at the far and near positions in life-like settings. Testing the effect of linear perspective cues and textures on the perceived size of the far and near stimuli in a VR environment can allow us to compare the effects that we observed for stimuli displayed over 2D flat images with 3D virtual stimuli.

Pictorial depth cues are not the only depth cues available in VR settings. Non-pictorial depth cues (i.e., vergence and binocular disparity) are also available in VR environments. A classic way to test the effect of non-pictorial depth cues on size constancy is to control viewing conditions. Although the role of binocular viewing in size constancy is well-reported in the real-world environment (e.g., Holway & Boring, 1941; Millard et al., 2020), the role of binocular viewing in virtual environments remains controversial. For example, in a classic study, Holway and Boring (1941) tested the effect of binocular vision on size constancy under binocular and monocular viewing conditions in a real-world environment. Their results revealed that the degree of size constancy was greater under binocular viewing condition. Eggleston et al. (1996) replicated Holway and Boring's experiment in a virtual environment. Yet, their results revealed that the degree of size constancy did not differ between the binocular and monocular viewing conditions in their virtual environment. This finding contradicts studies that have demonstrated how binocular vision significantly influences depth perception (Scarfe & Glennerster, 2021; Svarverud et al., 2010) and size judgments (e.g., Chen et al., 2019; Hornsey & Hibbard, 2021) within VR environments.

Differences in perceived depth and size perception between real and virtual environments can partly be explained by decoupling between vergence and accommodative responses which causes unnatural conflicts in processing visual information in VR environments (Hoffman et al., 2008). Whether or not non-pictorial depth cues provide reliable depth information in VR settings, despite vergence-accommodation conflict, is less understood. In a recent study, Rzepka et al. (2023) demonstrated that viewers tend to rely more on cognitive factors, such as familiar size, when non-pictorial depth cues (i.e., accommodation and vergence) were in conflict with each other. Their finding was partially aligned with Linton's (2020, 2021, 2023) minimal theory of vision, which explains size and depth judgments as cognitive responses influenced by natural scene statistics. The authors further argued that the effect of binocular disparity cues might also diminish due to the resolution of VR headset and the vergence-accommodation conflict, which consequently decrease the reliability of other non-pictorial depth cues as well. Hence, previously reported effects of non-pictorial depth cues on the degree of size constancy in virtual environments have been contradictory. The contradiction may arise from differences in the virtual environments studied and the methods used. Therefore, a systematic investigation of the influences of both binocular and pictorial depth cues on size constancy is necessary.

In the present investigation, we tested the effects of linear perspective cues and textures on size constancy under monocular (with one eye covered with an eye-patch) and binocular (with two uncovered eyes) viewing conditions. The effects of linear perspective cues and textures on size constancy were tested by systematically adding or removing these two pictorial depth cues from a hallway with walls and stones in a virtual environment (Figure 1).

Participants reported the perceived size of the far and near stimuli under the binocular and monocular viewing conditions. We hypothesised that if both pictorial and non-pictorial depth cues contribute to size constancy in VR environments (Chen et al., 2019; Hornsey & Hibbard, 2021; Scarfe & Glennerster, 2021; Svarverud et al., 2010), then size constancy would increase with an increase in the number of depth cues so that the virtual environment with both linear perspective cues and textures would produce the largest level of size constancy under the binocular viewing condition while the virtual environment without linear perspective cues and textures would produce the smallest level of size constancy under the monocular viewing condition. Based on our studies (Yildiz et al., 2019, 2021b), if perceptual rescaling mechanisms operate similarly for stimuli presented in virtual environments as they do for 2D scenes, then we anticipate observing the impact of location of standard circle on the size constancy. Specifically, we predict that stimuli placed at the 'far' position would exhibit greater size constancy.

2. Method

2.1. Participants

This study was conducted during the COVID-19 pandemic. Data were collected between November and December 2020.

Eighteen participants took part in this experiment (M_{Age} = 26.82 years, *SD* = 5.50, 8 males). Before the formal analyses were carried out, we checked whether or not all participants met quality control. To do so, we fitted psychometric curves to the participant's data using Palamedes toolbox (Kingdom & Prins, 2016) and calculated the goodness of fit measures of each psychometric curve using likelihood-ratio tests, each with 1,000 simulations. In this analysis, a *p*-value below 0.05 indicates an unacceptably poor fit (Kingdom & Prins, 2016). Based on this analysis, we removed three participants with goodness of fit values less than p = .05 from the final sample.

All participants had either normal or corrected-to-normal vision. None of the participants reported to have any previous history of psychiatric and neurological disorders. Before the experiment, we measured each participant's visual acuity and stereo-acuity using the Snellen Chart and Randot Contour Circles Test (Antona et al., 2015), respectively. Visual acuity was 20/25 or better in each eye and stereo acuity was 63 arcsec (0.02 arcdeg) or less for all participants.

Before starting the experiment, all participants were informed about the protocol and precautions regarding COVID-19. After this information phase, the participants provided written informed consent. All participants received gift cards to compensate for their time and any inconveniences. The study was approved by the Human Ethics Committee of La Trobe University.

2.2. Stimuli and Apparatus

We used the HTC VIVE Pro VR device (HTC Corporation, 2018) to present the stimuli in a 3D artificial environment. The device has a display resolution of 1440 × 1600 per eye, with a refresh rate of 90 Hz and a horizontal field of view of 110°. The experimental stimuli were created in Unity (Unity Technologies, 2005). We ran the HTC VIVE Pro VR device together with Unity and Steam VR. Unity was also used to call custom JavaScript codes that controlled experimental procedures. Interocular distance was fixed to 6.5 cm.

The perceived size of two red (RGB: 255, 0,0) circles was measured using the method of constant stimuli. One of the circles was designated as the standard stimulus while the other was designated as the comparison stimulus. In half of the trials, the standard circle was placed 5 m away from the viewer while the comparison circle was placed 10 m away from the viewer in the virtual environment. In the other half of the trials, the standard circle was placed 10 m away from the viewer while the comparison circle was placed 5 m away from the viewer in the virtual environment. In all trials, the near circle was presented 1 m to the left side of the viewer while the far circle was presented 0.4 m to the left side of the viewer. Due to these horizontal distances, the distance between the eyes and virtual near and far circles increased slightly (5.09 m for the near and 10.008 m for the far circle). Since these differences were indiscernible, the distances between the eyes and virtual circles were reported as 5 and 10 m for the near and far circles, respectively but the results reported below took into account horizontal distances. Both near and far circles were infinitely thin in the depth extent.

In the main experiment, the standard circle was kept constant at 1.5 m in diameter across all trials while the comparison circle varied around the initial estimation of the perceived size of the far and near circles in 10 increments of 0.15 m. A brief calibration process was completed before the main experiment to determine an initial estimation of the perceived size of the far and near circles with minimal depth cues (i.e., without all those that are possible to remove). The information obtained from this procedure allowed us to customise what incremental sizes of the comparison stimuli to present to participants in the main experiment. In the calibration phase, the perceived size of the far and near circles was measured in a completely dark virtual environment under the monocular viewing condition. The standard circle was kept constant at 1.5 m in diameter across all trials while the comparison circle varied around 1.5 m in 10 increments of 0.35 m. The perceived sizes of the far and near circles were calculated by fitting a psychometric curve to each participant's data (see Statistical Analyses). Estimated PSEs for the far and near circles were used as middle points of comparison circle sizes in the main experiment. The use of personalised middle points for comparison circle sizes in the main experiment allowed us to increase the precision of estimated PSE.

In the main experiment, four different virtual environments were used to determine the effects of different pictorial depth cues in the degree of size constancy: (1) linear perspective +

textures, (2) linear perspective, (3) textures, (4) no pictorial cues (Figure 1). To create a virtual environment that was rich in pictorial depth cues (linear perspective + textures), a hallway with walls and stones was used (Figure 1A). Three additional virtual environments were created by systematically removing linear perspective cues and/or textures from the virtual environment rich in pictorial depth cues. Specifically, the virtual environment with linear perspective cues only (Figure 1B) was created by removing stones from the virtual environment rich in pictorial depth cues while the virtual environment with textures only (Figure 1C) was created by removing the sidewalls from the virtual environment rich in pictorial depth cues. We also created a control virtual environment by removing both linear perspective cues and textures from the virtual environment rich in pictorial depth cues (Figure 1D). The control environment without pictorial depth cues served as a baseline. To assign a colour to the non-textured walls used both in the virtual environment with linear perspective cues and in the control environment, we measured the average colour of each textured wall using Adobe Photoshop and assigned that average colour to the walls in Unity. 2D images of a similar hallway were previously used to test the effects of linear perspective cues and textures on the strength of the corridor illusion (Yildiz et al., 2019, 2021b). However, in this study, we introduced a modification by adding a blue sky to the top of the hallway. To achieve this, we selected a default skybox without a sun source as the lighting mode in Unity software.

In the main experiment, we also examined the influence of the non-pictorial depth cues on the degree of size constancy by presenting the stimuli under the binocular and monocular viewing conditions. In each viewing condition, participants viewed the stimuli through VR goggles. Under the binocular viewing condition, both the left and right eyes received visual information. Under the monocular viewing condition, we covered the participants' left eye with a tissue. Thus, only the right eye received visual information under the monocular viewing condition.

2.3. Procedures

Participants in the experiment were seated throughout the study. Although they were not physically restrained to a chin rest, they were instructed to maintain their head in a consistent position during the entire duration of the experiment. Each participant completed two blocks in the calibration phase and 16 blocks in the main experiment. Each block corresponded to a different experimental condition. The standard circle was presented 10 m away from the participant in the virtual environment in half of the blocks while it was presented 5 m away from the participant in the virtual environment in the other half of the blocks. Thus, each of the virtual environments was presented twice under each viewing condition: once with a far standard circle and once with a near standard circle. Half of the participants completed the experimental blocks with the far standard circle before performing the experimental blocks with the near standard circle, while the other half of the participants did the reverse. In each experimental block, the comparison circle was presented 10 times at each increment. Thus, there were 100 trials in each experimental block. The order of trials within each experimental block was randomised for each participant. In the main experiment, the order of the virtual environment presentations and the order of viewing conditions were also randomised for each participant.

At the beginning of each block, the position of the standard circle was indicated by a white arrow to inform participants about the positions of standard and comparison circles. Both in the calibration phase and the main experiment, each trial started with a presentation of the standard circle in the virtual environment. After 1 sec, the comparison circle was presented. Both the standard and the comparison circles were displayed in the virtual environment until participants pressed a button to report whether the comparison circle was smaller or larger than the standard one. The comparison circle disappeared after the button pressing. The standard circle was always displayed in the virtual environment. Each experimental block lasted about 6 minutes. A self-paced break was provided at the end of each experimental block.

2.4. Statistical Analyses

Psychometric curves for each condition in each participant were created by counting the number of times the comparison circle was reported as appearing larger than the standard circle at each increment. The probability (P) of the participant reporting the comparison circle as appearing larger than the standard circle at each increment was calculated. Using the Palamedes toolbox (Kingdom & Prins, 2016), the following log-Quick function was fitted to the data:

$$P\ (x;\ \theta, \beta) = \left(1 - 2^{-10^{\beta(x-\theta)}}\right)$$

$$\Psi\ (x;\ \theta, \beta, \gamma, \lambda) = \gamma + (1 - \gamma - \lambda) \times P\ (x;\ \theta, \beta)$$

The function had four parameters: a slope (β), a threshold (θ), a guess rate (λ), and a lapse rate (γ). The lapse rate and guess rate were fixed at 0.02. The slope and the threshold were free parameters. The point of subjective equality (PSE) was calculated as $P = 0.5$. The PSE represented the size of the comparison circle at which the participant had an equal probability of judging the circle as being smaller or larger than the standard for a given experimental condition. The goodness of fit measures of each psychometric curve were calculated by conducting likelihood-ratio tests, each with 1,000 simulations. The goodness of fit analysis revealed that the estimated curves of the model fit well across the conditions for each participant (p ranged between 0.061 and 0.981). The resulting PSE values were used to estimate the degree of size constancy for the far and near circles in each experimental condition.

To calculate the degree of size constancy for the far circle, we reasoned that the participants would perceive the circles as having the same size despite changes in viewing distance if size constancy were perfect (100%). If this were the case, then the participants would perceive the 1.5 m comparison circle placed 5 m away from themselves as having the same size as the 1.5 m standard circle placed 10 m away. Conversely, the participants' judgments would be purely based on the retinal size of the standard and comparison circles if there were no size constancy (0%). If this were the case, then the participants would perceive the 0.75 m comparison circle placed 5 m away from themselves as having the same size as the 1.5 m standard circle placed 10 m away. Based on this reasoning, we used the following formula to estimate the degree of size constancy for the far circle:

$(\text{PSE}_{\text{Far Circle}} - 0.75) / (1.5 - 0.75) \times 100$

where 0.75 and 1.5 correspond to the expected PSEs if judgments were based on the retinal size and the perfect size constancy, respectively.

We followed a similar reasoning to calculate the degree of size constancy for the near circle. Specifically, we reasoned that the participants would perceive the 1.5 m comparison circle placed 10 m away from themselves as having the same size as the 1.5 m standard circle placed 5 m away if there were perfect size constancy (100%). Conversely, the participants' judgments would be purely based on the retinal size of the standard and comparison circles so that the participants would perceive a 3 m comparison circle placed 10 m away from themselves as having the same size as the 1.5 m standard circle placed 5 m away if there were no size constancy (0%). Based on this reasoning, we used the following formula to estimate the degree of size constancy for the near circle:

$(3 - \text{PSE}_{\text{Near circle}}) / (3 - 1.5) \times 100$

where 3 and 1.5 correspond to the expected PSEs if judgments were based on retinal size and the perfect size constancy, respectively.

We also calculated the curve width (ω) as:

$$\omega = P_{0.75} - P_{0.25}$$

The results of the psychometric function for x when P = 0.25 and P = 0.75 were used as $P_{0.25}$ and $P_{0.75}$, respectively. Curve widths were used to measure the degree of uncertainty in the participants' responses for each experimental condition (Yildiz et al., 2019, 2021a, 2021b). Namely, higher values of ω indicate greater perceptual uncertainty.

The resulting size constancy values and curve widths were analysed by conducting a 2 x 2 x 4 repeated measures analysis of variance (ANOVA) in JASP software package version 0.14.1 (University of Amsterdam, Amsterdam, Netherlands) with Viewing Condition ((1) Binocular, (2) Monocular), Location of Standard Circle ((1) Near Standard Circle, (2) Far Standard Circle) and Pictorial Depth Cues ((1) Linear Perspective + Textures, (2) Linear Perspective, (3) Textures, (4) No Cues) as within-subject factors.

Tukey's Honest Significance Difference (HSD) post-hoc pairwise comparison tests were performed to further examine significant interactions (Tukey, 1949). We applied Greenhouse-Geisser corrections whenever the assumption of sphericity was not met according to a Mauchly's sphericity test.

Finally, to examine the impact of Pictorial Depth Cues at an individual level, we conducted model comparisons using the Palamedes toolbox (Kingdom & Prins, 2016). Likelihood-ratio tests were employed to compare the fit of a fuller model, allowing thresholds to vary freely, with a lesser model, where both threshold and slope parameters were fixed, for both far and near stimuli in each viewing condition per participant. The fuller model allowed thresholds to take on any value, offering the ability to detect the influence of pictorial depth cues on perceived size at an individual level in the virtual environment. In contrast, the lesser model was defined as a special case of the fuller model, with fixed thresholds and slopes. Our comparative analysis used individual data sets for the far and near stimuli in each viewing condition, following the likelihood ratio test by Kingdom and Prins (2016). To determine the preferred model, we assessed 1,000 bootstrap samples, accepting the fuller model over the lesser model if its likelihood was higher in more than 95% of the samples. This approach enabled us to examine whether the data better supported the fuller model, which had fewer restrictions. In adopting this conservative approach, we only accepted the fuller model if it was necessary to effectively explain the data.

3. Results

In summary, in terms of the percentage of size constancy, there were no differences between conditions (i.e., far versus near) when the circles were presented in a completely dark virtual environment (see Calibration Phase in subsection 3.1). Curve widths also did not differ between the conditions (i.e., far versus near) in the calibration phase. In the main experiment, the presence of linear perspective cues increased the degree of size constancy, especially for the far circle, regardless of viewing conditions (i.e., monocular versus binocular). In terms of curve widths, perceptual uncertainty was consistently greater for the near compared to the far circle.

3.1. Calibration Phase: Size Constancy in Complete Darkness

3.1.1. % Size Constancy

The level of size constancy for the far and near circles presented in a completely dark virtual environment were compared with each other (Figure 2). A paired samples *t*-test showed that there was no difference in size constancy between the far and near circles, t (14) = 1.307, p = .212, d = 0.337.

3.1.2. Curve Widths

Curve widths for the far and near circles presented in a completely dark virtual environment were compared with each other (Figure 3). A paired samples *t*-test revealed that there was no difference in curve widths between the far and near circles, t (14) = 1.081, p = .298, d = 0.279.

3.2. Main Experiment: The Effects of Pictorial Depth Cues on Size Constancy under the Binocular and Monocular Viewing Conditions

3.2.1. % Size Constancy

The level of size constancy for the far and near circles in each of the four virtual environments were compared with each other under the binocular and monocular viewing conditions by conducting a 2 × 2 × 4 repeated measures ANOVA (Figure 4). An interaction was observed between Pictorial Depth Cues and Location of Standard Circle (F (3, 42) = 2.93, p = .044, η_p^2 = 0.174) (Figure 5).

To further examine the Pictorial Depth Cues × Location of Standard Circle interaction, we conducted Tukey's HSD pairwise comparison tests (Figure 5). These tests showed that the degree of size constancy was consistently greater for the far circle presented in the environments with linear perspective cues compared to the same stimulus presented in the environment without any pictorial cues (both p_{corr} = .001). There were no differences in the levels of size constancy for the far circle presented in the environment with textures versus the far circle presented in the environment without any pictorial cues ($p_{corr} \geq .999$). The degree of size constancy was consistently greater for the near circle presented in the environments with linear perspective cues compared to the same stimulus presented in the environment without any pictorial cues (both $p_{corr} \leq .031$). There were no differences in the levels of size constancy for the near circle presented in the environment with only textures versus the near circle presented in the environment without any pictorial cues (p_{corr} = .959). Linear perspective cues produced a greater degree of size constancy than textures for the far (p_{corr} = .001) but not for the near circle (p_{corr} = .308). Moreover, the degree of size constancy was greater for the far circle compared to the near circle in the environments with linear perspective cues (both $p_{corr} \leq .002$). The difference in the degree of the size constancy for the far and near circles disappeared in the environments with only textures (p_{corr} = .659).

All other interactions did not reach significance (all $p \geq .075$). There was the main effect of Location of Standard Circle (F (1, 14) = 7.93, p = .014, η_p^2 = 0.362) but not Viewing Condition (F (1, 14) = 0.39, p = .540, η_p^2 = 0.027). The main effect of Pictorial Depth Cues (F (2, 25) = 21.55, p < .001, η_p^2 = 0.606, Greenhouse-Geisser corrected) was also significant.

To investigate the effect of Pictorial Depth Cues at an individual level, we conducted model comparisons using the Palamedes toolbox (Kingdom & Prins, 2016). In both binocular and monocular viewing conditions for the far and near circles, we analysed data from 15 participants. For 11 out of 15 participants, the fuller model, which included threshold as a free parameter, demonstrated a better fit than the lesser model for the far circle. Similarly, for the same number of participants, the fuller model provided a better fit for the near circle under the monocular viewing condition. Under the binocular viewing condition, the fuller model provided a better fit for the near circle in 10 out of 15 participants. Taken together, these findings indicate that linear perspective cues contributed to size constancy mechanisms, especially for the far circle, regardless of viewing conditions. Additionally, we observed that the effect of pictorial depth cues was consistent at an individual level for more than 66% of participants across viewing conditions for both the far and near circles.

3.2.2. Curve Widths

Curve widths for the far and near circles in each of the four environments were compared with each other by conducting a 2 × 2 × 4 repeated measures ANOVA (Figure 6). Results revealed that main effects of Location of Standard Circle (F (1, 14) = 77.17, p < .001, η_p^2 = 0.846) and Pictorial Cues (F (2, 27) = 5.15, p = .014, η_p^2 = 0.269, Greenhouse-Geisser corrected) were significant, but the main effect of Viewing Condition (F (1, 14) = 0.73, p = .407, η_p^2 = 0.050) was not. Namely, the perceptual uncertainty was consistently greater for the near compared to the far circle (p_{corr} < .001) (Figure 7). The perceptual uncertainty decreased in the environment with only textures and in the environment without any pictorial cues compared to the one with both linear perspective cues and textures (both $p_{cor} \leq .011$). Interactions did not reach significance (all $p \geq .279$).

4. Discussion

The present VR study investigated the effects of linear perspective cues and textures on the degree of size constancy under binocular and monocular viewing conditions. Our results demonstrated that the degree of size constancy for both the far and near circles increased in the virtual environment rich in pictorial depth cues compared to the virtual environment without any pictorial depth cues. The effect of pictorial depth cues on size constancy was more pronounced for the far compared to the near circle. Moreover, our results revealed that size constancy mechanisms were mainly driven by the presence of linear perspective cues rather than textures, as the degree of size constancy for the condition with linear perspective cues only yielded similar results with the condition where all pictorial cues were available. We found no difference between monocular and binocular viewing conditions across the four different virtual environments. Thus, the presence of linear perspective cues increased the degree of size constancy, especially for the far circle, regardless of viewing conditions.

VR technology provides the opportunity to simulate real-life situations and allows users to actively interact in life-like settings. For example, VR simulations have been used in real estate showrooms to give users a better sense of the size and scale of a building and in aviation and military training for the purposes of active or exploratory practice (Ke et al., 2023; Morice et al., 2021; Skarbez et al., 2022). Moreover, the effects of VR-based tasks on executive functions and visuospatial abilities reveal that VR is a promising tool for neurorehabilitation (for review, see Riva et al., 2020) and can be used in the assessment and treatment of unilateral spatial neglect (Riva et al., 2020), amblyopia (Jimenez-Rodriguez et al., 2021), and Parkinson disease (Canning et al., 2020).

In all of the cases listed above, VR users are expected to transfer what they learnt from the virtual environment to the real world. Yet, previous reports demonstrated that there are inaccuracies in the perception of virtual environments. Although inaccuracies seem to be less prominent in newer VR headsets (Kelly, 2022), perceived distance (Hayashibe, 2002; Kelly et al., 2017; Sahm et al., 2005) and size (Hornsey & Hibbard, 2021; Hornsey et al., 2020; Kenyon et al., 2007; Murgia & Sharkey, 2009) are persistently reported as being underestimated in virtual environments compared to the real world. The unnatural viewing geometry, which consequently creates vergence-accommodation conflict, has been used to explain the misperception of space in virtual environments (Hoffman et al., 2008; Tong et al., 2022).

Many have argued that the presence of various pictorial depth cues might help to minimise this distortion. For example, Chen et al. (2019) tested the degree of size constancy both in real world and virtual environments with and without pictorial depth cues. In the real world environment, they presented a stimulus at either 40 or 80 cm away from the observer and asked their participants to adjust the size of the stimulus presented at the other distance. Stimuli were displayed over a black background on the monitor. A similar procedure was repeated in a virtual environment comprising a corridor rich with pictorial depth cues and a virtual control environment without pictorial depth cues. Their results revealed that the degree of perceptual size constancy was higher in the real world (95.9%) compared to the virtual environments with (50.7%) and without (26.2%) pictorial depth cues.

In line with Chen et al. (2019), our results revealed that the degree of perceptual size constancy was higher in the virtual environment with pictorial depth cues (52%) compared to the one without pictorial cues (36%). Their larger differences in size constancy might be explained by differences in viewing distances used in their (40 or 80 cm) versus our (5 and 10 m) study. Because we have not tested the perceived sizes of the far and near circles in the real environment, we cannot compare the degree of size constancy obtained in our VR setting with the real world. Based on previous reports, we argue that size constancy in the real world would have been higher than the 52% that was obtained here with the virtual environment with pictorial depth cues. Previously, Murgia and Sharkey (2009) demonstrated that the ratio between the sizes of real and virtual stimuli was close to unity in the immersive virtual reality environment (CAVE) with pictorial depth cues. Notably, in their study, the effects of pictorial depth cues on the degree of size constancy were demonstrated indirectly by using an object placement task. Namely, the participants' task was to place a virtual sphere to the position where they have seen a virtual cube. A real cube and a real sphere that matched the size of their virtual counterparts were presented in the CAVE to provide reference to participants. The authors hypothesised that if the participants assessed the relative size of the sphere and the cube correctly, then the accuracy of estimated depth would increase and participants would perform more accurately in the object placement task. The reasons for why the degree of size constancy in the virtual environment matched almost perfectly with the objects' real size when an indirect measure was used in this study remain unknown.

We further showed that linear perspective cues exert a stronger influence than textures on size constancy. This result aligns with Witmer and Kline's (1998) findings, which showed that textures had minimal impact on distance estimates in virtual environments. Similarly, the recent work of Yoo, Lee, and Joo (2023) further supports our conclusions, demonstrating that linear perspective cues significantly outweigh texture gradients and binocular disparity cues, particularly in cases of incongruency between depth signalled by binocular disparity and pictorial depth cues. Our findings seem to diverge from our earlier results, which suggested similar effects of linear perspective cues and textures on perceptual rescaling mechanisms in the corridor illusion. This inconsistency between 2D images with pictorial depth cues and their 3D counterparts may be attributed to differences in screen resolutions; low resolutions can make texture gradient edges and boundaries less distinguishable. Notably, brick patterns, incorporating linear perspective cues, have shown a notable increase in the degree of size constancy in VR settings (Sinai et al., 1999). This finding further supports the significance of linear perspective cues in determining size perception in virtual environments.

Importantly, our results revealed that neither the degree of size constancy nor the level of perceptual uncertainty showed any significant difference between the virtual environment with both linear perspective cues and textures and the one with only linear perspective cues. These results contradict the prevalent statistical optimal combination assumption of the linear maximum likelihood estimation (MLE) model. According to this model, estimates derived from multiple depth cues should be combined based on their relative reliability, leading to the most probable 3D interpretation (Ernst & Bulthoff, 2004, but also see Kemp, Cesanek, & Domini, 2023). However, our results suggest a different scenario, potentially due to the textures' considerably lower reliabilities. As a consequence, the effects of textures appear to have been predominantly suppressed by the presence of highly reliable and robust linear perspective cues.

Our results also indicated that the degree of size constancy was greater for objects positioned at farther distances within the 3D virtual environment. This finding aligns with our previous research demonstrating a more pronounced perceptual rescaling effect for stimuli placed in positions where pictorial depth cues suggest greater depth in 2D flat images (Yildiz et al., 2019, 2021a, 2021b). Notably, it is worth considering that since both standard and comparison stimuli were presented within the same virtual environment at varying virtual distances, the size constancy scale used in this study may not be a pure index solely measuring perceived size for objects at far and near positions. This design corresponds to a direct comparison task, which is commonly employed to assess perceived size in 2D flat images (Brislin, 1974; Cretenoud et al., 2020; Leibowitz, et al., 1969; Rennig, Karnath, & Huberle, 2013). However, the estimated perceived size in direct comparison tasks may not be a completely pure measure. In our previous studies, we compared the estimated perceived size from direct comparison tasks with those obtained using indirect comparison tasks (Yildiz et al., 2019, 2021a). In the indirect comparison task, we presented the comparison stimulus outside of the background image with pictorial depth cues. The results demonstrated that perceptual rescaling was stronger for stimuli positioned where pictorial depth cues indicated greater depth in 2D flat images, compared to stimuli placed in positions with minimal or no depth cues. Additionally, perceptual rescaling mechanisms influenced the perceived size of stimuli presented at positions where pictorial depth cues suggested little or no depth in the direct comparison task, but not in the indirect comparison task. We propose that conducting the degree of size constancy assessment using an indirect comparison task in a virtual environment would likely yield similar effects.

Interestingly, we found no difference in size constancy between binocular and monocular viewing conditions in VR. It remains unknown as to why binocular vision would not increase the degree of size constancy in some cases. Some have argued that observers' head movements effectively boost participants' performance in perceptual rescaling during monocular viewing (Witmer & Kline, 1998). Indeed, motion is a dominant cue that influences the salience of other depth cues, including stereopsis. Although participants were instructed not to move their heads, small head movements that may have occurred could have yielded depth information in the form of motion parallax under monocular viewing conditions (Aytekin & Rucci, 2012). This could also explain why we observed 30% size constancy in the calibration task, in which participants viewed the stimuli under monocular viewing conditions in a completely dark VR environment. In the calibration task, we used relatively larger increments for the comparison stimulus, such that in some trials, one of the stimuli appeared behind the other one. This occlusion cue could have also contributed to the unexpectedly greater degrees of size constancy reported in the calibration task.

Another possible reason for why we found no difference between binocular and monocular viewing conditions in VR environment is that the vergence-accommodation conflict diminishes the overall reliability of non-pictorial depth cues so that the visual system gives more importance to pictorial depth cues while establishing size constancy. In line with this, Linton (2020, 2021) has shown that when vergence and accommodation are dissociated, vergence signals do not contribute to distance perception and our size and distance perceptions rely exclusively on cognitive knowledge about changes in viewing distance. In light of these previous findings, it is not surprising to find no contribution of binocular vision in VR and a greater reliance on cognitive influences. Moreover, we employed fixed interocular distance values for each participant. While using fixed interocular distance is a common practice in VR studies, it may lead to a reduction in the reliability of binocular depth cues.

Conclusions

The present study demonstrates that the presence of pictorial but not the non-pictorial depth cues increased the degree of size constancy in virtual environments. The effect produced by linear perspective cues was more pronounced for the far compared to the near circle. These findings contribute to a better understanding of how virtual environments should be modelled for creating life-like settings in which the users can transfer what they learnt from the virtual environment to the real world.

Code availability Code used for processing is not publicly available. Reasonable requests may be considered by the corresponding author.

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Data Availability The data can be accessed here: https://figshare.com/articles/dataset/main_experiment/24578869

Open Practices Statement None of the materials for the experiments reported here is available, and none of the experiments was preregistered.

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Figure 1

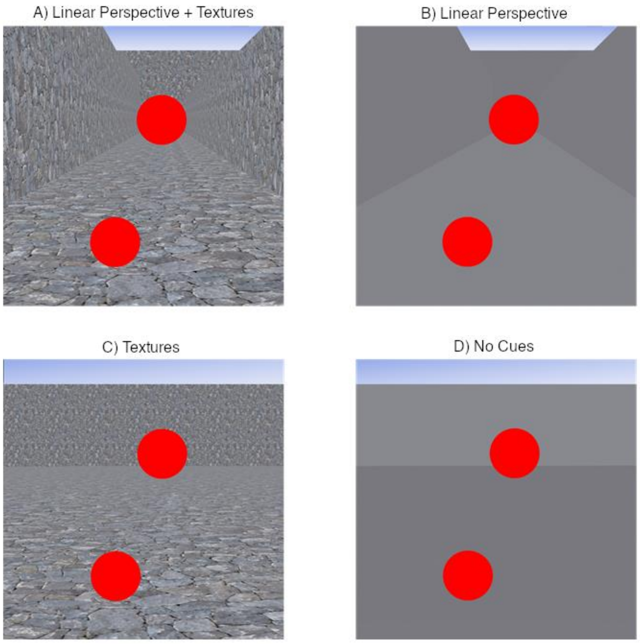

Figure 1. Illustration of virtual environments used in the present study. A) A hallway with stones (textures) and walls (linear perspective cues). B) A hallway with walls (linear perspective cues). C) A hallway with stones (texture gradients). D. Control virtual environment without pictorial depth cues.

Figure 2

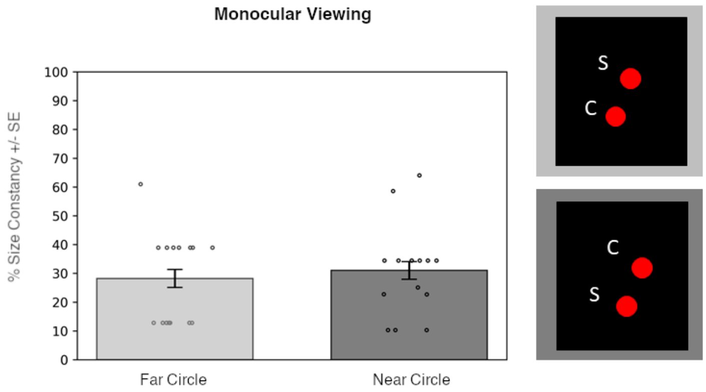

Figure 2. Mean percentages of size constancy for the far and near circles in the calibration experiment. Mean percentages of size constancy were computed by calculating the difference between the physical size of the circle and its corresponding PSE. Error bars represent the standard errors around the mean for within-subject contrasts. We used procedures described by O'Brien and Cousineau (2014) to calculate the error bars.

Figure 3

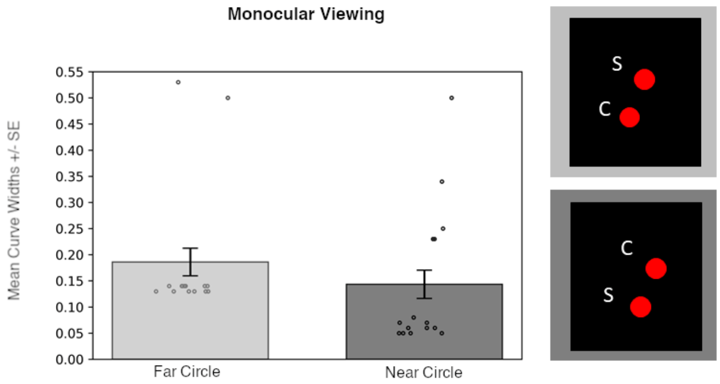

Figure 3. Mean curve widths for the far and near circles in the calibration phase. Mean curve widths were computed by subtracting P = 0.25 from P = 0.75. Error bars represent the standard errors around the mean for within-subject contrasts. We used procedures described by O'Brien and Cousineau (2014) to calculate the error bars.

Figure 4

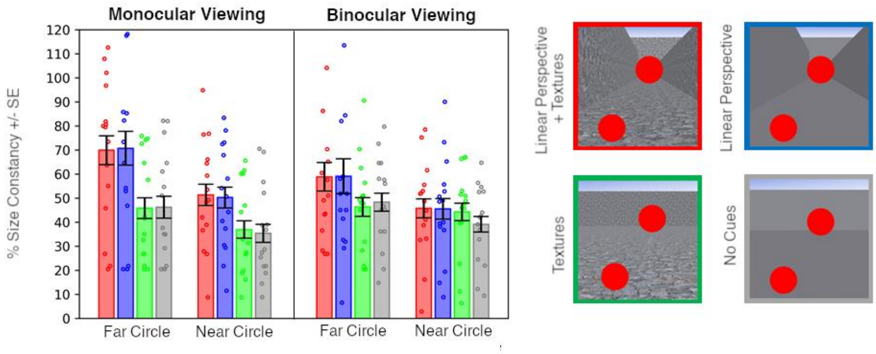

Figure 4. Mean percentages of size constancy for the far and near circles in each of the four virtual environments under the binocular and monocular viewing conditions. Mean percentages of size constancy were computed by calculating the difference between the physical size of the circle and its corresponding PSE. Error bars represent the standard errors around the mean for within-subject contrasts. We used procedures described by O'Brien and Cousineau (2014) to calculate the error bars.

Figure 5

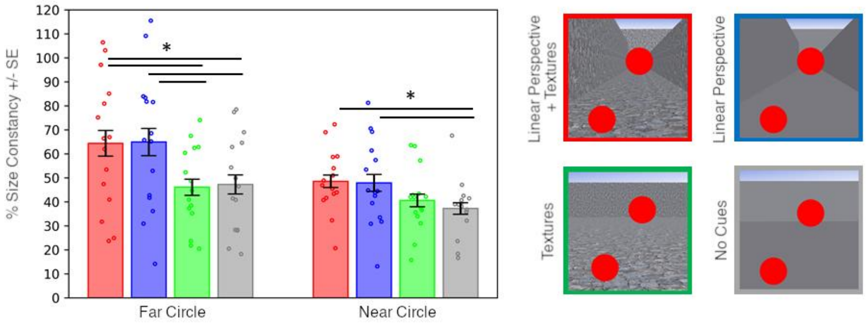

Figure 5. Mean percentages of size constancy for the far and near circles in each of the four virtual environments. Mean percentages of size constancy were computed by calculating the difference between the physical size of the circle and its corresponding PSE. Asterisks represent significant differences from the no cues condition at $p < .05$ after Tukey's HSD corrections were made for multiple comparisons. Error bars represent the standard errors around the mean for within-subject contrasts. We used procedures described by O'Brien and Cousineau (2014) to calculate the error bars.

Figure 6

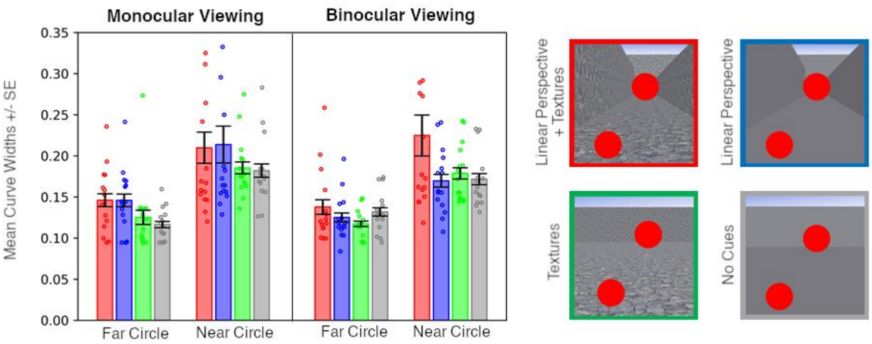

Figure 6. Mean curve widths for the far and near circles in each of the four virtual environments under the binocular and monocular viewing conditions. Mean curve widths were computed by subtracting P = 0.25 from P = 0.75. Error bars represent the standard errors around the mean for within-subject contrasts. We used procedures described by O'Brien and Cousineau (2014) to calculate the error bars.

Figure 7

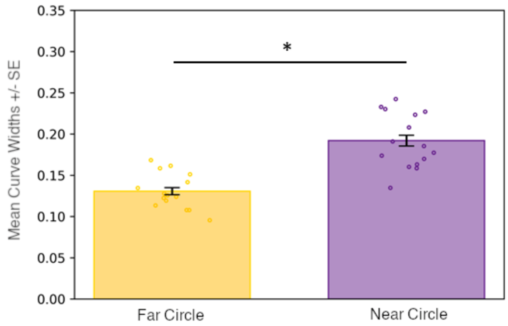

Figure 7. Mean curve widths for the far and near circles. Mean curve widths were computed by subtracting P = 0.25 from P = 0.75. Error bars represent the standard errors around the mean for within-subject contrasts.