Am I Floating or Not? : Sensitivity to Eye Height Manipulations in HMD-based Immersive Virtual Environments

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ABSTRACT

Eye height manipulations have previously been found to affect judgments of object size and egocentric distance in both real and immersive virtual environments. In this short paper we report the results of an experiment that explores people's sensitivity to various offsets of their eye height in VR using a forced-choice task in a wide variety of different architectural models. Our goal is to better understand the range of eye height manipulations that can be surreptitiously employed under different environmental conditions.

We exposed each of 10 standing participants to a total of 121 randomly-ordered trials, spanning 11 different eye height offsets between -80cm to $+80\text{cm}$, in 11 different highly detailed virtual indoor environments, and asked them to report whether they felt that their (invisible) feet were floating above or sunken below the virtual floor. We fit psychometric functions to the pooled data and to the data from each virtual environment and each participant individually. In the pooled data, we found a *point-of-subjective-equality* (PSE) very close to zero (-3.8cm), and 25% and 75% detection thresholds of -16.1cm and $+8.6\text{cm}$ respectively, for an *uncertainty interval* of 24.7cm . We also observed some interesting variations in the results between individual rooms, which we discuss in more detail in the paper. Our findings can help to inform VR developers about users' sensitivity to incorrect eye height placement, to elucidate the potential impact of various features of interior spaces on people's tolerance of eye height manipulations, and to inform future work seeking to employ eye height manipulations to mitigate distance underestimation in VR.

CCS CONCEPTS

• **Human-centered computing** → **Virtual reality**; • **Computing methodologies** → **Perception**.

KEYWORDS

Virtual reality, spatial perception, eye height

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1 INTRODUCTION

In most immersive virtual reality (VR) experiences, the user inherently interprets what they see as if it were a view from their own eyes [Leyrer et al. 2015b]. Several common and uncommon situations have the potential to create a dissociation between the user's simulated eye height in VR and their concurrent actual eye height in the real world, however. When multiple users all share the same view, for instance on an immersive projection display, only one of them will see the virtual environment from their own eye height, and this situation has been associated with errors in spatial judgments about the depicted scene [Pollock et al. 2012]. VR applications designed for seated use may not adjust the presented viewpoint to match the user's actual eye height, either from a standing or seated vantage point. Some applications provide the user with locomotion controls that allow unconstrained 3DOF movement in VR; the relationship between the virtual viewpoint and the user's real world eye height can then be rapidly lost. Finally, some applications deliberately manipulate the user's eye height in VR to achieve various purposes, such as to support the illusion of being a giant [Kim and Interrante 2017] or to help users make more accurate judgments of egocentric distances [Leyrer et al. 2011].

Our goal in this paper is to seek a better understanding of people's sensitivity to discrepancies between their actual standing eye height in the real world and the height off the floor of their virtual vantage point in VR. This information has the potential to inform developers of VR applications how much leeway they are likely to have in pre-setting or adjusting a user's eye height in VR before they would be likely to notice that their eye height is wrong. For applications that rely on eye height manipulations, it is possible that surreptitious manipulations could have different effects than manipulations that are overt.

2 RELATED WORK

Egocentric distance perception has been well-studied in both VR and the real world. A large body of prior work focuses on egocentric judgments of horizontal distances over a groundplane, which are generally found to be underestimated in VR relative to in the real world [Renner et al. 2013]. A much smaller body of work has specifically looked at egocentric distance perception in the vertical direction; it is reported to be generally *overestimated*, especially from the top looking down [Stefanucci and Proffitt 2009]. In VR, most research has found that embodiment in a size-matched self-avatar enables more accurate judgments of egocentric distances both horizontally [Mohler et al. 2010; Ries et al. 2008] and vertically [Lin et al. 2015].

There is a modest body of research on the impact of eye height offsets on size and distance perception. Wraga [1999] used a false floor in real world experiments to surreptitiously manipulate people's effective eye height in relation to the groundplane on which objects could be seen to sit and found a strong effect of the eye height manipulation on object size (height) perception, for both seated and standing observers. Dixon et al. [2000] found that surreptitious eye height manipulations in VR had a similar effect on size perception for generic objects resting on the same groundplane as the observer. Kim and Interrante [2017], however, found no impact

of overt eye height manipulations on users' perception of the size of a generic object embedded in a richly detailed realistic virtual room.

Langbehn et al. [2016] investigated participants' sense of whether it was they or their environment that had changed size after coordinated manipulations of eye height and IPD and found that participants were more likely to believe that their surrounding environment, rather than they themselves, had changed size when they were embodied than when not. Piumsomboon et al. [2018] found that stereo disparity (IPD) in conjunction with eye height

Figure 1: Views of each of the virtual environments used in our experiment, taken from an eye height of 150cm and facing in the default initial direction. The Lightroom model was created by "Koola". The Berlin Flat model was created by Xoio. The SciFi Bunk model was created by Liam Tart. The Sun Temple [Games 2017], Zen Garden, Scifi Hallway, Realistic Room and Blueprint Office models were created by Epic Games.

Figure 2: Views of the SciFi Bunk with each of the different eyeheight offsets applied. Top row (left to right): +80cm, +32cm, +12cm, +5cm; Middle row: +2cm, 0cm, -2cm; Bottom row: -5cm, -12cm, -32cm, -80cm.

manipulations influenced people’s sense of being a giant versus flying in VR when no embodiment was visible.

Leyrer et al. [2011] found that eye height manipulations of +50cm or -50cm had a significant impact on participants’ judgments of egocentric distance in a highly realistic indoor environment and were unnoticed by participants when a between-subjects experimental design was used; Leyrer et al. [2015a] showed that eye height manipulations could be successfully used to correct for distance estimation errors in VR in an individualized way, regardless of whether the eye height manipulation was noticed or not.

3 OUR EXPERIMENT

As eye height offsets have been shown to affect judgments of size and distance in VR, and situations arise in which such offsets may occur (either by design or by accident), we felt that it would be useful to investigate the extent to which and conditions under which people are likely to be aware of the existence of a displacement between their standing eye height and the altitude of their virtual viewpoint.

3.1 Design

We used a within-subjects, forced-choice experiment in which participants were asked to report the direction (“above” or “below”) of the offset of their virtual viewpoint over 121 total trials spanning 11 different offsets ranging from -80cm to +80cm in approximately equal log intervals (-80, -32, -12, -5, -2, 0, +2, +5, +12, +32, +80) in each of 11 different richly detailed architectural environments containing both floor and ceiling surfaces. Figure 1 shows what each of these environments looks like. Figure 2 shows what each of the different eyeheight offsets looks like, applied in the SciFi Bunk model.

3.2 Participants

We recruited 10 participants (6M, 4F), ages 21-34 ($\mu = 25.9 \pm 4.7$), by word of mouth from our local university community. Participants were compensated with a \$10 gift card to an online retailer.

3.3 Materials

Participants viewed the virtual environment using an HTC Vive head-mounted display, which weighs ~1 lb and has two 1080 × 1200 OLED displays, one for each eye, presenting a stereo view over a combined 100°h × 110°v. We used Valve’s Lighthouse tracking system to dynamically track the position and orientation of the HMD within a ~15’ × ~15’ area at one end of a larger open lab space; the eye height offset was added to this tracked position as a constant displacement in the z-direction. The virtual environment models were all obtained as free assets from the Unreal Engine Marketplace or are built-in assets in the Unreal game engine. The virtual environment was rendered using Unreal Engine on an ORIGIN PC with an Intel Core i7 6850K Hex-Core 3.6GHz processor, 32GB DDR4 SDRAM (2800MHz), and a single 8GB NVIDIA GeForce GTX 1080 Founders Edition graphics card.

3.4 Procedure

Participants were screened for normal visual acuity and stereo vision ability. After giving written informed consent, they were asked to read written instructions explaining the experiment procedure. The instructions informed them that they would be immersed in a series of different virtual interior and exterior spaces, and in each one they should briefly look around (without walking to a different position) and then verbally indicate whether they felt that their feet (which we told them they would not be able to see in VR) would be floating above (“above”) or sunken below (“below”) the virtual floor, if they were not invisible.

At the start of the experiment, the participant stood at a comfortable location within the tracked space and put on the HMD and a pair of noise-cancelling headphones. The experimenter verified that the headset was properly secured. Each participant completed a total of 121 trials in each of which they were immersed in one of a series of 11 different virtual environments with one of 11 different eye height offsets. The 121 stimuli were presented in a different random order for each participant. To ensure comfortable transitions and discourage pairwise comparisons of eye height between trials, the participant's view was faded out to black after they made each judgment, and remained black for a few seconds before the next environment faded in. To avoid fatigue, participants were invited to take a short break after 44 and 88 trials, during which time they were invited to enjoy some sparkling water and snacks. Participants were allowed to proceed at their own pace and everyone completed all of the trials in under 1 hour (most took only about 30 minutes).

4 RESULTS

We used the `psignifit` toolbox¹ to fit a psychometric function to the pooled data from all 10 participants (Figure 3), with a goodness-of-fit of 0.00062. We found a very slight overestimation of eye height, corresponding to a PSE of -3.8cm , and a modest uncertainty interval of 24.7cm , with 25% of participants responding "above" at an eyeheight offset of -16.1cm and 75% responding "above" at an eyeheight offset of 8.6cm . The horizontal error bars around the PSE and each of the endpoints of the uncertainty interval indicate the 95% confidence intervals for each of these values, provided by `psignifit` [Schütt et al. 2016].

We also fit psychometric functions to the data from each room separately (Figure 4). Due to the smaller number of data points, the average goodness-of-fit for these curves was only 0.0079 (about 10x worse than for the pooled data). We found a modest variation of the uncertainty intervals between the different rooms, as well

¹ <https://github.com/wichmann-lab/psignifit/archive/master.zip>

Figure 3: A psychometric fit to the pooled data from all trials by all participants.

Table 1: Individual Participants' Data

EyeHeight	25%	PSE	75%	Uncertainty Interval
152cm	78.68%	79.23%	79.79%	1.10%
142cm	77.71%	84.99%	92.26%	14.56%
161cm	89.34%	96.09%	102.84%	13.49%
159cm	92.32%	97.83%	103.33%	11.01%
171cm	91.38%	98.88%	106.38%	15.00%
140cm	90.63%	99.14%	107.66%	17.04%
161cm	97.75%	100.78%	103.81%	6.05%
145cm	98.68%	102.73%	106.78%	8.09%
157cm	96.89%	103.51%	110.12%	13.23%
142cm	96.73%	105.02%	113.31%	16.58%

as some interesting differences in the PSE. Details are provided in Figure 4 and discussed in section 5 below.

Finally, we additionally fit separate psychometric functions to the data from each participant (Table 1), with each offset represented as a percentage of the participant's eye height. Eight of the ten participants had a PSE within 5% of their actual eye height, but the other two exhibited a strong bias to respond "above".

5 DISCUSSION

While our general finding of a slight overestimation of eye height is consistent with the findings of Stefanucci and Proffitt [2009], it may also be somewhat skewed by the responses of the 1-2 participants who more rarely reported the impression of their feet being under the virtual floor, despite the fact that the confidence interval around the PSE is entirely within the negative range. Replicating the experiment with a larger number of participants, or re-doing it using a potentially more sensitive psychometric method, would allow this observation to be stated with greater certainty. Overall, we note that the majority of our participants seemed relatively sensitive to modest eye height manipulations when they knew to look for them, a finding that expands upon the observations of Leyrer et al. [2015a] whose participants typically did not report awareness of eye height manipulations up to $\pm 50\text{cm}$ when the manipulations were encountered in a between-subjects design.

We also note that uncertainty intervals for eye height manipulations tended to be smallest in the scenes that contained elements capable of providing strong familiar size cues, such as people, doors, and items of furniture that are ergonomically-constrained in their design. Previous research has shown that familiar objects not only have an assumed canonical size, which can influence the perception of their distance [Epstein 1963] but also that people tend to recall familiar objects from a preferred canonical perspective that reflects, in part, their accumulated visual experiences with them [Konkle and Oliva 2011]. This might explain why uncertainty intervals tended to be larger in the scenes that featured larger-than-typical spaces and higher-than-typical ceilings, such as the Blueprint Office and Sun Temple, or that lacked familiar features that could serve as reliable points of reference for judging eye height, such as the Lightroom environment in the nighttime viewing configuration. However, we caution that due to the small number of participants, the amount of

Figure 4: Plots of the psychometric fits to the data for each room separately.

data available for each room is likely insufficient to enable robust pairwise comparisons.

6 CONCLUSIONS AND FUTURE WORK

Our small study makes a modest first step towards a better understanding of the range of offsets over which eye height manipulations are likely to go unnoticed by standing users in common VR scenarios. In future work, we plan to extend these findings through additional experiments using more sensitive psychometric methods, with more participants, considering a seated as well as standing posture, and incorporating a self-avatar. It also remains an interesting open question the extent to which people might be able to use the awareness of the existence of an offset in their eye height to compensate for the perceptual distortions that would otherwise be expected to occur [Vishwanath et al. 2005]. The answers to that question could be informative to video-see-through applications that rely on cameras that are offset from the eyes' positions.

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REFERENCES

- Melissa W. Dixon, Maryjane Wraga, Dennis R. Proffitt, and George C. Williams. 2000. Eye Height Scaling of Absolute Size in Immersive and Nonimmersive Displays. *Journal of Experimental Psychology: Human Perception and Performance* 26, 2 (2000), 582–593. <https://doi.org/10.1037/0096-1523.26.2.582>
- William Epstein. 1963. The influence of assumed size on apparent distance. *American Journal of Psychology* 76 (1963), 257–265. Issue 2. <https://doi.org/10.2307/1419162>
- Epic Games. 2017. Unreal Engine Sun Temple, Open Research Content Archive (ORCA). <http://developer.nvidia.com/orca/epic-games-sun-temple>
- Jangyoon Kim and Victoria Interrante. 2017. Dwarf or Giant: The Influence of Interpupillary Distance and Eye Height on Size Perception in Virtual Environments. In *Proceedings of the International Conference on Artificial Reality and Telexistence and Eurographics Symposium on Virtual Environments (ICAT-EGVE '17)*. Eurographics Association, Goslar Germany, Germany, 153–160. <https://doi.org/10.2312/egve.20171353>
- Talia Konkle and Aude Oliva. 2011. Canonical visual size for real-world objects. *Journal of Experimental Psychology: Human Perception and Performance* 37 (2011), 23–37. Issue 1. <https://doi.org/10.1037/a0020413>
- Eike Langbehn, Gerd Bruder, and Frank Steinicke. 2016. Scale Matters ! Analysis of Dominant Scale Estimation in the Presence of Conflicting Cues in Multi-Scale Collaborative Virtual Environments. In *Proceedings of the IEEE Symposium on 3D User Interfaces (3DUI)*. IEEE, Piscataway, NJ, USA, 211–220. <https://doi.org/10.1109/3DUI.2016.7460054>
- Markus Leyrer, Sally A. Linkenauger, Heinrich H. Bühlhoff, Uwe Kloos, and Betty Mohler. 2011. The Influence of Eye Height and Avatars on Egocentric Distance Estimates in Immersive Virtual Environments. In *Proceedings of the ACM Symposium on Applied Perception in Graphics and Visualization (APGV '11)*. ACM, New York, NY, USA, 67–74. <https://doi.org/10.1145/2077451.2077464>
- Markus Leyrer, Sally A. Linkenauger, Heinrich H. Bühlhoff, and Betty J. Mohler. 2015a. Eye Height Manipulations: A Possible Solution to Reduce Underestimation of Egocentric Distances in Head-Mounted Displays. *ACM Transactions on Applied Perception* 12, 1, Article 1 (Feb. 2015), 23 pages. <https://doi.org/10.1145/2699254>
- Markus Leyrer, Sally A. Linkenauger, Heinrich H. Bühlhoff, and Betty J. Mohler. 2015b. The Importance of Postural Cues for Determining Eye Height in Immersive Virtual Reality. *PLoS ONE* 10, 5 (2015), 1–23. <https://doi.org/10.1371/journal.pone.0127000>
- Qiufeng Lin, John Rieser, and Bobby Bodenheimer. 2015. Affordance Judgments in HMD-Based Virtual Environments : Stepping Over a Pole and Stepping Off a Ledge. *ACM Transactions on Applied Perception* 12, 2 (2015), 1–21. <https://doi.org/10.1145/2720020>
- Betty J. Mohler, Sarah H. Creem-Regehr, and William B. Thompson. 2010. The Effect of Viewing a Self-Avatar on Distance Judgments in an HMD-Based Virtual Environment. *Presence: Teleoperators and Virtual Environments* 19, 3 (2010), 230–242. <https://doi.org/10.1162/pres.19.3.230>
- Thammathip Piumsomboon, Gun A. Lee, Barrett Ens, Bruce H. Thomas, and Mark Billinghurst. 2018. Superman vs Giant : A Study on Spatial Perception for a Multi-Scale Mixed Reality Flying Telepresence Interface. *IEEE Transactions on Visualization and Computer Graphics* 24, 11 (2018), 2974–2982. <https://doi.org/10.1109/TVCG.2018.2868594>
- Brice Pollock, Melissa Burton, Jonathan W. Kelly, Stephen Gilbert, and Eliot Winer. 2012. The Right View from the Wrong Location : Depth Perception in Stereoscopic Multi-User Virtual Environments. *IEEE Transactions on Visualization and Computer Graphics* 18, 4 (2012), 581–588. <https://doi.org/10.1109/TVCG.2012.58>
- Rebekka S. Renner, Boris M. Velichkovsky, and Jens R. Helmert. 2013. The Perception of Egocentric Distances in Virtual Environments - A Review. *Comput. Surveys* 46, 2 (2013), 1–40. <https://doi.org/10.1145/2543581.2543590> arXiv:1502.07526v1
- Brian Ries, Victoria Interrante, Michael Kaeding, and Lee Anderson. 2008. The Effect of Self-Embodiment on Distance Perception in Immersive Virtual Environments. In *Proceedings of the ACM Symposium on Virtual Reality Software and Technology (VRST '08)*. ACM, New York, NY, USA, 167–170. <https://doi.org/10.1145/1450579.1450614>
- Heiko H. Schütt, Stefan Harmeling, Jakob H. Mackee, and Felix A. Wichmann. 2016. Painfree and Accurate Bayesian Estimation of Psychometric Functions for (Potentially) Overdispersed Data. *Vision Research* 122 (2016), 105–123. <https://doi.org/10.1016/j.visres.2016.02.002>
- Jeanine K Stefanucci and Dennis R Proffitt. 2009. The Roles of Altitude and Fear in the Perception of Height. *Journal of Experimental Psychology: Human Perception and Performance* 35, 2 (2009), 424–438. <https://doi.org/10.1037/a0013894>
- Dhanraj Vishwanath, Ahna R. Girshick, and Martin S. Banks. 2005. Why Pictures Look Right When Viewed From the Wrong Place. *Nature Neuroscience* 8 (2005), 1401–1410. Issue 10. <https://doi.org/10.1038/nn1553>
- Maryjane Wraga. 1999. Using Eye Height in Different Postures to Scale the Heights of Objects. *Journal of Experimental Psychology: Human Perception and Performance* 25, 2 (1999), 518–530. <https://doi.org/10.1037/0096-1523.25.2.518>