International Conference on Artificial Reality and Telexistence
Eurographics Symposium on Virtual Environments (2017)
R. Lindeman, G. Bruder, and D. Iwai (Editors)

Dwarf or Giant: The Influence of Interpupillary Distance and Eye Height on Size Perception in Virtual Environments

Jangyoon Kim and Victoria Interrante

Department of Computer Science and Engineering, University of Minnesota

Abstract

This paper addresses the question: to what extent can deliberate manipulations of interpupillary distance (IPD) and eye height be used in a virtual reality (VR) experience to influence a user's sense of their own scale with respect to their surrounding environment – evoking, for example, the illusion of being miniaturized, or of being a giant? In particular, we report the results of an experiment in which we separately study the effect of each of these body scale manipulations on users' perception of object size in a highly detailed, photorealistically rendered immersive virtual environment, using both absolute numeric measures and body-relative actions. Following a real world training session, in which participants learn to accurately report the metric sizes of individual white cubes (3"–20") presented one at a time on a table in front of them, we conduct two blocks of VR trials using nine different combinations of IPD and eye height. In the first block of trials, participants report the perceived metric size of a virtual white cube that sits on a virtual table, at the same distance used in the real-world training, within in a realistic virtual living room filled with many objects capable of providing familiar size cues. In the second block of trials, participants use their hands to indicate the perceived size of the cube. We found that size judgments were moderately correlated ($r = 0.4$) between the two response methods, and that neither altered eye height (± 50cm) nor reduced (10mm) IPD had a significant effect on size judgments, but that a wider (150mm) IPD caused a significant ($\mu = 38\%$, $p < 0.01$) decrease in perceived cube size. These findings add new insights to our understanding of how eye height and IPD manipulations can affect peoples' perception of scale in highly realistic immersive VR scenarios.

CCS Concepts

- Computer Graphics → Graphics Systems and Interfaces; Perception, Virtual reality

1. Introduction

In the fiction work Alice's Adventures in Wonderland [Car65], the main protagonist, Alice, drinks a bottle of mystery liquid and becomes the size of a mouse. Then, she eats a cake made from mystery ingredients and becomes the size of an elephant. The scale changes to Alice's body allowed her to see the same room from two completely different perspectives. Such an experience is not available in reality, but could we use virtual reality to replicate the feeling of becoming a dwarf or a giant?

There is an inherent ambiguity between the situation of experiencing a "right-sized" world as if one were a giant, and experiencing a miniaturized world from one's own "right-sized" perspective: the essential relative size relationship between oneself and one's surroundings is the same in each case. Langbehn et al. [LBS16] explore this issue in the context of the collaborative, multi-scale exploration of a shared virtual environment by a group of users. They proportionately scale both eye height and IPD (together) either up or down relative to a static external virtual world, and examine how the style of the environment, the presence or absence of a self-avatar, and the sizes of the other group members affect a participant's sense of whether the observed scale change reflects a change in their own size or a change in the scale of their surrounding environment.

Our experiment has a different aim: we are interested in exploring how changes in eye height and IPD, both separately and together, can affect a person's sense of the relationship between their own scale and the scale of the environment around them, independently of the question of whether it is the person or the environment that is changing size. Most importantly, we examine this question in the context of a highly realistic virtual environment filled with multiple common objects that can provide rich and abundant cues to familiar size. This represents a departure from most previous studies, which have primarily studied the impact of eye height and/or IPD variations in the context of severely impoverished environments. In particular, we aim to better understand the extent to which modifications to eye height and/or IPD can override strong familiar size cues to create a compelling illusion of a significant relative scale change (e.g. feeling like a giant in a miniature virtual world or a dwarf in an over-sized environment).

2. Previous Work

Many previous studies have looked at various effects of interpupillary distance on size and depth perception in stereo displays. Scot Best [Bes96] looked at how interpupillary distance affects 2D size perception when using an HMD. Participants were asked to judge the size of a two-dimensional object under four different IPD conditions: their own anatomical IPD, a minimum IPD of 5cm, the adult mean IPD of 6.3cm, and a maximum IPD of 7.4cm. He found no evidence that the interpupillary distance influenced size judge ments; rather, IPD only seemed to affect the user's comfort.

Utsumi et al. [UMT*94] investigated the impact of IPD mismatch on depth perception errors in mixed reality. Participants were asked to adjust a virtual red ball to the perceived depth of a real red ball that was placed between themselves and a projection-type display. Measurements were made under multiple levels of stereo disparity between 6.6–8cm, at distances of 70, 80, and 90cm between the physical ball and the display. The results indicated that IPD mismatch could cause a significant misperception of depth.

Similarly, Renner et al. [RSM*15] found that participants judged a virtual tennis ball, suspended within arm's reach in a realistically rendered virtual environment, to be both farther away and "too big" when viewed on a CAVE display with reduced (70%) stereo disparity, and closer and "too small" when viewed with exaggerated (130%) disparity.

When Willemsen et al. [WGT*08] asked participants to estimate distances to targets located 5-15m away in an immersive virtual environment under a variety of different HMD stereo viewing configurations, they found no significant differences between any of the tested conditions: using the user's actual IPD; a fixed 65mm IPD; zero IPD; and monocular viewing. This suggests that variations in IPD may only affect depth perception in the near range.

Bruder and Steinicke [BS11] investigated the relationship between participants' actual IPD and the geometric IPD (GIPD) they felt was most natural when viewing a realistic virtual replica of their research lab, displayed using a ProView SR80 HMD. Results showed a large variance in preferred GIPD, both within and between subjects. With the largest field of view tested – 76.88˚ diagonal – they found that participants tended on average to prefer a GIPD that was about 25% greater than their actual IPD. This suggests that people may not be particularly sensitive to IPD manipulations, and that even "exact matching" IPD settings may not be perceived to be accurate in the context of HMD viewing.

Sedgwick [Sed80] proposed that people use their own eye height to scale their perception of absolute object size, a phenomenon known as eye height scaling. When a person is standing on an infinite horizontal ground plane, the horizon line will appear to be at eye level. If the observer knows their own eye height (EH), it is then theoretically possible to derive the absolute height of a target object (Y) that rests on the same groundplane, based on the visual angle α between the horizon and the base of the target, and the visual angle β between the horizon and the top of the target. For example, as seen in Figure 1, when Y > EH we have:

$$Y = [1 + \tan\beta/\tan\alpha] \times EH$$

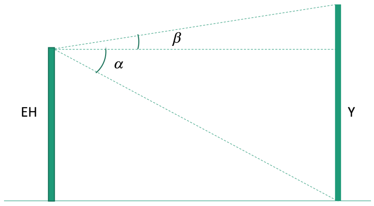

Figure 1: *Eye height scaling [Sed80].*

It follows from this that misperception of the angular declination, (e.g. due to misunderstanding the location of the horizon line or the groundplane with respect to the viewing position), or misjudgment of the existence of a shared horizontal ground plane, may then lead to misperceptions of size, particularly under impoverished viewing conditions.

Wraga [Wra99a] asked participants to judge the heights of rectangular targets on the floor of an otherwise featureless environment, viewed monocularly through a small tube from three different vantage points: floor-level, seated eye height, and standing eye height, in three different postural conditions: standing, sitting, and lying prone. She found that height judgments were similar in the standing and sitting conditions, and in the prone position when eye height was at the sitting level. However, targets appeared significantly shorter when viewed from a prone position with the eye height at floor level, as participants appeared to rely on linear perspective more than eye height in that case. Also, she found that when targets were placed on a falsely raised floor (17cm off the ground), effectively lowering the eye height unbeknownst to the participants, size judgements were overestimated compared to judgments of targets on a normal floor, for both seated and standing observers.

Dixon et al. [DWP*00] studied the effect of eye height scaling on absolute size judgments in simple immersive virtual environments. Participants wore an HMD and were placed in a virtual environment consisting solely of a flat ground plane and a large cube. They saw 3 different sizes of cubes at two different distances and from two different virtual eye heights, while standing. Results showed that participants perceived the virtual cube to be larger when the virtual eye height was reduced from the actual eye height. These findings suggest that size perception in VR can be highly sensitive to virtual eye height, under reduced cue conditions.

Leyrer et al. [LLB*15] explored the potential to use manipulations of virtual eye height to compensate for egocentric distance underestimation in HMD-based virtual reality. They placed participants in both realistic and cue-reduced virtual environments under different eye height conditions (–50cm, 0cm, +50cm) and asked them to perform blind walks to targets at different distances. Their results supported the idea that distance underestimation could be avoided by rendering the virtual environment from a camera height suitably lower than the user's actual eye height.

It has been widely recognized that size and distance perception are intertwined, leading to the size-distance invariance hypothesis, which states that the perceived size S and perceived egocentric distance D of a visual stimulus that has an apparent visual angle of α are related by the following equation [McC85]:

$$S / D = \tan(\alpha)$$

However, newer research suggests that the relationship between size and distance perception may be more complicated. Haber and Levin [HL01] argue that size and distance perception not only serve different purposes, but also rely on different visual information. They observe that humans use dynamic estimates of egocentric distances to navigate through their environment, an inherent skill that is not derived from or compensated by memories or experiences. On the other hand, they contend that size perception is primarily a cognitive or memorial process, in which people leverage information from previous encounters with similar objects.

To test this hypothesis they conducted studies (in the real world) showing that people are able to make highly accurate size estimates of prototypical objects from memory, and that peoples' size estimation accuracy is independent of distance, while their distance judgments can be more accurate when the targets better support the use of familiar size cues.

Several prior studies have explored the effect of virtual self-body size on users' perception of object sizes and distances in virtual environments. Leyrer et al. [LLB*13] found that the effects of eye height manipulations on distance judgments were not significantly impacted by whether or not the participant was embodied in an avatar that was scaled to the eye height that was experienced. However when Linkenauger et al. [LLB*13] asked participants to make object size and graspability judgments while embodied in self-avatars whose hands (only) were of greatly varying sizes, they found that people judged similarly-sized spheres to be smaller when located next to their own avatar's enlarged hand (14cm wide), and larger when located next to their avatar's miniaturized (3.5cm) hand, while apparent sphere sizes were unaffected by variations in the hand sizes of other peoples' nearby avatars. Similarly, Jun et al. [JSC*15] found that when participants were "embodied" in VR as (just) a pair of virtual shoes, controlled by the tracked movements of their own feet, they judged gap sizes to be smaller in the context of larger shoes. However, they found no effect of shoe size on peoples' ratings of how tall they felt in the virtual environment.

To sum up, much prior research has found that eye height manipulations can affect size perception. However, all of that research was done in reduced-cue environments. Our experiment revisits this question in the context of a rich-cue environment. Prior research has found that eye height manipulations can influence *distance* judgments in action space in both cue-impoverished virtual environments and in realistc virtual environments filled with objects that provide familiar size cues. This suggests that eye height manipulations might be similarly effective at evoking scale change illusions, but this has not yet been explicitly tested via object size perception judgments. Similarly, prior research has found no impact of virtual eye separation on object size judgments. IPD manipulations have been found to affect depth judgments within arm's reach but not at larger distances. Our experiment explores the effects of IPD on size judgments in a cue-rich environment where the participant is surrounded by familiar objects at many different distances.

3. Experiment

Our experiment begins with a training phase, followed by a test phase. In the training phase, participants learned (via feedback) to correctly report the absolute sizes (in inches) of six different featureless white cubes and were iteratively tested with three additional white cubes until their performance was perfect. The test phase consisted of two blocks of 9 trials each. In the first block, participants were asked to verbally report the absolute size of a featureless white cube presented in the context of a highly realistic immersive virtual environment under nine different conditions of virtual camera height and virtual camera stereo disparity. In the second block, participants experienced the same nine different display conditions but this time were asked to use their hands to indicate the absolute size of the cube. Unbeknownst to the participants, in all conditions the actual size of the 3D cube model remained constant. The goal of our experiment was to see how the different eye height and IPD settings might affect participants' size judgments. In light of previous work, we hypothesized that participants might perceive the cube as being smaller when the scene was presented from a virtual viewpoint that was elevated with respect to their actual eye height, and larger when the virtual viewpoint was artificially lowered. Although prior work had generally not found an effect of IPD, we hypothesized that the cube might be perceived as larger when the stereo disparity was smaller than the person's own IPD and perceived as smaller when the stereo disparity was artificially expanded.

3.1 Participants

Nineteen participants (12 m, 7 f), ages 18–32 ($\mu = 21.42 \pm 4.07$), were recruited from our university community using flyers approved by our Institutional Review Board. Participants signed an approved statement of informed consent and were compensated for their time with a $10 gift card.

3.2 Materials

We physically constructed a set of nine white cubes of the exact sizes: 2", 3", 5", 8", 10", 12", 15", 18" and 20", using 3/16" thick foam core boards and glue. The cubes were carefully constructed so as to appear visually identical in all respects except for their size. To ensure a seamless join at each edge, we cut six square pieces for each cube, each of the prescribed size and then carefully scraped off an approximately 3/16" wide strip of the inner layer of foam along two opposing edges of two of the six faces and along all four edges of two other faces. We then united the faces by applying superglue along the exposed strips and abutting the untrimmed edges of the other faces so that the adjoining sides met exactly. For extra stability, the largest cubes were internally supported by ¼" diameter square wooden dowels and wood glue was used to fill in any exposed gaps within the cube interior. The 2" and 3" cubes were constructed with all six faces, but for the remaining cubes we elected to leave off the bottom face so as to facilitate nesting the cubes for more efficient storage and transport. Figure 2 shows what the finished set of cubes looked like.

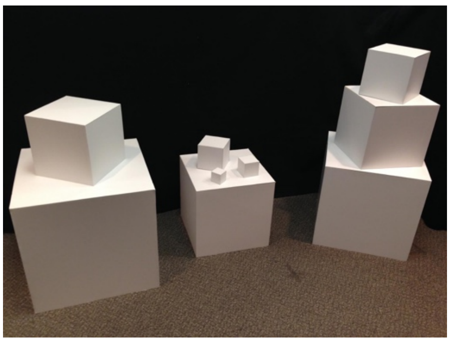

Figure 2: *Cubes used for training.*

The experiment was implemented using the Unreal Engine 4.10 game development software. The virtual environment model (Figure 3) was obtained from the Unreal Engine Realistic Rendering demo [Unr17]. A 9” virtual white matte cube was added atop the center of the coffee table, and the other objects formerly on the table in the original model were removed. The virtual camera position was mapped to the location of the HMD so that when the participant was seated in front of the computer, the virtual camera was located at eye height above the sofa, facing directly forward into the room. No self avatar was shown. The virtual environment was presented using an Oculus Rift CV1, which has a 110˚ diagonal field of view and a display resolution of 1080x1200 pixels in each of the two eyes. The computer used to run the experiment had an Intel Core i7-6850K (3.60GHz) processor, 32GB of main memory, and an Nvidia GeForce GTX 1080 graphics card.

Figure 3: *The virtual environment used [Unr17].*

3.3 Procedure

Before beginning the experiment, participants were given written instructions explaining the experimental procedures. Each participant was then tested for visual acuity above 20/70 at a viewing distance of 14 feet, via an online visual acuity testing program [Buf16] calibrated for a 15” monitor, and then tested for stereo visual ability using random dot stereograms presented in an NVisor SX60 HMD. As the Oculus Rift does not readily accommodate glasses, participants who normally wore glasses were required to remove them before the acuity and stereo testing.

3.3.1 Training. The experiment began with a training session (Figure 4), in which the participant was asked to sit in a chair that was positioned at a measured distance in front of a small table, facing the wall. The training session consisted of three phases. In the first phase, the experimenter brought out, one at a time in random order, each of the six “training” cubes sized 2”, 3”, 5”, 10”, 15” and 20” from behind a short black-curtained divider, and placed it on the table in front of the participant, telling the participant a number corresponding to the cube’s size (e.g. “This is a 3”). In the second phase, the experimenter re-presented each of the training cubes individually, again in random order, and asked the participant to say its size. The experimenter confirmed if the response was correct, or told the participant the actual size if their response was incorrect (e.g. “No, this is a 5”). Cubes whose size the participant correctly identified were set aside, and cubes whose sizes were not correctly identified were re-tested, until the participant was able to correctly identify all of the training cubes. In the third phase of training, the experimenter brought out one of the three “test” cubes sized 8”, 12” or 18” and asked the participant to name its size. If they answered incorrectly, they had to repeat phases 1 and 2 before being tested again with a different cube from the “test” set. This process continued until the participant had correctly identified the size of each test cube without ever being told its size. We recorded the total time each participant took to complete the training session as well as the order in which each block was shown or re-shown and the user’s size estimates in each case. Training was capped at 30 minutes.

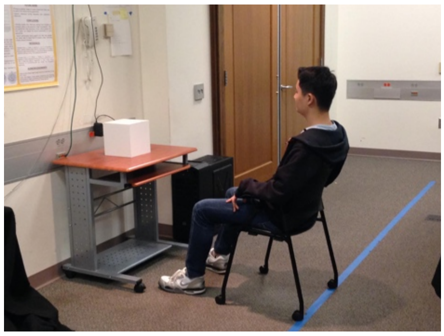

Figure 4: *Training session.*

3.3.2 Main Experiment. After completing the training phase, participants were asked to fill out a baseline simulator sickness questionnaire (SSQ) [KLB*93]. They were then instructed to sit in a different chair in front of a computer running the virtual reality experiment. The chair was positioned so that the virtual viewpoint of the participant would be the same distance (90cm) in front of the virtual cube as their real viewpoint was in front of the real cubes during the training session (Figure 5). Each participant’s interpupilary distance was measured using the software provided by the Oculus Rift’s configuration utility.

Figure 5: *Virtual reality session.*

Each trial began with the participant seeing a black void, before the virtual environment was faded in. There were nine trials in total, spanning all combinations of three different virtual eye heights and three different virtual eye separations. The eye heights used were: 1) the user’s actual eye height, wherein the virtual camera was located at the same distance from the floor in the virtual room as the participant’s own eye height was from the floor in the physical lab room; 2) 50cm higher than the user’s actual eye height; 3) 50cm lower than the user’s actual eye height. We chose those offsets because they were similar to the offsets that had been used by others in the related prior work. Figure 6 shows what the scene looked like from each eye height.

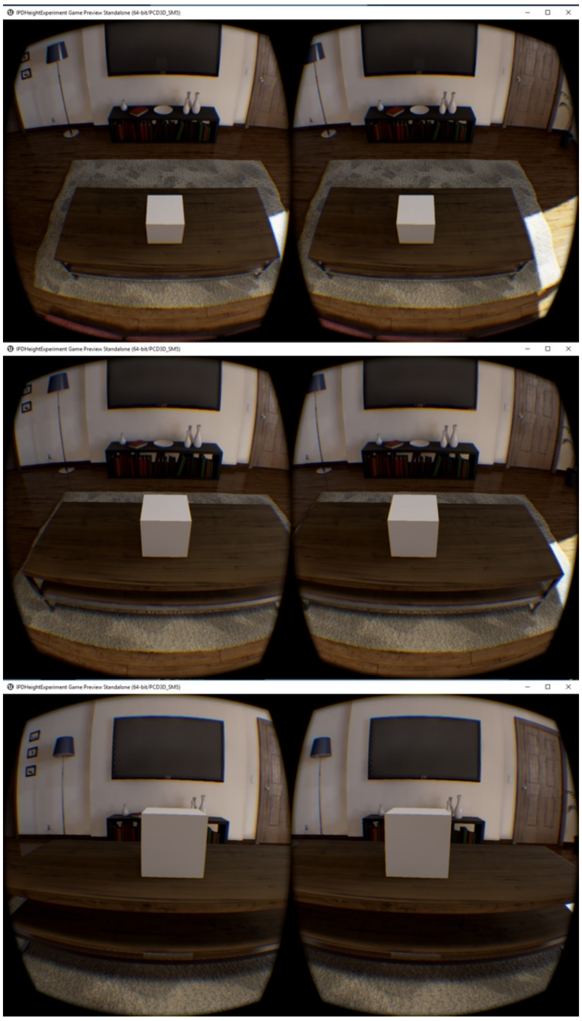

Figure 6: *The cube as seen from the different eye heights.*

The eye separations we used were: 1) the user's own IPD, as measured using the Oculus Rift's configuration utility; 2) 10mm; 3) 150mm. The first condition experienced was always the one with the user's own eye height and own IPD, and the other eight conditions were presented after that in a random order determined ahead of time by the computer program. Head motion was not constrained, and participants were explicitly instructed to look carefully around the virtual room before looking at the cube and judging its size. Participants were free to move their heads from side to side if they wished, but we did not explicitly encourage or note the use of that strategy. We did not anticipate any significant impact of head movement as Beall et al. [BLP*95] had previously found that absolute, observer-produced motion parallax does not significantly contribute to the perception of scale. A three second blackout was enforced between each trial to prevent any attention to changes in the view.

As well as recording participants' size judgments for each trial, we also recorded the time taken for each response, so as to have the ability to detect any potential incidences of responses that might not have been well thought out. However, we did not find any evidence of subjects who appeared to be trying to just rush through.

After the first block of nine trials was completed, participants were asked to take off the HMD, enjoy some refreshments, and complete another SSQ. The second block of trials then proceeded in exactly the same way as the first, except that instead of providing verbal size judgments, participants were asked to indicate the size of the cube using their hands. The experimenter measured the demonstrated distance with a tape measure. Participants were not embodied in an avatar and could not see their hands while wearing the HMD. Following the second block of trials, participants again completed the SSQ.

4. Results

Figure 7 shows the summary charts of the results. We performed a 2-way ANOVA analysis on the cube sizes reported as a function of the virtual eye height and virtual eye separation. In the data from the verbal reports, we found a significant main effect of eye separation {$F(2,162)$, $p < 0.001$}, but no significant main effect of eye height {$F(2,162)$, $p = 0.278$}. Similarly, in the data from the hand measures, we again found a significant main effect of eye separation {$F(2,162)$, $p < 0.001$}, but no significant main effect of eye height {$F(2,162)$, $p = 0.863$}. In neither case did we see any significant interaction between eye height and eye separation.

We performed a Fisher Least Significant Difference test between the different eye separation conditions and found that, both with verbal reports and with hand measures, participants judged the cubes to be significantly smaller when viewing with the high IPD than when viewing with either the actual or low IPD ($p < 0.001$ in each case). There was no significant difference in cube size judgments between the actual and low IPD conditions, either when indicated via verbal report ($p = 0.182$) or hand measure ($p = 0.966$).

Table 1 shows the average cube sizes (and standard deviation) estimated via verbal reports under each of the different combinations of eye height and eye separation. The actual cube size shown in each case was 9". Individual estimates ranged from a low of 3 to a high of 20, and the overall variance was 10.97.

Table 1: *Mean cube size (stdev) indicated by verbal report under the nine eye height and eye separation conditions.*

	Low Height	Actual Height	High Height
Low IPD	8.58 (3.36)	9.53 (3.78)	8.84 (4.43)
Actual IPD	7.84 (1.57)	8.53 (1.35)	8.33 (3.16)
High IPD	4.84 (1.30)	5.42 (1.87)	6.58 (4.10)

Table 2 shows the average cube sizes (and standard deviation) estimated via hand separation under each of the different combinations of eye height and eye separation. Individual estimates ranged from a low of 3 to a high of 18.5, and the overall variance was 8.16. Overall, the responses obtained via verbal report and hand measure were very similar. At the granularity of each individual, there was a correlation of $r = 0.40$ between their verbal size estimates and hand separation estimates for judgments in the same viewing conditions.

Table 2: *Mean cube size (stdev) indicated by hand separation under the nine eye height and eye separation conditions.*

	Low Height	Actual Height	High Height
Low IPD	8.55 (3.17)	7.92 (2.61)	8.03 (3.27)
Actual IPD	8.13 (2.68)	8.07 (3.05)	8.29 (3.30)
High IPD	6.17 (2.13)	6.22 (1.91)	5.74 (2.00)

With regard to the training phase, we noted considerable variation in the length of time that it took for different participants to learn the sizes of the cubes. Four participants finished the training in under 5 minutes, never giving a single wrong answer, while at the other extreme five participants required more than 15 minutes, and one participant requested to proceed to the VR phase of the experiment after 24 minutes of training in which they were repeatedly unable to correctly identify the size of the 18” test cube (at which point we told them the correct answer).

We did not observe any significant evidence of cybersickness in the SSQ responses given by our participants, although we certainly expected that it might be a problem. We speculate that the brief duration of the experiment may have been a factor in avoiding the incidence of cybersickness, as well as the fact that participants were seated, favoring a more stable head position due to reduced incidental postural sway. Additionally, the experiment did not afford much translational movement, though we did ensure that all participants looked around at the start of each trial as instructed.

5. Discussion

Our first observation is that participants’ estimates of the sizes of the displayed cubes varied considerably across the different viewing conditions, even though the actual size of the displayed virtual cube was a constant 9”. Even the most consistent participant gave verbal estimates that differed over a range of 3”, and the median range, over all participants, between each individual’s largest and smallest estimate, was 8”. This suggests that the changes in viewing conditions did in fact lead to different percepts, though it cannot be ruled out that some of this variation could reflect arbitrary randomness in peoples’ responses, given the implicit demand conditions of the experiment. Specifically, since we had trained participants with cubes of different sizes, there is a possibility that they might have felt that they were expected to give different answers even if they actually believed that they were just seeing the same sized cube over and over again. Nevertheless, the relatively large spread in reported sizes certainly suggests the existence of a real effect.

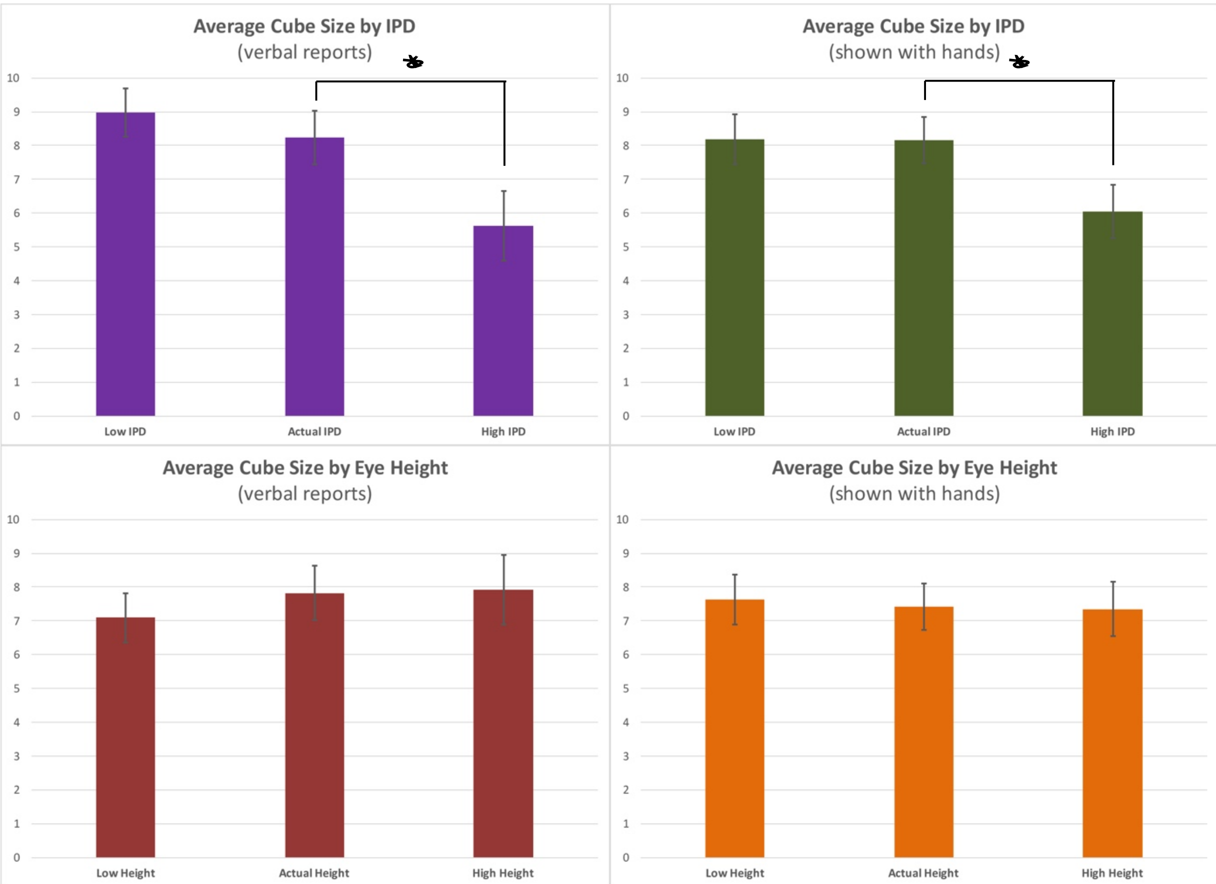

Figure 7: *Average cube size estimates given via verbal report (left) and hand separation (right), under the different virtual eye height and virtual eye separation conditions.*

The fact that we found no significant effect of eye height manipulation on cube size estimates is an interesting new contribution to the literature, given that previous research has convincingly shown that artificial manipulations of eye height in VR can lead to misperceptions of both object height and egocentric distance. However, we note that the all of the previous studies finding an impact of eye height on object size judgments took place in highly impoverished environments and relied on the explicit or implicit assumption that both the participant and the object being viewed rested on a common horizontal ground plane. It could be that the more realistic and ecologically valid conditions of our experiment, in which the cube rested on a coffee table viewed from a sitting posture in the context of a highly detailed virtual living room, privileged the use of alternative size cues. Although the cube's position was likely outside the zone of eye height utility [WP00] in the raised eye height condition, we note that other features of the environment, such as the ceiling height, remained available for potential eye height scaling. Most likely, the richly detailed scene, which included many realistically rendered canonical objects, supported a robust sense of size constancy under conditions of varying eye height. Most people have had abundant prior experience seeing their surroundings from a modestly elevated vantage point, such as when walking down stairs, or standing on a balcony, and we rarely experience illusions of a relative scale change as a result – though in less commonly-experienced extreme height situations, such as from an airplane or skyscraper, it is not unusual for people to remark that distant objects look like miniatures. We had anticipated a potentially higher likelihood of observing an eye height effect on apparent size perception in the low eye height condition because there is no similar common experience of viewing the world from an upright vantage point that is close to the floor, but our data in this experiment did not bear that out.

Likewise, our finding of a significant impact of increased eye separation on size perception under our tested conditions is also a novel contribution to the literature, as prior results had only found an impact of IPD settings on comfort but not on size perception. With regard to the apparent asymmetry in the impact of virtual eye separation on apparent size perception, wherein making the virtual eyes farther apart evoked a significant perceptual scaling of the scene while bringing the virtual eyes closer together did not, we note that the eye separation manipulation we used was considerably more extreme, as a percentage of the actual IPD, in the wide IPD condition than in the narrow IPD condition, where the range was naturally restricted. We chose to use an extreme eye separation for the wide IPD because we wanted to make sure that our manipulation would be large enough for us to be able to see an effect if any was likely. Now that we know IPD can have an effect, we can in the future experiment with using less severe manipulations, which might of course also be better tolerated when the head moves around a lot.

The fact that we found a slightly greater overall variance in the verbally reported cube size estimates (σ = 10.97, computed over all IPD and all eye height conditions) than in the size estimates indicated by hand separation (σ = 8.16) is consistent with previous observations of greater variability in verbal reports compared with action-based measures. Note that we did not train people in the action-based measure because such training is not appropriate to such measures, which are intended to reflect how people naturally and instinctively act on what they see, based on their accumulated lifetime experience of interacting with the physical world around them. We trained the verbal reports of size estimates in the real world rather than in the virtual world because we felt that the former would lead to more robust and ecologically valid results.

We observe that the high similarity between the verbal and action-based measures of the cube size suggests that participants were primarily experiencing the apparent size change as a change in the scale of the occupied environment rather than as a change in their own size. If people had perceived themselves as growing or shrinking within an environment of unchanging size, they should have provided more constant verbal measures of the cube size, even though with action-based measures a change would be expected either way – for example, a person's hands would have to come together more closely to touch a cube's sides when there is a relative scale change that is due either to the environment shrinking or to the body getting larger.

Finally, we note that the average absolute reported cube sizes of 8.53" and 8.07", obtained using the verbal and gesture-based reporting measures respectively, are each slightly smaller than the actual represented cube size of 9". It is possible that our participants could have been experiencing some slight amount of distance underestimation in the virtual environment, in which case we might expect a slight reduction in apparent size judgments due to the distance misperception, because a closer cube would need to be smaller than a more distant one in order to subtend the same visual angle. However, given that the standard deviations are 1.35 and 3.05, respectively with each measure, it is not clear that this size difference is significant.

6. Conclusions and Future Work

Our study is one of the first to separately consider the impact of eye height and IPD variations on a viewer's sense of their relative scale (e.g. dwarf or giant) with respect to a richly detailed and highly realistic surrounding virtual environment. The results of our study suggest that changing a user's eye height alone will generally not be sufficient to evoke an Alice in Wonderland illusion in a richly detailed immersive virtual environment filled with objects that provide robust cues to familiar size. This is somewhat disappointing in the context of prior work that has shown that lowering eye height can increase egocentric distance estimates over distances between 5-15m. Additionally, we found that decreasing the IPD in a stereo view also does not help to evoke an impression of a scale change in oneself or the surrounding environment, despite the widely-recognized importance of stereo cues to vision in the near field. More encouragingly, we found that a drastic widening of the virtual eye separation was successful in evoking a compelling illusion of being present in a miniaturized virtual environment regardless of the position of the virtual vantage point.

In future work, we plan to study the impact of eye height manipulations on scale perception when participants are standing, as it is possible that such changes might have more effect in that case. We also plan to experiment with using smaller amounts of IPD exaggeration, so as to reduce the magnitude of expected problems with cybersickness.

Acknowledgments

This work was supported by the National Science Foundation through grants CHS: Small: Transforming the Architectural Design Review Process through Collaborative Embodiment in HMD-based Immersive Virtual Environments (1526693) and II-NEW: Virtual Reality Infrastructure and Technology Development to Support Architectural Education and Basic Research in Immersive Design, Embodied Interaction, Spatial Cognition (1305401), and by the Linda and Ted Johnson Digital Design Consortium Endowment.

References

[BLP*95] BEALL A.C., LOOMIS J.M., PHILBECK J.W., FIKES T.J.: Absolute motion parallax weakly determines visual scale in real and virtual environments. *In Proc. SPIE 2411: Human Vision, Visual Processing, and Digital Display VI* (Apr 1995), 288–297. doi: 10.1117/12.207547.

[Bes96] BEST S.: Perceptual and oculomotor implications of interpupillary distance settings on a head-mounted virtual display. *In Proc. IEEE National Aerospace and Electronics Conference*, vol. 1, (1996), 429–434. doi: 10.1109/naecon.1996.517685.

[BS11] BRUDER G., STEINICKE F.: Perceptual evaluation of interpupillary distances in head-mounted display environments. *In Proc. Virtuelle & Erweiterte Realität: 8. Workshop der GI-Fachgruppe VR/AR*, (2011). https://basilic.informatik.uni-hamburg.de/Publicatons/2011/BS11a/paper.pdf

[Car65] CARROLL L.: *Alice's Adventures in Wonderland*. Macmillan & Co., London, 1865. https://www.adobe.com/be_en/active-use/pdf/Alice_in_ Wonderland.pdf

[DWP*00] DIXON M.W., WRAGA M., PROFFITT D.R., WILLIAMS G.C.: Eye height scaling of absolute size in immersive and nonimmersive displays. *J. Exp. Psych.: Human Perception and Performance 26*, 2 (Apr 2000), 582–593. doi: 10.1037//0096-1523.26.2.582.

[HL01] HABER R.N., LEVIN C.A.: The independence of size perception and distance perception. *J. Exp. Psych.: Perception & Psychophysics 63*, 7 (Oct 2001), 1140–1152. doi: 10.3758/bf03194530.

[JSC*15] JUN E., STEFANUCCI J.K., CREEM-REGEHR S.H., GEUSS M.N., THOMPSON W.B.: Big Foot: Using the size of a virtual foot to scale gap width. *ACM Transactions on Applied Perception 12*, 4 (Sept 2015), Article 16, 12 pages. doi: 10.1145/2811266.

[KLB*93] KENNEDY R.S., LANE N.E., BERBAUM K.S., LILLENTHAL M.G.: Simulator Sickness Questionnaire: an enhanced method for quantifying simulator sickness. *Int. J. Aviation Psych. 3*, 3 (Apr 1993), 203–220. doi: 10.1207/s15327108ijap0303_3.

[LBS16] LANGBEHN E., BRUDER G., STEINICKE F.: Scale matters! Analysis of dominant scale estimation in the presence of conflicting cues in multi-scale collaborative virtual environments. *In Proc. IEEE Symposium on 3D User Interfaces* (Apr 1996), 211–220. doi:10.1109/3dui.2016.7460054.

[LLB*11] LEYRER M., LINKENAUGER S.A., BÜLTHOFF H.H., KLOOS U., MOHLER B.J.: The influence of eye height and avatars on egocentric distance estimates in virtual environments. *ACM Symp. Applied Perception* (Aug 2011), 67–74. doi: 10.1145/2077451.2077464.

[LLB*15] LEYRER M., LINKENAUGER S.A., BÜLTHOFF H.H., MOHLER B.J.: Eye height manipulations: a possible solution to reduce underestimation of egocentric distances in head-mounted displays. *ACM Transactions on Applied Perception* (Mar 2015), Article 1, 23 pages. doi: 10.1145/2699254.

[LLB*13] LINKENAUGER S.A., LEYRER M., BÜLTHOFF H.H., MOHLER B.J.: Welcome to wonderland: the influence of the size and shape of a virtual hand on the perceived size and shape of virtual objects. *PLoS ONE 8*, 7 (Jul 2013), e68594. doi: 10.1371/journal.pone.0068594

[McC85] MCCREADY D.: On size, distance, and visual angle perception. *Perception & Psychophysics 37*, 4 (Jul 1985), 323–334. doi: 10.3758/bf03211355.

[RSM*15] RENNER R.S., STEINDECKER E., MÜLLER M., VELICHKOVSKY B.M., STELZER, R., PANNASCH S., HELMERT, J.R.: The influence of the stereo base on blind and sighted reaches in a virtual environment. *ACM Transactions on Applied Perception 12*, 2 (Mar 2015), Article 7, 18 pages. doi: 10.1145/2724716.

[Buf16] UNIVERSITY AT BUFFALO: Interactive Visual Acuity Chart. http://www.smbs.buffalo.edu/oph/ped/IVAC.html (last accessed 10/14/16)

[Unr17] UNREAL ENGINE REALISTIC RENDERING LIVING ROOM MODEL: http://docs.unrealengine.com/latest/INT/Resources/Showcases/RealisticRendering (last accessed 5/29/17)

[UMT*94] UTSUMI A., MILGRAM P., TAKEMURA H., KISHINO F.: Investigation of errors in perception of stereoscopically presented virtual object locations in real display space. In *Proc. Human Factors and Ergonomics Society Annual Meeting 38*, 4 (Oct 1994), 250–254. doi: 10.1177/154193129403800413.

[WGT*08] WILLEMSEN P., GOOCH A.A., THOMPSON W.B., CREEM-REGEHR S.H.: Effects of stereo viewing conditions on distance perception in virtual environments. *Presence: Teleoperators and Virtual Environments 17*, 1 (Feb 2008), 91–101. doi: 10.1162/pres.17.1.91.

[Wra99] WRAGA M.: Using eye height in different postures to scale the heights of objects. *J. Exp. Psych.: Human Perception and Performance 25*, 2 (Apr 1999), 518–530. doi: 10.1037/0096-1523.25.2.518.

[WP00] WRAGA M., PROFFITT D.P.: Mapping the zone of eye height utility for seated and standing observers. *Perception 29*, 11 (Nov 2000), 1361–1381. doi: 10.1068/p2837.