Does scaling player size skew one's ability to correctly evaluate object sizes in a virtual environment?

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ABSTRACT

This study attempts to evaluate whether a navigation technique based on scaling the user's avatar impacts the user's ability to correctly assess the size of virtual objects in a virtual environment. This study was realized during the CERN Open Days with data from 177 participants over eighteen years old. We were able to observe well-established phenomena such as the effect of interpupillary distance (IPD) on perception of scale, as well as original results associated with scaling factor and avatar embodiment. We observed that the user is more prone to overestimate object sizes from the Virtual Environment (VE) when provided with an avatar, while scaling the IPD according to the scale of the user's avatar contributes to a reduction in the overestimation of object sizes within the VE.

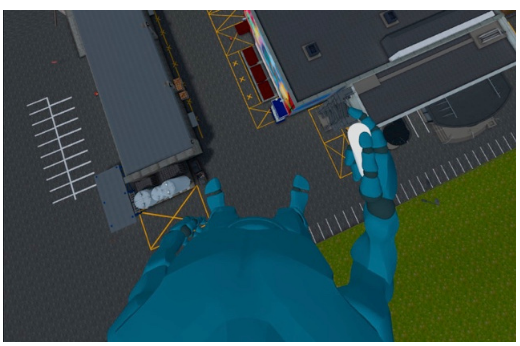

Figure 1: Illustration of locomotion in "Giant Mode" while navigating around the a virtual representation of CERN's main site

CCS CONCEPTS

• **Human-centered computing** → **User studies**; **Virtual reality**; **Interaction techniques**.

KEYWORDS

Virtual Reality, Embodiment, Avatar Scaling, User Interaction, Navigation

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1 INTRODUCTION

Virtual Reality (VR) experiences often demand that players navigate in order to discover and interact with the environment. However, current technical limits prevent players from navigating over long distances while maintaining a link between the real, physical movement performed and the one displayed in the headset. Different techniques have attempted to bridge the gap between the physical movement of the user and the locomotion of the player within the VE, from treadmills [Fung et al. 2006], rolling spheres, and sliding on a curved floor with slippers [Warren and Bowman 2017] to traditional techniques like navigating with joysticks, as in traditional video games, or teleportation [Bozgeyikli et al. 2016]. But all of these techniques have serious drawbacks. Solutions that require additional hardware limit the potential number of users who can experience them, and teleportation does not allow continuous movement, which can be fatiguing and disorienting when traveling over long virtual distances.

Several researchers and developers have recently begun to experiment with a novel navigation technique which attempts to mitigate these disadvantages. This technique involves allowing the user to change scale, or euphemistically, to become a Giant, in order to be able to continuously traverse more distance with less disruption. One such early system, named GulliVR [Krekhov et al. 2018] is used as the basis for this paper. While GulliVR used the "Giant mode" technique, it did not employ an avatar, which many subsequent studies have done, including a hybrid approach by the same authors which combines a Giant avatar with teleportation [Cmentowski et al. 2019].

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Other researchers have also found that the "Giant Mode" navigation technique is particularly promising. [Abtahi et al. 2019] examined three means of boosting a user's navigation speed: speed gain, walking as a Giant, and scaling up the user (as a Giant) while maintaining the head at the ground level; users preferred the simple Giant mode. A variant of walking as a Giant involves flying like Superman, which puts the user's eyeline at the same level, but with somewhat different characteristics - i.e. no Giant avatar and an inter-pupilary distance (IPD) that would be associated with a human. This technique, examined in [Piumsomboon et al. 2018], found that scaling IPD when changing a user's eye-height more strongly modifies the user's perception of scale of the environment; effectively, to be a Giant, one must see like a Giant. The researchers involved did not use an avatar in their study, but did highlight the value it would have in giving natural cues to the user during navigation.

With the advent of new, low-cost devices, VR experiences are now accessible to a broader public than ever before, and with less hardware investment, making the technique of navigating like a Giant attractive to an increasing number of users.

Due to the perceptual manipulations necessary to use this technique, however, we decided to study whether it would impact the user's judgement of the scale in the VE compared to the typical scale distortion observed in VEs in general.

2 RELATED WORK

2.1 Scale in a Virtual Environment

Perception in virtual environments, and specifically judgement of distance and scale within those environments, has been studied for decades. It has long been observed that a user's judgement of scale is impaired when using a virtual environment. While there is little commonality in the numerous experiments that have evaluated this effect, the overwhelming conclusion is that users underestimate distance (and by extension scale) in a virtual environment relative to the real world. The magnitude of this effect varies heavily with experimental conditions, technology used to view the virtual environment (type of device, field of view, binocularity, resolution), and the details of the virtual environment (image quality, richness, texture, lighting, real-world visual cues, and experience). The underestimation of scale ranges from a factor of 2, as observed through egocentric observations of distance to an object by untrained observers [Knapp 1999], to roughly 20%, as determined by a study of architects that were given virtual or real tours of a museum, and then asked to evaluate distances (height of a ceiling, length of a wall) [Henry and Furness 1993].

2.2 The Body (or Avatar) as a Scale Reference

It has been shown that the body acts as a scale reference for the outside world, both in near personal space and beyond [Van Der Hoort et al. 2011]. In the "Being Barbie…" study, the user is attributed, through a video-relay system, the body of a mannequin ranging in size from 30cm to 4m. The user is asked to judge both distance and object scale, and the results show that the user mis-estimates scale based on the body that is attributed. The smallest body results in an over-estimation of real-world scale, while the largest body results in an under-estimation. The results vary from approximately a factor of 2 mis-estimation in the small-body case, to a factor of about 1.5 in the large-body case. Interestingly, even the normal case results in an under-estimation of scale (though slightly lower than the amount measured in the large-body case), echoing other studies that have shown that it is not the qualities of the environment that affect this error, but the intrinsic nature of representation through a virtual display.

2.3 Vision Characteristics as a Scale Reference (Superman)

The roles of eye height and inter-pupillary distance (IPD) have also been studied in the literature in the context of estimation of scale of a virtual environment [Kim and Interrante 2017]. In a simulation with no bodily representation (i.e. no avatar) there are two possibilities for assuming an eye level above the normally-expected human height: either flying (if the IPD is conserved at normal human size, i.e. Superman) or growing (if the IPD scales with the position above ground level, i.e. Giant). These two conditions are compared in the study "Superman vs. Giant," [Piumsomboon et al. 2018] where it is found that, in the mode without IPD manipulation (Superman) half of the users felt that their body size was larger (even though no body is visible) and half thought that it was normal, yet flying. Conversely, in the mode with IPD manipulation, users judged themselves to have a Giant body more than 90% of the time [Piumsomboon et al. 2018].

In examining whether this estimation of body size (even though no body was visible) had an effect on the estimation of environment sizes, it was found that indeed the manipulation of IPD led to a skew in the estimation of scale; smaller IPD resulting in over-estimation, and larger IPD resulting in under-estimation, as is congruent with the previously discussed experiments. This effect has also been found in other studies where IPD and height have been manipulated both up and down, i.e. Dwarf vs. Giant, which show that indeed manipulation of height as well as IPD result in a change in ability to estimate scale. However, with relatively small changes in height (i.e. plus or minus 50cm), the effect of increasing eye height seems to have small effects, whereas decreasing it is more pronounced [Kim and Interrante 2017]. The opposite effect was found in a similar study which used the same 50cm offset, where the significance was found in reducing eye height and not increasing it [Leyrer et al. 2015]. This second study also analysed the role of an avatar in these two conditions, and it found no significant effect.

While these studies of eye height and IPD show some conflicting results, they all used relatively modest adjustments in IPD and height, as well as feature rich virtual environments, where many environmental size cues were available.

2.4 Summary and Contributions

Prior research shows one clear conclusion: a user's ability to judge the scale of an environment presented through virtual means can be manipulated through three key variables:

- The size of the user's inferred or visibly-attributed body (avatar)
- The user's eye height above ground level
- The user's IPD

While some elements, like magnitude of the manipulation, visual richness of the environment, placement of objects in the visual field, etc., may have an impact on magnitude and sensitivity of the results, it is almost universally observed that increasing the key variables listed above leads to an under-estimation of the scale of the virtual environment, whereas decreasing them has the opposite effect.

Our contributions hinge on assessing the impact of the "Giant mode" as a means of effective navigation. For this purpose we propose a system based on GulliVR [Krekhov et al. 2018]. This system allows the user to navigate in a VE in the direction of regard, which is intrinsically intuitive, by simply pressing a button on the hand controller. In order to move more quickly through the environment, and to obtain a reference point for the layout of the surroundings, a simple function allows the user to scale their avatar to Giant scale (and to move correspondingly faster through the environment, unimpeded by buildings and terrain). A controlled experiment evaluates user performance in a size assessment task within a between-group design including five combinations of the following three factors: avatar, Giant mode and IPD scaling.

3 EXPERIMENTAL DESIGN

3.1 Question

In order to make a technique like Giant navigation interesting, it must entertain scale shifts larger than those attempted in previous studies. Scale ratios of 20-40 have not been studied in depth. In addition, the effect of an avatar in such a large scale offset has not been studied, and by incorporating it as an additional variable, allows the comparison of five distinct groups. Lastly, such a navigation technique is naturally episodic and temporal. In this respect, there is no existing research which examines the effect of time, and changeability, on a user's estimation of scale in a virtual environment.

As such, the research question can be simply stated as: to what extent do the factors of avatar, eye height, IPD, and time have on a user's estimation of scale in a feature-rich, openly navigable virtual environment?

3.2 Hypotheses

Based on the literature, we expect to verify several well-supported hypotheses, as well as investigate new, untested ones related to time and avatar.

(1) H1 - Users in the control groups (no Giant mode) will underestimate the scale of the VE as observed in general in virtual environments
(2) H2 - Users in Giant modes will underestimate the scale of the VE in higher proportions than the control groups
(3) H3 - Users with an avatar will show more under-estimation effect than those without an avatar
(4) H4 - Users with larger IPD will show more under-estimation effect than those with normal IPD
(5) H5 - Users who spend more time in Giant mode will show a stronger under-estimation effect

3.3 Groups

To study the impact of these factors, we divided the experiment into 5 groups as shown in Table 1. Time was studied as a fourth, pseudo-independent variable.

Table 1: List of the different groups used during the experiment

Group Name	Avatar	Giant Mode	IPD Scaling
Control	No	No	N/A
Avatar Control	Yes	No	N/A
Superman	No	Yes	No
Avatar Scale	Yes	Yes	Yes
Without Avatar Scale	No	Yes	Yes

3.4 Evaluation

In order to evaluate the accuracy of the perception of size within the virtual environment, we implemented several binary questions constructed as illustrated in Figure 3. The user is faced with a choice between a small figure and a large one. Neither response is correct, but one response is closer to the correct answer than the other. The user is informed of this fact at the outset, and is requested to make the choice that is closest to the correct answer. A response is considered correct when it corresponds to the figure that is closest to the true scale. When the contrary choice is made, it is considered incorrect, and the error direction is defined as either under or over, depending on which way the question is skewed. The list of the eight questions and their correct and incorrect answers, as well as error direction, is given in annex.

3.5 Experimental Protocol

The design of the VR experience allows users to navigate freely within a virtual environment and to decide (with the exception of the control groups) the amount of time that they spend in either normal or Giant scale. At the outset, the user is given a short tutorial, and for those in a group that allows scaling, is prompted to scale up and down once so that they are aware of this capability.

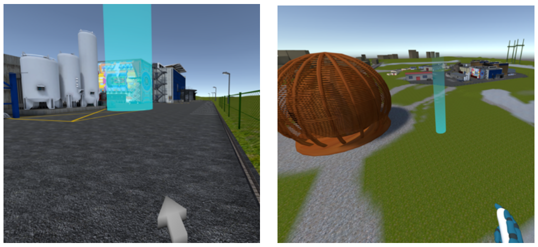
Once inside the VR experience, the user is guided by prompts, which invite the user to move through a series of checkpoints, each indicated by a directional arrow and a column of blue light, which is visible from either normal or Giant scales (Figure 2). Each checkpoint is associated with a virtual object in the VE.

Once at a checkpoint, the user is reduced to normal scale and oriented towards the object of interest at that checkpoint (or maintains normal scale in the control group) so that there is an equivalence of perspective between all experimental groups at this stage. The user is asked to judge the scale of the object in question, following the binary choice as previously described in Figure 3 according to subsection 3.4.

4 EXPERIMENTAL RESULTS

4.1 Results

We conducted our study at the CERN main site located in Meyrin, during the week-end of the CERN Open Days. During this period



(a) From the Normal Perspective (b) From the Giant Perspective

Figure 2: Navigation Markers

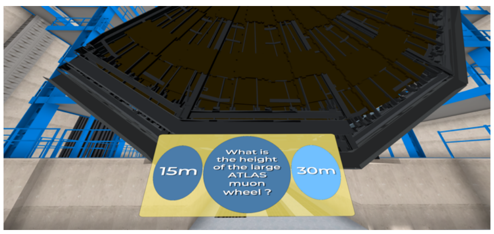


Figure 3: Scale question prompt, showing the binary choice between a small figure and a large one

we collected data from 342 participants, aged between 5 and 99, running twelve Oculus Go headsets in one room simultaneously.

4.1.1 Data preprocessing. In order to eliminate inconsistent data from the population, we applied three different filters. We removed results from participants under the age of 18, participants that did not complete the outdoor phase of the experience, and only considered responses and time spent at Giant scale for the outdoor part of the experiment, as the size scaling in indoor areas is non-uniform and depends on the height of the room's ceiling.

After filtering, the dataset contains 177 entries (96 male and 81 female).

Size accuracy was computed as the rate of correct answers over total questions. Given that each question had a designated "correct" answer and designated "error" (cf. annex) we were able to determine a normalized error direction for the user's size evaluation. A user that judges the correct object size for every question would receive an error direction of 0. Otherwise for each error we added +1 or -1 to the error trend depending on the direction of the error and then divided it by the number of errors.

As results are drawn from discrete values we only considered non parametric tests for the analysis.

Boxplot representations show the median (large red line in the middle of the notch), the mean (small dotted blue line), first and last quartile (colored area). Whiskers represent the contained population between $Q1 - 1.5 \cdot (Q3 - Q1)$ up to $Q3 - 1.5 \cdot (Q3 - Q1)$ while circles represent outliers (values beyond these whiskers). Finally, notches represent the 95% confidence interval of the median.

4.1.2 H1. To assess that the direction of the error of the scale estimation in control groups is lower than zero we started by aggregating data from the "Control" group with the "Avatar Control" group. Then we applied a Wilcoxon test to reject the null hypothesis that the evaluation error trend is not null. We obtained a p-value of 0.86 meaning that we cannot consider a significant difference in the obtained value from 0. Thus our data does not support the first hypothesis of the paper.

4.1.3 H2. In order to determine the potential effect of Giant mode we concatenated samples from the "Control" group with the "Avatar Control" group (the two without access to Giant mode) in one sample with the remaining groups in another sample. Then we compared both samples using the Ranksum test and obtained a p-value of 0.17. As as result we find that Giant mode alone is not sufficient to validate our second hypothesis.

4.1.4 H3. We used the same approach to check for a more pronounced scale underestimation for groups where subjects were provided with a virtual body (avatar). Thus we aggregated data from "Avatar Scale" and "Avatar Control" into one sample and the other groups in the comparative sample, obtaining a p-value of 0.040 (Ranksum) highlighting a significant difference between the two samples for the direction of the evaluation error. To retrieve which direction we performed a one-tailed Mann-Whitney U test giving us a p-value of 0.016, indicating that groups with an avatar presented a higher overestimation of virtual object sizes relative to non-avatar groups, soundly rejecting our third hypothesis. A plot of scores from these two samples are available in Figure 4.

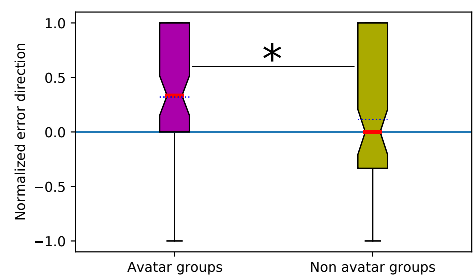


Figure 4: Comparison of normalized score of evaluation error direction between groups with an avatar and those without

4.1.5 H4. As above, to determine the effect from IPD on the underestimation of object size we concatenated data from "Avatar Scale" and "Without Avatar Control" groups into a first sample and remaining ones into a comparative sample. With a p-value of 0.010 for the Ranksum test we were able to highlight a significant difference between these samples. As before, the direction was then assessed using a one-tailed Mann-Whitney U test with a p-value of 0.004, showing that the group with IPD scaling (with or without avatar) tended to overestimate less the sizes of objects, thus validating our fourth hypothesis. These results can be seen in Figure 5.

4.1.6 H5. To test our final hypothesis we aggregated data from all groups where subjects experienced the Giant mode (i.e. all groups except "Control" and "Avatar Control"). This sample was split into two samples using the median of the time spent as Giant as a delimiter, which was calculated as approximately 60 seconds.

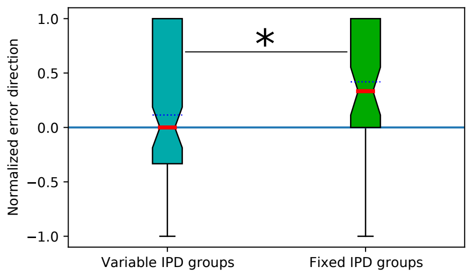


Figure 5: Comparison of normalized score of evaluation error direction between groups with variable IPD and those with a fixed IPD

The Ranksum test didn't provide us a p-value low enough (0.21) to highlight a significant difference between these two samples which doesn't allow us to validate our last hypothesis.

4.1.7 Other results.

Group - Size evaluation error trend. We also compared the distribution of error direction of the scale estimation between each group using Ranksum tests (10 in total). Using the Bonferonni correction we observed one significant difference between "Control" and "Avatar Scale" groups with an uncorrected p-value of 0.0022. With a one-tailed Mann-Whitney U test with a p-value of $7.3 \cdot 10^{-4}$ we found that subjects from the avatar scale group tended to overestimate object sizes more than ones from the control group. Plots of these scores are available in Figure 6.

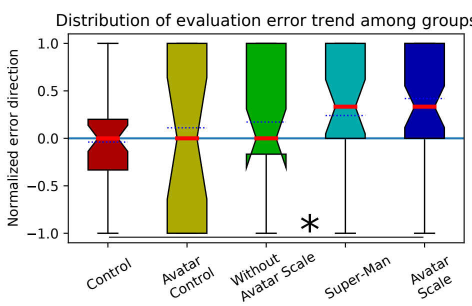


Figure 6: Comparison of normalized score of evaluation error direction between experimental groups

Grouped groups - Size evaluation error trend. In order to assess some of the more complex interactions at play between study variables, we compared the distribution of error direction amongst concatenated subgroups. Namely, we compared the avatar groups "Avatar Control", "Avatar Scale" and the remaining non-avatar groups using Ranksum tests (3 in total). Using the Bonferonni correction we observed one significant difference between the "Avatar Scale" and the remaining groups with an uncorrected p-value of 0.010. With a one-tailed Mann-Whitney U test with a p-value of 0.004 we found that subjects from the avatar scale group tended to overestimate object sizes more than ones from the remaining groups, as shown in Figure 7.

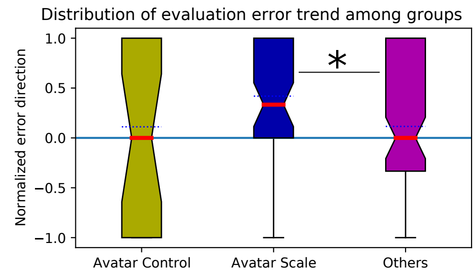


Figure 7: Comparison of normalized score of evaluation error direction between concatenated groups

5 DISCUSSION AND CONCLUSION

Most studies on the estimation of scale in virtual environments have been performed in highly controlled conditions. Our intention was to take an increasingly popular navigation technique - traveling at Giant scale - and assess whether it induces similar effects on scale estimation when employed in an open, real-world, self-directed, and feature-rich environment.

In contrast to our initial expectations, we showed that some commonly observed effects did not always present themselves. For instance, our first hypothesis assuming a general underestimation of object size for control groups (i.e. no Giant size) wasn't observed in this experiment. While we were not able to demonstrate uniform scale underestimation, as might have been expected, we did witness that users only showed about 60% size accuracy in their judgements, even though there was no predictable error direction. As presented earlier, it has been observed that in feature-rich environments [Henry and Furness 1993], size estimations may be skewed by as little as 20 percent. Given the feature-richness of our environment, and the wide range of self-direction allowed, it is perhaps not surprising that users demonstrated a less one-directionally skewed understanding of the scale of the environment.

Our second hypothesis, that scaling to Giant mode would skew size estimation more strongly, was not observed either. While at first glance this may seem surprising, given the large scale of the Giant mode we employed, it is perhaps to be expected in an experience where the user continually shifts from small to large scale. In addition, we forced users to return to 1:1 scale at every experimental question. While this ensured a uniform reference point, it meant that those using Giant mode were suddenly asked to evaluate the size of something from a vastly reduced relative scale, whereas the users who had been navigating at 1:1 scale witnessed no such change. The Giant mode users may have therefore interpreted their Giant size as the reference, and the 1:1 size as a "shrunken" body. This effect would have directly counteracted the underestimation effect, obscuring the role of Giant mode in size estimation, or, more importantly, showing that if a user can control their scale, perhaps they are not subject to the same scale distortion as might be expected.

Curiously, we showed the opposite of our third hypothesis, that subjects provided with an avatar would show more size underestimation than those without. This effect may again be explained by the construction of the experimental questions, as previously described. When the user is provided with an avatar, its presence may accentuate this effect. In order to test this hypothesis, we compared avatar subgroups which included this potential "shrinking" effect (Avatar Scale), without it (Avatar Control) and the remaining non-avatar groups. Indeed, we found that the Avatar Control group, see Figure 7, tended to overestimate, while the remaining groups did not demonstrate this effect, thus suggesting that our explanation for this effect is plausible.

Our hypothesis that variable IPD would result in decreased overestimation was readily validated by our experiment. In practical terms, this means that user scaling, as compared to the superman technique, maintains a better estimation of the true scale of the environment. This result may be unsurprising, given what we know about binocular vision, but its verification nonetheless reinforces the validity of the user-scaling approach to maintaining the most natural navigation in a virtual environment.

Moreover, the two previous results above agree with the additional observation that there is a statistically significant difference between the "Control" and "Avatar Scale" groups in terms of the error direction of size evaluation, as both differ in terms of the two relevant variables: IPD and the presence of an avatar.

Our last hypothesis, that the amount of time spent as a Giant would have an effect on size estimation, was not demonstrated. There may be a few reasons for that. First of all, users did not spend a large amount of time in Giant mode, with an average of approximately 47 seconds, out of an average total experience time of more than 6.5 minutes (so only approximately 10 percent time on average). Secondly, they were clustered quite narrowly around the mean, so distinctions between users may be difficult to observe. Lastly, the design of the experience, with constant switching from one scale to another, may in fact counteract the effect of time. Once a user becomes familiar with the two scales at play, they may not need to be exposed for a longer period in order for it to have a significant effect on their size judgement.

Conclusion. We observed trends which both contradicted and confirmed some well-known phenomena. Users with variable IPD showed a tendency to underestimate the VE scale compared to those with fixed IPD (Giant vs. Superman), but the net results amounted to over-estimation, rather than the underestimation taken to be the norm for users in a VE. The presence of an avatar indeed increased the magnitude of over-estimation, but again in the opposite sense to that predicted by the literature. Indeed, only the presence of both avatar and scalable IPD (Avatar scale group) provided results statistically significant when compared to the controls.

We presented a plausible explanation for the results we observed, namely an inversion of reference frame between normal and Giant, which suggests further work that could be done to better understand the variables at play in this novel navigation technique, particularly in the real-world case of feature-rich, open, freely-navigable virtual environments.

6 FUTURE WORK

The design of the experiment could be modified by including experimental groups where the user is not forced to normal scale at the time of experimental questioning, thereby examining the potential inversion of reference effect that was discussed. Time-based effects could also be examined by enforcing a specific amount of time in Giant mode for different experimental groups.

The complex nature of the interactions between the key variables examined here leaves ample room for re-imagining this experiment in different forms. With the increasing interest in viable navigation techniques in VR experiences, it seems that the utilisation of Giant scale navigation may increase, and that its effect on user perception and behaviour will become an increasingly interesting area for study.

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