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Published in:
Proceedings of Conference on Computer-Human Interaction and Applications, CHIRA 2022

DOI (link to publication from Publisher):
10.5220/0011376400003323

Publication date:
2022

Document Version
Accepted author manuscript, peer reviewed version

Citation for published version (APA):
Bach, M. T., Jensen, P. A., Lucaci, A-I., Pupczyk, D. G., & Madsen, C. B. (2022). Effect of Environment Size on Spatial Perception in Virtual Reality. In *Proceedings of Conference on Computer-Human Interaction and Applications, CHIRA 2022* (pp. 97-104). SCITEPRESS Digital Library. International Conference on Computer-Human Interaction Research and Applications https://doi.org/10.5220/0011376400003323

Effect of Environment Size on Spatial Perception in Virtual Reality

Morten Trier Bach[1], Poul Anker Jensen[1], Andrei Iuliu Lucaci[1], Damian Grzegorz Pupczyk[1]
and Claus Brøndgaard Madsen[1] [a]
[1] *Computer Graphics Group, Department of Architecture and Media Technology, Aalborg University, Aalborg, Denmark*
bach97@live.dk, poulankerjensen@yahoo.dk, lucaci_andrei@ymail.com, damianpupczyk@gmail.com, cbm@create.aau.dk

Keywords: Virtual Reality, Virtual Environments, Spatial Perception, Blind Walking

Abstract: A trend of distance underestimations in Virtual Reality (VR) is well documented, but the reason still remains unclear. Therefore, this paper investigates the effect of differently sized Virtual Environments (VEs) on egocentric distance perception in VR as a potential influence. Verbal assessment, blind walking, and our own proposed method: walk and assess, were compared in an experiment, and blind walking was found to be the most accurate. A virtual replica of a real-life location was created as a transitional environment, while small (15m^2), medium (35m^2) and large (95m^2) rooms were created to investigate the effect of VE size on spatial perception in VR. To establish the differences in estimations between the real world and VR when using blind walking, a study was conducted with the virtual replica and its real life counterpart at distances between 1 and 10 meters. Following this, the three distinct room sizes were used in an experiment to investigate the effect of the size of rooms on spatial perception in VR. The findings showed consistent underestimates of distances, and a trend for underestimation to grow as the distance grows was observed. Similarly, underestimates grew with the size of the environment.

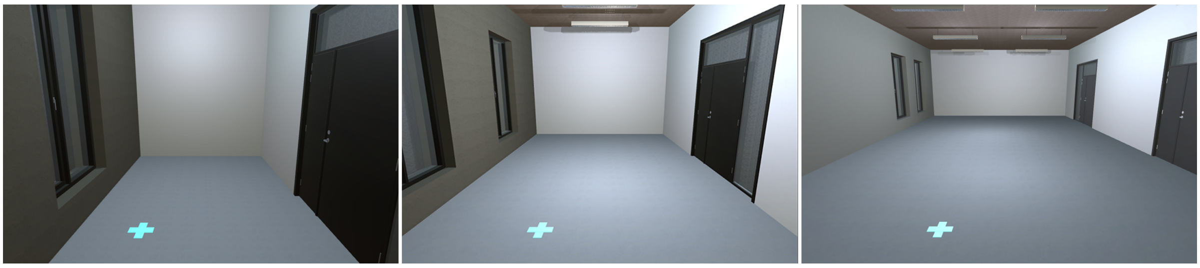

Figure 1: The three differently sized rooms used in the *Room Size Experiment* in Section 6.

1 INTRODUCTION

Virtual Reality (VR) as a technology has been shown to be influential within the world of architecture, where it is used to represent and simulate architectural spaces Loyola (2018). Unfortunately, quite a few researchers have found that distances in Virtual Environments (VEs) are generally underestimated by 10 to 26 percent (Loyola (2018), Witmer and Sadowski Jr. (1998), Ahmed et al. (2010), Renner et al. (2013)), which threatens the validity of the platform as a medium for representation of spaces, and makes it a subject worth exploring.

In an experiment done by Lucaci et al. (2022), findings indicated general overestimation of distances. They hypothesized that it might have been due to the relatively small size of the environment (12.6m^2) compared to previous research which used larger environments ranging from 13m^2 to 233m^2 (Simpson et al. (2018), Moscoso et al. (2021), Zhao et al. (2019)).

Lucaci et al. (2022) used *Verbal Assessment* to measure perceived distances, however, Thompson et al. (2004) have criticised the method for being subjected to bias and noise.

With this in mind, the aim of this study was to *identify a reliable method of quantifying perceived distances, and use that to investigate the effect of different sizes of VEs on spatial perception in VR.*

2 SPATIAL PERCEPTION IN VIRTUAL REALITY

Spatial perception is a combination of physiological and cognitive processes which utilize a variety of perceived depth cues to turn a two-dimensional image into a three-dimensional representation of the world (Renner et al., 2013).

Perceived distances can be either ego-centric or exo-centric. Ego-centric distances refer to distances between an observer and a point, while exo-centric distance is the distance between two external objects. (Maruhn et al. (2019), Renner et al. (2013))

Underestimation of ego-centric distances in Virtual Reality (VR) was found to be 19% by Loyola (2018) and 15% by Witmer and Sadowski Jr. (1998), while real-world distances were found to be underestimated by 8% by Witmer and Sadowski Jr. (1998), and 4% by Messing and Durgin (2005). These underestimations are particularly evident with egocentric distances above 1 meter. On the other hand, some studies have indicated that exo-centric distances in VR may be overestimated in VR. (Maruhn et al., 2019)

However, the focus of this paper is only on ego-centric distances to emphasize the room size effect. It is also applicable to more methods of distance estimation than exo-centric distances (see Section 4).

2.1 Depth Cues

To properly understand spatial perception, a basic understanding of the depth cues which allow us to perceive depth is needed. Such an understanding can aid in identifying what might lead to errors in distance estimations.

The depth cues used to inform the three-dimensional understanding of the world can be divided into two categories; pictorial and non-pictorial cues. Pictorial cues are cues that can be obtained from a motionless image, while non-pictorial cues are largely from motion in the scene or the human visual system (Renner et al., 2013). The pictorial cues include occlusion, relative and familiar size, horizon ratio, shading and texture gradients (Proffitt and Caudek, 2012).

Non-pictorial cues include binocular disparity, motion parallax and ocular motor (accomodation and vergence) (Proffitt and Caudek, 2012). Maruhn et al. (2019) suggest that visual cues might differ between physical environments and VR in a multitude of ways, such as by introducing the vergence-accomodation conflict, which is a result of presenting different images to each eye using stereoscopic displays.

This phenomenon can be a source of visual discomfort and dizziness.

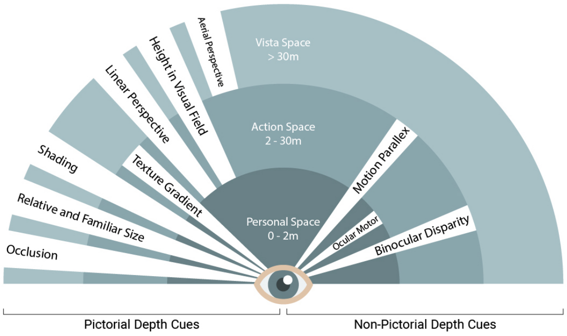

Figure 2: The interplay between segmentation of egocentric distances and most important visual cues.

When discussing distance perception of the world, one should also consider the circular segmentation of egocentric distances around a moving observer as presented by Cutting and Vishton (1995). The segments and their associated depth cues are shown in Figure 2. The first of these segments is referred to as *Personal Space*, and is the area closest to an individual (within arm's reach) delimited by Cutting and Vishton (1995) to 2 meters. The second segment is called *Action Space* which extends from the bounds of the personal space out to about 30 meters - one can move relatively quickly, speak, teach and toss objects with relative ease in this segment. The final segment is called the *Vista Space* which extends beyond 30 meters, at these distances the benefits of binocular vision and movement of the observer significantly diminishes. (Cutting and Vishton, 1995)

3 ROOM SIZES IN VIRTUAL REALITY

When acting in an environment, the size and layout of it profoundly impacts ones perceived personal, action, and vista spaces, as distances to objects and walls might limit the area one can interact in and the available depth cues. To our knowledge, no prior research has been done with a particular focus on the effect of room sizes on spatial perception. Nevertheless, the sizes of Virtual Environments (VEs) used in Virtual Reality (VR) research can be incorporated to inform the design of our VEs.

Sizes of rooms used in such studies vary from just 13.46m^2 in a study by Zhao et al. (2019) all the way to 233.26m^2 (21.44m x 10.88m) in a study by Moscoso et al. (2021).

While Moscoso et al. (2021) only used two different rooms in their studies, Simpson et al. (2018) incorporated 7 square rooms with the sizes 16m^2, 18.75m^2, 21.34m^2, 25m^2, 28.40m^2, 32.14m^2, 36m^2, and uniform heights of 2.74m to study the impact of visual design elements on perception of spaces.

Zhao et al. (2019) used 4 square rooms of sizes 16m^2, 21.80m^2, 28.40m^2, and 36m^2 to the influence of what is seen through windows of a room on perceived spaciousness of rooms. Zhao et al. (2019) also presented a room of 13.46m^2 size as a reference to spaciousness of 1, and a room of size 40.06m^2 as a reference for spaciousness 10.

3.1 Categorization of Room Sizes

Based on the rooms used by Simpson et al. (2018), and Zhao et al. (2019), a survey was designed and distributed to 45 people. The survey consisted of 10 rectangular floor plans (9m^2, 19m^2, 29m^2, 39m^2, 49m^2, 59m^2, 63m^2, 75m^2, 86m^2, and 97m^2), which were presented to participants in random order. Participants were asked to rate whether they found each room to be *small*, *medium* or *large*.

The weighted average of the results were computed for each group; the boundary between *small* and *medium* was $\sim$25m^2 and between *medium* and *large* was $\sim$52m^2.

From these results the intervals were defined as: 0-25 m^2 for *small*, 25-50 m^2 for *medium*, and above 50 m^2 for *large*. This categorization was used to inform the sizes of rooms used in the *Room Size Experiment* presented in Section 6.

4 METHODS FOR QUANTIFYING PERCEIVED DISTANCES

To investigate and compare perceived distances in a set of virtual environments, one must be able to quantify them. Two of the most prominent methods for quantifying perceived distances are:

- **Verbal Assessment** (Loyola (2018), Peer and Ponto (2017), Armbrüster et al. (2008), Gagnon et al. (2020), von Castell et al. (2018), Kelly et al. (2017), Klein et al. (2009))
- **Blind Walking** (Interrante et al. (2006), Kelly et al. (2018), Li et al. (2015), Kelly et al. (2017), Ahmed et al. (2010))

It was decided to evaluate *Verbal Assessment*, *Blind Walking*, and *Walk and Assess* (a method where participants walk a distance of their choice from a starting point, and then estimate it verbally, devised by us) with participants to identify the method that performed most similarly between real life and VR with the highest accuracy. The experiment was conducted on 30 participants with perfect 20/20 or corrected vision, who would estimate three distinct distances for each chosen method. *Verbal Assessment* resulted in 22% average error in VR and 13% in the Real World (RW), *Walk and Assess* showed 25% average error in VR and 18% in RW, and *Blind Walking* showed 12% average error in both VR and RW. Due to the fact that *Blind Walking* performed most similarly between VR and RW, and resulted in the least average error in both VR and RW, we chose this method to be used in the succeeding experiment.

5 BLIND WALKING BASELINE EXPERIMENT

To establish what difference might exist in estimates between the Real World (RW) and Virtual Reality (VR) when using *Blind Walking*, an experiment to evaluate the method was designed. The purpose was the establishment of a baseline difference between VR and RW, as well as it being a pilot test of the method for the final investigation of room sizes effect on spatial perception in VR.

5.1 Participants

40 participants were recruited with normal (20/20) or corrected vision. All participants were university students recruited by convenience, and had an average Interpupilary Distance (IPD) of 65mm.

5.2 Apparatus

A Quest 2 Head Mounted Display (HMD) was used, untethered to allow free movement, connected to a laptop with Oculus Airlink. The laptop had a Nvidia Rtx 3060 graphics card and ran Windows 11.

In order to minimise the blurriness that participants might experience from an uncalibrated HMD, each participant's Interpupillary Distance (IPD) settings were measured and adjusted to one of the three physical settings on the Quest 2 (58mm, 63mm, and 68mm).

The Field of View (FOV) of the Quest 2 was also measured, and found to be 94°(IPD 58mm), 93°(IPD 63mm) and 95°(IPD 68mm) vertically, with the horizontal FOVs being 93°(IPD 58mm), 94°(IPD 63mm) and 86°(IPD 68mm).

5.3 Procedure

The participants would enter a large empty room (130m^2) assigned as a testing area (as shown on Figure 3) and complete a consent form.

A facilitator (facilitator 2 in Figure 3) shortly briefed each participant of the procedure of the experiment, and would keep the participants informed of what would happen next during the experiment. A Latin square was utilized to counterbalance the order of the conditions and distances between participants.

In the real world condition participants were first shown a target point, after which they were asked to blindly walk to the target point. The participants were asked to close their eyes and wear a sleeping mask to prevent them from seeing the target point while walking. After assessing a distance by walking to the point, the distance was measured by a facilitator with a laser range finder, and the participants were asked to return to their starting position which was marked on the floor with a cross. The process was repeated until all distances were assessed.

In the VR condition, participants entered a virtual replica of the empty room and went through the same process as described above. Instead of a sleeping mask, the screen in the HMD was faded to black after participants were informed to close their eyes. The participants' walk was assessed by the software instead of a laser range finder. The changing of targets, fading to black, and noting of measurements was done by facilitator 1 as seen in Figure 3.

To ensure participants' safety during their *Blind Walking*, facilitator 3 (in Figure 3) would prevent them from colliding with walls should they have walked too far.

Figure 3: Visualization of the test setup for the *Blind Walking baseline experiment*.

5.4 Results

To compare the distance assessments across conditions and distances, the amounts of error in the assessments were expressed in percentage. The absolute values of results were analyzed in the context of accuracy, defined as *"how much the assessments deviate from the actual distances"* (Loyola, 2018), while the standard deviation of relative values were used to represent the precision of the assessments, defined as *how similarly participants within a certain group assessed the distances* (Loyola, 2018).

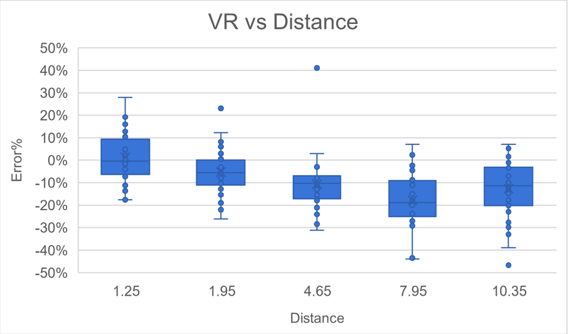

Figure 4: Participants' precision in VR at given distances reveals a tendency to underestimate as distances gets larger.

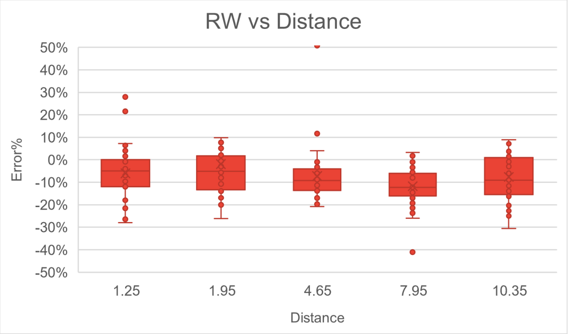

Figure 5: Participants' precision in RW at given distances shows a similar trend of underestimation as in the VR condition in Figure 4.

The mean relative error for the VR condition was -9.21%, and the mean relative error for the RW condition was -6.84% - this shows that on average, participants underestimated distances in both conditions, with underestimations being greater by 2.37% in VR than RW. The standard deviation of the relative errors in VR was 7.42%, while the standard deviation for the real world condition was 8.9%. As the VR condition had a slightly lower standard deviation (1.51% difference), it shows that the VR condition had slightly higher precision than in the RW condition. This was shown to not be a statistically significant difference (p-value $= 0.22 > 0.05$).

Plots showing the relative errors at each distance for the VR condition can be seen on Figure 4, and the relative errors at each distance for the RW condition can be seen on Figure 5. The plots show a clear trend towards greater degrees of underestimation as the distance increases, which is both observed in VR and RW. Also noteworthy is that the underestimation gets slightly smaller in the final estimate (10.35m) potentially due to it being close to the physical end of the room used for testing.

The mean absolute error in the VR environment was found to be 12.26%, and 10.76% in the RW environment, suggesting that the estimates in the RW were more accurate than in VR, and the difference between the two conditions were found to be statistically significant (p-value $= 0.04 < 0.05$).

This study of *Blind Walking* as a method, establishes that the degrees of underestimation between VR and RW are fairly similar ($\sim 2\%$ difference), with less underestimation in RW than VR. The RW underestimation were in line with the prior research presented in Section 2, while the degree of underestimation in VR was also lower than what was found by prior research. As the method performed similarly to prior work in the field, with little difference between VR and RW, it was chosen to be utilized in the final experiment regarding the effect of room sizes on spatial perception in VR (described in Section 6).

6 ROOM SIZE EXPERIMENT

As a baseline for the relationship between Virtual Reality (VR) and the Real World (RW) was already established in Section 5, the rest of the experiments were conducted purely in VR.

To investigate the influence of room size on spatial perception three different rooms were designed: a small room ($\sim$15m^2), a medium room ($\sim$35m^2) and a large room ($\sim$95m^2). The sizes of the rooms were based on the research described in Section 3.1 and were all chosen to have the same 3:5 aspect ratio. All the rooms give access to the personal and action spaces, while the vista space is never reached, which afforded the depth cues presented in Figure 2. The rooms can be seen side by side in Figure 1.

6.1 Participants

36 participants were recruited with normal (20/20) or corrected vision. Participants consisted of university students recruited by convenience. The average IPD of the participants was measured to be $\sim$65mm.

6.2 Apparatus

The apparatus used for the *Room Size Experiment* was the same as for the *Blind Walking Baseline Experiment*, as presented in Section 5.2.

6.3 Procedure

The participants would enter the same large empty room as in the *Blind Walking Baseline Experiment* with an area of 130m^2, where they were informed of the procedure of the experiment and filled out a consent form.

Participants then entered a transitional environment in Virtual Reality (VR), which resembled the large empty room they were present in. After a brief delay, they would then be transported to the first room of the experiment (either the small, medium or large one).

In each of the rooms of the experiment, participants would be presented with blue crosses on the ground which served as targets, and once they said that they felt ready to walk there without vision, they were asked to close their eyes and the screen would fade to black. This procedure would be repeated for 4 targets in the small room, 6 targets in the medium room, and 8 targets in the large room as indicated on Figure 6.

All targets and rooms were presented in random orders (based on a Latin square) for each participant, and since the targets 0.9m, 1.7m, 2.6m and 3.2m were presented to participants in both the small, medium and large rooms they would serve as the basis of later comparisons. We refer to these distances as the *universal distances*.

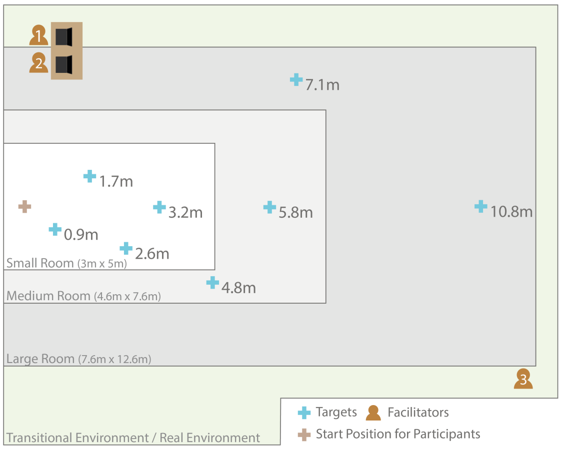

Figure 6: Visualization of the transitional environment setup with the three overlapping rooms and distances

6.4 Results

The mean relative error for the *universal distances* was found to be -4% in the small room, -5% in the medium room, and -6% in the large room. This shows a consistent tendency towards underestimation of distances, regardless of the room size, which seems to grow slightly larger as the room size does. The relative error for *universal distances* was found to be normally distributed, and no statistically significant difference was found between the small and medium rooms ($p = 0.49 > 0.05$), however, a statistically significant difference was found between the small and large room ($p = 0.03 < 0.05$). A statistically significant difference was also found between the error estimates for the medium (8%) and large room (9%) ($p = 0.04 < 0.05$) when comparing all overlapping distances (*universal distances*, 4.8m and 5.8m).

The standard deviation for the *universal distances* was found to be 12% for the small room, 13% for the medium room and 11% for the large room. This indicates that the *precision* is not linearly influenced by the room size.

The relative error estimates for each distance in each room size are presented in Table 1. The table shows a general trend towards greater degrees of underestimation as the distance increases. It is also worth noting that the first distance, 0.9 meters, was consistently overestimated regardless of room size.

A statistically significant difference was found between all distance estimates of consecutive distances ($p < 0.05$), except for between 2.6m and 3.2m in the small room, 1.7m and 2.6m in the medium room, and 3.2m and 4.8m in the large room. In most cases the statistical significance shows growing underestimation, with the exception of the cases 3.2m to 4.8m in the medium room, and 5.8m and 7.1m in the large room.

Table 1: Relative error of each distance and room size in percentage. *Universal distances* are highlighted in green. Light blue shows overlapping distances between medium and large, and light purple are only for the large room.

Average Error in Estimates			
Distance (meters)	Small Room	Medium Room	Large Room
0.9	+4%	+3%	+3%
1.7	-4%	-4%	-6%
2.6	-7%	-7%	-11%
3.2	-11%	-12%	-11%
4.8		-10%	-11%
5.8		-16%	-20%
7.1			-14%
10.8			-19%

The mean absolute error, representing the *accuracy*, was found to be 10% for the small room, 11% for the medium room, and 11% for the large room. The small room showed the lowest absolute error, but no statistically significant difference was found between any of the room sizes (small-large [$p = 0.21 > 0.05$], small-medium [$p = 0.58 > 0.05$], medium-large [$p = 0.31 > 0.05$]). The absolute error data was found to be non-normally distributed.

7 DISCUSSION

The mean relative errors for the *universal distances* were found to be -4% in the small room, -5% in the medium room, and -6% in the large room. The large room was found to have statistically significantly different estimates from the small and medium rooms. However, this was not the case between the small and medium rooms. This observation indicates that room size affects participants' ability to perceive distances, with a tendency of larger rooms causing greater underestimations.

The small and medium rooms showed no statistically significant differences in participants' error degree, which suggests that the difference in size between the small and medium room has to be bigger for the effect to have a statistically significant influence on the results.

The results of the experiments also show a tendency of longer distances being underestimated more than shorter distances. This is shown by most consecutive distance estimates being statistically significantly different from each other, while also maintaining a trend of increasing underestimation.

In the *Blind Walking Baseline Experiment* as a method for quantifying perceived distances, the average error was roughly -9% for Virtual Reality (VR) and roughly -7% for Real World (RW). These degrees of underestimation are largely consistent with previous studies investigating spatial perception in VR, using *Blind Walking* as a method. Ahmed et al. (2010) found underestimations to be 10% and Witmer and Sadowski Jr. (1998) reported 15% underestimation in VR. The 7% underestimation found for the RW condition is also in line with previous research, especially insofar as being lower than the VR underestimations. Loyola (2018) found 10% underestimation, Witmer and Sadowski Jr. (1998) found 8% underestimation in RW.

Based on the results from the *Blind Walking Baseline Experiment*, it can also be theorized that the presence of a physical wall close to the furthest distance affected the estimations. As can be seen in Figures 4 and 5, in both conditions the accuracy decreased the longer the distance - until 10.35, which was the distance closest to the wall. A reason for this might have been some participants putting out their hands in front of them to try to feel the wall, which was a flaw of the experiment.

Similarly, in the *Room Size Experiment* we observed that estimation points close to the side walls had less underestimation, with 4.8m being the closest to a wall in the medium room and 7.1m in the large room as seen in Figure 6 than the furthest point, and the point before them. This was not seen in the small room, likely because the points were similarly spaced from the walls.

A noteworthy deviation from prior research is the advancement of VR technology in the recent years allowing the display of images in a higher resolution and at higher refresh rates. Another difference is that most previous studies used tethered HMDs for their experiments, while this study used an untethered HMD. This might be a reason for the lower degree of underestimations found in this study, since being untethered affords more freedom of movement.

7.1 Validity and Reliability Concerns

The implications of this study should be evaluated with caution due to some threats to the validity and reliability of the results. One of them being the fact that the experiments were carried out on a convenience sample of university students, opposed to a random sample. This could affect how adequately they represent the general population. Nevertheless, as mentioned in Section 6.4, the relative error data was normally distributed. Additionally, since most of the participants who took part in the experiments were students pursuing technology and design related degrees, it is also likely that some of them were experienced with VR. This could affect the results of the experiments, as it could translate into better performance due to being more used to acting in a virtual space.

Another potential threat affecting the results could be the sound cues caused by the movement of the facilitator, who ensured that participant's would not collide with walls, as it might have affected their spatial awareness.

Additionally, the distances used in all experiments were consistent across conditions, with the same groups of participants testing in all conditions per experiment. This could entail some carryover effects that could affect the results, such as practice and visual fatigue. To account for these effects, the experiments were designed with the use of Latin squares, randomizing the order of distances. To further prevent visual fatigue, the experiments were designed to take up a short amount of time (on average 10 minutes per participant).

8 CONCLUSION

The aim of this study was two-fold: to identify a reliable method of quantifying perceived distances, as well as to use the identified method to investigate the effect of different sizes of Virtual Environments (VEs) on spatial perception in Virtual Reality (VR).

To investigate the reliability of the methods, they were compared between VR and the Real World (RW). *Blind Walking* was identified as a promising method, as it resulted in the lowest degree of underestimation in both VR (12%) and RW (12%) and it also performed the most similarly between RW and VR compared to verbal assessment and walk and assess. The method was further investigated in a large (130m^2) empty room to establish a baseline for the difference between error estimation in VR and RW, where underestimation of distances were found to be ∼9% in VR and ∼7% in RW.

The effect of different VE sizes on spatial perception was then investigated using VR and three differently sized rooms: a small room (15m^2), a medium room (35m^2) and a large room (95m^2). Underestimations were found to be 4% in the small room, 5% in the medium room, and 6% in the large room for the *universal distances* (distances between 0.9m and 3.2m) in the *Room Size Experiment*. This indicates that distances become more underestimated the larger the area of the VE. It is worth noting that no statistically significant difference in estimates was found between the small and medium rooms, however, the large room had a statistically significantly greater degree of underestimation than the small and medium rooms.

In general, the underestimations from the *Blind Walking Baseline Experiment* and *Room Size Experiment* are in line with previous literature as presented in Section 2. Additionally a tendency for underestimation to grow with the distance was found.

More importantly, the *Room Size Experiment* indicated that room size could influence spatial perception in VR, however, more research is needed to validate this and find the exact threshold where room size begins to have a clear effect.

In conclusion, this study contributes to a better understanding of spatial perception in VR, how it is affected by the size of the environment, as well as the performance of *Blind Walking* as a method of quantifying perceived distances.

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