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Abstract. The interception of the action-perception loop in virtual reality [VR] causes that understanding the effects of different display factors in spatial perception becomes a challenge. For example, studies have reported that there is not size-constancy, the perceived size of an object does not remain constant as its distance increases. This phenomenon is closely related to the reports of underestimation of distances in VR, which causes remain unclear. Despite the efforts improving the spatial cues regarding display technology and computer graphics, some interest has started to focus on the human side. In this study, we propose a perceptual calibration method which can ameliorate the effects of non-size-constancy in heterogeneous VR displays. The method was validated in a perceptual matching experiment comparing the performance between an HTC Vive HMD and a four-walls CAVE system. Results show that perceptual calibration based on interpupillary distance increments can solve partially the phenomenon of non-size-constancy in VR.

1 Introduction

The phenomenon of non-size-constancy is closely related to the enigma concerning distance perception in VR. Several studies have shown that distances are generally underestimated, but its causes remain unclear (see [23] for a complete review). With the advent of modern VR displays, the underestimation effects have begun to ameliorate but only when is measured using visually directed action tasks, such as blind walking ([6], [3]). In contrast, using other valid measurement tasks, such us blind-throwing and blind triangulated-pointing, the degree of underestimations increase and can vary significantly ([20]).

Similarly, the kind of display also influences the spatial perception. For example, divergences in large-immersive-projection displays [LIPDs] (such us immersive walls or CAVE systems) seem less stronger compared with head-mounted displays [HMDs]. Also, LIPDs have asymmetric performances which are closely related to the physical boundaries of the system. For example, there exists overestimation or underestimation of distances depending on if the target object is located between the subject and the projection wall (negative stereoscopic parallax) or behind the wall (positive stereoscopic parallax). Hence, the perception of distance could be different, not only in comparison with the physical world but also between heterogeneous VR displays.

Due to its dependency on distance perception, the underestimation effects also impact the perception of size. In HMDs, objects tend to increase its apparent size whereas, in LIPDs, similar asymmetric effects are produced. These effects were first reported by Kenyon et al. (2007) [7] using a CAVE system. They used a perceptual matching task to measure indirectly the perception of distance, requesting subjects to estimate the apparent size of a virtual object located at different distances over a virtual table, as it is shown in Figure 1. The virtual object was a replica of an equivalent physical one used as a reference. Besides, the distances were selected to represent the asymmetric effects related to the boundaries. Thus, their results showed that: only 55% of the population developed size-constancy and the errors were stronger for positive stereoscopic parallax as the target distance increased.

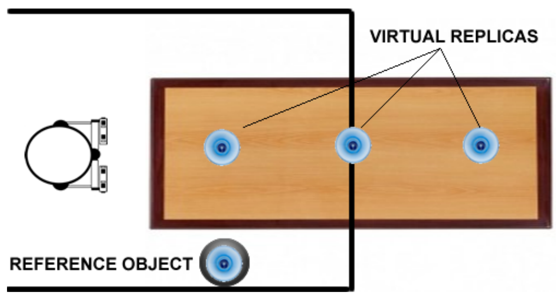

Fig. 1. Size-constancy-table experiment in a CAVE. Subject has to estimate the apparent size of an object located at different distances using a physical object as reference.

In this study, we reproduced this experiment using modern technology and we explored the effect of perceptual calibration, which is a method that has shown good results improving distance perception. Also, we were interested in comparing the differences between heterogeneous VR displays. For example, studying the same effects in HMDs is a challenge because it is impossible to visualize the physical object and its virtual replica at the same time. In this sense, we designed a perceptual calibration method targeting the differences in spatial performance between an HTC Vive HMD and a four-walls CAVE system. Therefore, the proposed method is an adaptation of Kenyon et al. experiment that is able to work in HMDs.

2 Related work

2.1 Distance and size perception in the real world

Different methods have been proposed to assess how people perceive egocentric distances: (1) verbal estimates, the most straightforward method but also the less accurate [1]; (2) perceptual matching, where subjects are asked to reproduce a distance span based on a previously perceived physical target [25] and with a degree of underestimation relatively low at shorter distances [11]; (3) visually directed action, the most popular method, where subjects are asked to estimate a distance performing an equivalent action physically ([12], [24]). Hence, the size-constancy-table experiment is a kind of perceptual matching task.

Size perception is mostly visual and distance perception dependent. Is ruled by the phenomenon known as "size-constancy" where an object is perceived as being of the same size regardless of its distance. The perceive size of an object follows the size-distance-invariance hypothesis (SDIH) $s = d\tan(\alpha)$, with s the perceived size, d the distance to the object and α its visual angle. For this reason, the perception of size can also be used as an indirect measure of distance perception using perceptual matching tasks.

2.2 Distance and size perception in VR

The most of the work on spatial perception in VR have been focused in egocentric distance perception, where a consensus exists that distances are generally underestimated, but its causes remain unclear. Most of past work were done using HMDs ([6], [27], [24]), where neither the limited field of view [FOV] nor the stereo viewing conditions nor the lack of realistic graphics contributes significantly to the underestimation effects. Although these results suggest that the display factors are not the cause, recent evidence suggests that the causes could be related to the nature of the peripheral light stimulation induced by the display [9].

An interesting phenomenon is the differences that exist between HMDs and LIPDs, either using immersive walls [21], [17]) or CAVE systems ([16], [13], [2]). We can highlight 3 important aspects about LIPDs on these studies: (1) underestimation effects seem to be less stronger than in HMDs, (2) the physical space between the user and the projection screen is the most important factor and, (3) the effects are asymmetric with underestimation for objects at positive stereoscopic parallax and slight overestimation with objects at zero or negative stereoscopic parallax. Thus, as in the previous study, we took into consideration these aspects in our experiment.

Regarding size perception, it has been demonstrated that the SDIH holds in VR [18]. Also, when the complexity of the scene increases, subjects make better judgments based on surrounding objects ([7], [16]). These characteristics make it suitable as a method to assess distance perception indirectly using perceptual matching approaches ([16], [4]). In this sense, the size-constancy-table test is an excellent task to study the phenomenon of non-size-constancy.

2.3 Methods to approximate spatial performance

Geometric calibration is focused on fixing possible discrepancies between the geometric FOV and the display FOV. Unfortunately, most of the work has been done in the field of augmented reality, where an object in the VE could be properly aligned with an object in the physical world [5]. Geometric calibration of Non-see-through HMDs is not straightforward, and there exists some evidence that even when the GFOV is calibrated, distance underestimation effects are reduced but not substantially [5].

Perceptual calibration is an alternative method that uses inverse geometric models to determine the perceptually correct viewing parameters ([15],[22]) and, its application has shown to improve distance perception in CAVE systems [22]. The method is based on the idea of defining camera positions that are wider or deeper than the values obtained using standard calibration practices, with the purpose of influencing the perception of size and distance. We develop our first approach based on the study developed in [22], and we extended it to support HMDs.

Other methods use a "computer vision" approach applying perspective projection adjustments: Minification is a method which compresses the imaginary to artificially increasing the FOV of a display, and its application can improve distance perception ([8], [28], [10]). Lowering the horizon is another similar method which had good results ([14], [19]). Unfortunately, these methods have undesired effects on size perception due to the reduction on the imaginary or the apparent change in the perceiver's height.

3 Perceptual calibration method

In VR, virtual cameras are usually calibrated via two viewing parameters: the interpupillary distance [IPD] and the optical center depth [OCD] (the artificial middle point between the eyes). HMDs and LIPDs implement different immersion modalities, but both share the same perceptual geometric model based on these parameters (Fig. 2 Left). To produce the correct image impression in each eye, a diverged representation of the object is generated. Thus, the perceived object size s is proportional to its distance d and its visualization angle θ (Eq. 1). Likewise, the perceived object distance can be computed from the IPD and the convergence angle α (Eq. 1).

$$s = d \tan\left(\frac{\theta}{2}\right), \; d = \frac{IPD}{2 * \tan\left(\frac{\alpha}{2}\right)} \tag{1}$$

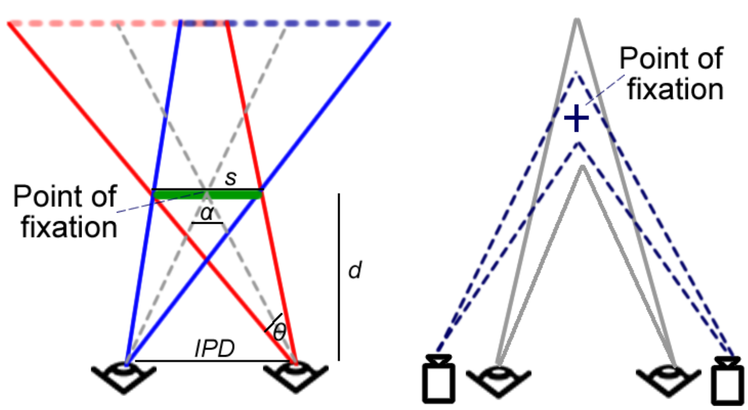

Fig. 2. Left: Geometric model for the perception of size and distance of an object in VR. Right: The effect of increasing the IPD on depth perception.

Perceptual calibration is based on the idea that perception in VR is distorted, and defining calibration parameters based on the viewer's eyes morphology is a simplistic approximation, since it depends on how the actual geometry is interpreted by the visual system which is out of observation ([22],[15]). A typical perceptual calibration procedure generates a set of perceptual camera positions by adjusting the IPD and OCD dynamically, with the purpose of finding a set of virtual cameras positions that approximate the subject's spatial perception to the physical world.

Figure 5-right shows the effects of increasing the IPD. Depth perception results from the disparities in the projections of corresponding points on the eyes' retina by calculating the relative positions in front of and behind the point of binocular fixation. A greater IPD causes an increase in retinal disparity producing hyperstereopsis, an exaggerated stereoscopic depth perception ([26]). The adjustments in the convergence angle α and the visualization angle θ gives the impression that the object is further and larger like occupying "more space than usual".

Based on the study developed in [22], we requested subjects to judge the superimposition of a virtual box with a physical one with the same dimensions. Before starting the test, we measured the subject's physical IPD and we estimated an OCD equivalent to 5 cm (using the tracker position in the CAVE condition as reference). At first glance, the virtual box may seem slightly misaligned, bigger or smaller. Then, we request subjects to adjust the IPD and OCD dynamically using a standard Gamepad, until they consider the boxes perceptually match and we repeat the process iteratively at different target distances (0.5m, 1.5m, and 2.5m). The distances were selected to represent the different underestimation/overestimation effects of positive, close to zero or negative stereoscopic parallax (Logically, at 2.5m we assume the inverse value of 0.5m for the CAVE).

The proposed perceptual calibration procedure in two heterogeneous displays is shown in Figure (Fig. 3). In the CAVE, the physical box is made of glass which makes straightforward to fuse them and align them visually (Fig. 3 Left). In the HMD, we added a small screw at the top of the box, and we asked subject to compare its alignment by pointing to the same virtual position. A stick attached to the tracked HTC Vive controller enabled subjects to judge their alignment, comparing the visual cues with their proprioceptive responses (Fig. 3 Right). In both kinds of displays, the box is located on the floor and at the same distances of the subject.

In the HMD, we expected that subjects tend to set perceptual values for IPD and OCD that increase the perception of distance to compensate the underestimation effects. In the CAVE, due to the effects of negative stereoscopic parallax related to the physical boundaries, we expected that subjects tend to set perceptual values that decrease the perception of distance.

3.1 Effects on distance and size perception

To validate our calibration procedure on distance and size perception, we used the size-constancy-table test. Similarly, we requested subjects to estimate the perceived size of an object located at 0.5m, 1.5m, and 2.5m over a set of virtual tables (Fig. 4). However, the set of tables was aligned starting with a physical one with the same dimensions, making a perceptual continuum. This is, the physical table provided a

Fig. 3. Perceptual calibration procedure in both displays. Left, CAVE. Right, HMD.

strong proprioceptive cue for distance and size perception, making subjects believe that its physical longitude was longer.

The experiment procedure was also similar: by using the physical object and the table as a reference, subjects had to estimate which could be the perceived size, either of a carbonated drink or a juice box, at the target distances and inside two heterogeneous displays (A HTC Vive HMD and a 4 walls CAVE). They could adjust the scale of the virtual object according to the target distance using a standard Gamepad and, using only their sense of touch and their proprioceptive cues. This restriction was important because subjects cannot compare the perceived size of the virtual object with the physical one in the HMD condition.

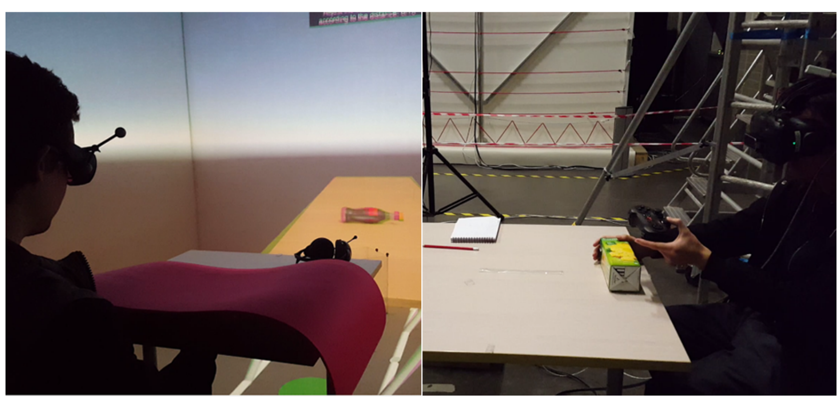

Fig. 4. Subject performing the size-constancy test. Left: CAVE, Right: HMD

3.2 Hypothesis

Our hypothesis were as follows:

– H1. In the HMD condition, we expected greater IPD values or smaller OCD for all distances to compensate the underestimation effects.
– H2. In the CAVE condition, we expected smaller IPD values or greater OCD values to compensate the overestimation effect due to the negative stereoscopic parallax.
– H3. Although we did not expect similar perception of distance and size between displays, we expect size-constancy. In other words, the perceived size remains constant independently of distance for both displays.
– H4. There should exist a middle point where the spatial perception between both VR displays should converge.

3.3 Procedure

Eight subjects (all male, $M = 22.85 \pm 1.06$ years old) participated in our experiment. All participants signed a letter of consent reporting a normal vision condition and good health at the moment of the experiment, without previous history of relevant diseases. We designed a within-subjects experiment where the participants perform the test with both displays with counterbalance order between subjects. In the beginning, we measured their IPD and calibrated the display according to these parameters. Also, to prevent bias with the first environment, we alternated the physical object between a carbonated drink and a juice box. Subjects adjusted the perceived scale of the object 6 times at each target distance with aleatory order between trials. For each trial, the virtual object was presented with an exaggerate dimension equivalent to the 25% or 400% of its actual size. Then, the subject had to adjust the scale of the object according to the perceived distance. In short, this gave us a configuration of 6 adjustments x 3 target distances x 2 objects x 2 VR display conditions.

3.4 Results

A paired sample t-test was used for all the measures. Figure 5 Left shows the results of the perceptually calibrated viewing parameters defined for each display. In the HMD condition, contrary to our predictions, we found significant greater IPD values ($M = 0.0794 \pm 0.0311$), $t(7) = 28.347$, $p = 0.000$ compared with the average subject physical IPD. In term of OCD values, we did not found significant differences ($M = 0.051 \pm 0.056$), $t(7) = 0.56, p = 0.631$ in comparison with the default OCD. These results suggest that H1 partially holds for the IPD parameter. Contrary to our expectations, in the CAVE condition we found significant greater IPD values ($M = 0.081 \pm 0.054$), $t(7) = 11.721$, $p = 0.000$ compared with the average subject physical IPD. Also, we did not found significant differences with in terms of OCD values $M = 0.055 \pm 0.013$), $t(7) = 1.71, p = 0.286$ with a greater variability, which suggest that H2 did not hold.

We believe that these partial successfully results could be due to artifacts in our calibration procedure. In the CAVE condition, we believe this could be related to a problem of perspective: from the viewer's point of view, the virtual box seems misaligned to the physical, even when its size was the same. In the HMD condition,

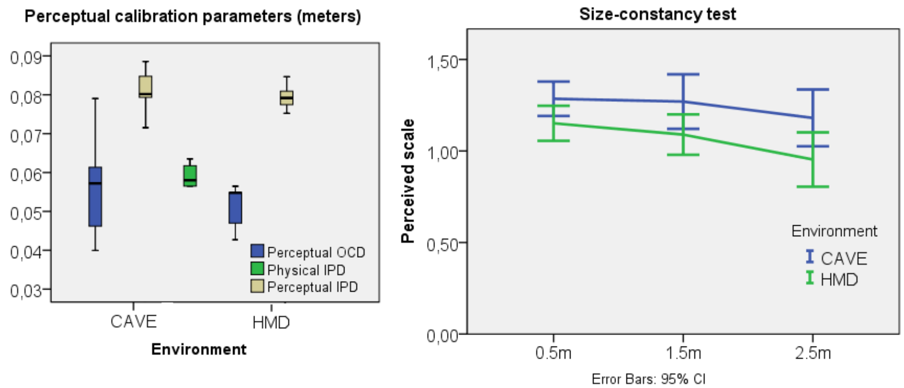

Fig. 5. Left: Result of the perceptual calibration procedure. Right: Results of the size-constancy-table test in both displays.

it was difficult for the subjects to judge the alignment of the box using only proprioceptive cues and, to compare the declination angle of the stick because we did not provide rigid body collision feedback. Hence, we noticed that some subjects were not confident enough about the perceptual alignment of the boxes.

Although we did not confirm completely hypothesis H1 and H2, we got some interesting results on the effects in distance and size perception based on the size-constancy-table test, which are described in Figure 5 Right. The results of the calibration procedure causes an increase in the perceived object' size that correspond to the increase in the perceptual IPD. We have to notice here that increasing the IPD is affecting the perception of distance and size asymmetrically, the perceived distance of the object is increased but also its perceived size. Thus, the object's perceived scale is overestimated as consequence of the correction on the perceived distance.

Regarding the differences between the displays, using a paired sample t-test, we found that the spatial perception is significantly different between the CAVE and the HMD at 0.5m $(M = 1.28 \pm 0.10, M = 1.15 \pm 0.10, t(7) = 5.680, p = 0.01)$, at 1.5m $(M = 1.26 \pm 0.16, M = 1.08 \pm 0.11, t(7) = 3.046, p = 0.023)$ and at 2.5m $(M = 1.18 \pm 0.16, M = 0.95 \pm 0.16, t(7) = 3.42, p = 0.014)$. Particularly, we noticed a great tendency to size-constancy in the CAVE condition and non-size-constancy in the HMD condition, which suggest that H3 partially holds for the CAVE. Finally, due to the lines did not intercept, this means that H4 did not hold, indicating that the perception of size is diametrically different.

4 Discussion

We proposed a novel method to ameliorate the phenomenon of non-size-constancy in heterogeneous VR displays. Regarding the perceptual calibration procedure, adjusting the IPD was more effective than adjusting the OCD. Regarding the OCD, selecting correctly the hypothetical position for this "cyclopean eye" is a challenge, since the value selected was an estimation which could be influenced by different display and subject factors (head size, optics, among others). Also, we noticed that adjusting the OCD some millimeters does not produce stronger effects on the object's projected image and their effects on size and distance were almost imperceptible. Thus, we consider that adjusting the OCD is not very suitable for perceptual calibration.

Interestingly and contrarily to our predictions, subjects rather perform IPD increments in the CAVE condition than decrements, causing an equivalent increase in the perceived size. We can explain this anomaly as consequence of the effects of hyper-stereopsis on negative stereoscopic parallax conditions, where the effects in depth perception are possible inverted. However, independently of this effect, there is a higher tendency in the CAVE to size-constancy for negative stereoscopic parallax (at 0.5m and 1.5 m) and very few underestimation effects for positive stereoscopic parallax (at 2.5m), which confirms the influence of the physical boundaries reported by Kenyon et al.

Unfortunately, in HMDs we did not get size-constancy, the perceived distances were underestimated and the perceived size varies as consequence. There may exist some explanation for these poor results such as the use of different sensory modalities or the deficiencies in our calibration procedure. However, we believed that the underestimation effects are so strong in HMDs that just adjusting the IPD is not enough because the range of possible values is limited by the threshold were stereopsis is comfortable. Also, the HMD condition lacks other important spatial cues, such as visualizing of the physical body or being inside a familiar environment. In this sense, we consider that the scope of perceptual calibration based on IPD increments was limited for HMDs.

5 Future work

The main challenge in the perceptual calibration procedure for HMDs is the impossibility of visualizing simultaneously the physical object and its virtual replica. As future work, we are exploring ways to perform perceptual matching tasks that do not require seeing the physical world but requires some action. A great part of the popularity of visually directed action methods, such as blind walking, is their independence on the visual stimulus during the measurement procedure. For example, a possible method could be using subject's affordances to estimated the perceived size of a gap at different distances using their body lenght as reference and their propioception [4].

Finally, we are planning to include other spatial cues, such as allowing subjects to visualize their hands (using a Leap Motion) and providing a familiar environment recreating the test room in the VE. Also, since that adjusting the IPD has the negative effect of affecting the perception of depth, we are planning to explore the methods based on "computer vision" approaches described in section 2.3 that performs perspective projection adjustments. Our objective is to find ways that we can alter the image formation process producing images that have a sense (from the perception point of view) and can influence the perception of size and distance.

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