Perceptual Evaluation of Interpupillary Distances in Head-mounted Display Environments

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Abstract:

Head-mounted displays (HMDs) allow users to explore virtual environments (VEs) from an egocentric perspective. In order to present a realistic view, the rendering system has to be adjusted to the characteristics of the HMD, e. g., the display's field of view (FOV), as well as to characteristics that are unique for each user, in particular, the interpupillary distance (IPD). In the optimal case, the rendering system is calibrated to the binocular configuration of the HMD, and adapted to the measured IPD of the user. A discrepancy between the user's IPD and stereoscopic rendering may distort the perception of the VE, since objects may appear minified or magnified.

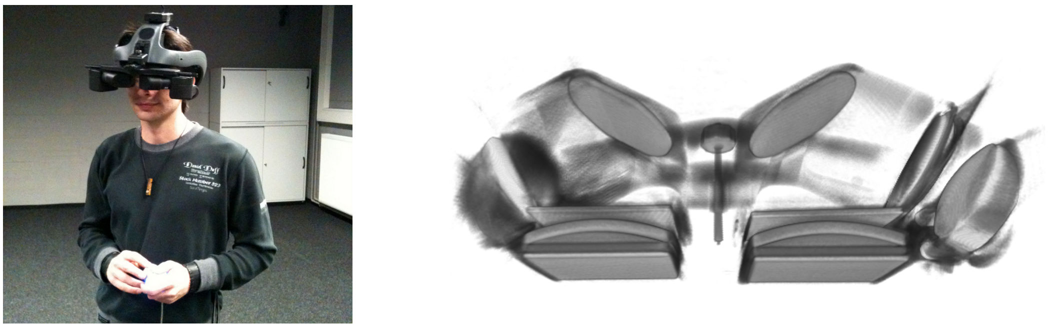
In this paper, we describe binocular calibration of HMDs, and evaluate which IPDs are judged as most natural by HMD users. In our experiment, subjects had to adjust the IPD for a rendered virtual replica of our laboratory until perception of the virtual replica matched perception of the real laboratory. Our results motivate that the IPDs which are estimated by subjects as most natural are affected by the FOV of the HMD, and the geometric FOV used for rendering. In particular, we found that with increasing fields of view, subjects tend to underestimate their geometric IPD.

Keywords: Head-mounted displays, interpupillary distance, perceptual evaluation

1 Introduction

Immersive virtual environments are often characterized by head-mounted displays and tracking systems for measuring a user's position and orientation. Such head- or helmet-mounted displays are head-worn devices, which present visual information to the eyes of a user via either one (*biocular*) or two (*binocular*) miniature visual display units. Mapping tracked real-world movements of a user to motions in the virtual world can present virtual information as seen from the user's egocentric perspective, which has great potential as an enabling technology for immersive exploration in many domains.

Most professional HMDs make use of binocular display designs that allow a user to perceive visual content stereoscopically. Binocular cues support distance judgments of objects



(a) (b)

Figure 1: (a) ProView SR80 HMD and (b) computed tomography scan of the optics showing lenses in front of the user's eyes, as well as mirrors.

up to a distance of about 2−8m [Mat09], depending on the visual acuity provided by the HMD [MM97]. Stereoscopic presentation of immersive VEs can contribute to higher cognitive functions of human observers, such as the sense of presence [IdH+98, IdRF+01]. Most HMDs make use of two separate miniature display units that can provide views directly to the eyes of the user. HMD optics require the eye pupils of a user to be adjusted in specific volumes in front of the display units for the user to perceive a correct view to the image source. Since these *eye box* volumes are usually quite small, professional HMDs provide mechanical adjustments for precise six degrees of freedom placement of the optics in front of a user's eyes. Such affordances often include small adjusting knobs for moving the display units fore or aft, up or down, or sideways, and rotate the optics around yaw, pitch or roll axes. In particular, the horizontal distance between the two display units in front of the user's eyes has to be adjusted to the interpupillary distance of the individual user, and the distance of the eyes to the display units has to be adjusted along the optical view axis for providing an unobstructed field of view.

In the optimal case, the user's IPD would initially be measured in the laboratory, the display units would be adjusted correctly, and the user's measured IPD would be applied to the stereoscopic rendering process. Inaccuracies at each of those steps may distort the perception of the VE, since objects may appear to have different stereoscopic depth or appear minified or magnified [MM97]. However, in many HMD laboratories it is considered impractical to measure a user's IPD, thus applying average IPDs from the general adult population (e. g., male IPDs ranging between 52mm and 78mm with $M \approx 65$mm, and female IPDs ranging between 52mm and 76mm with $M \approx 62$mm according to the US Army Anthropometric Survey (ANSUR) [Dod04]). Moreover, it is often left to the user to adjust the display optics in front of the eyes, which can result in inaccurate positioning of the display optics by inexperienced users. Finally, the complex nature of HMD optics resulted in a broad variety of different interpretations and generalizations of what "correct" stereoscopic rendering for HMDs is, and, combined with limited available data from the manufacturers, this can cause incorrect rendering techniques to be used in good faith.

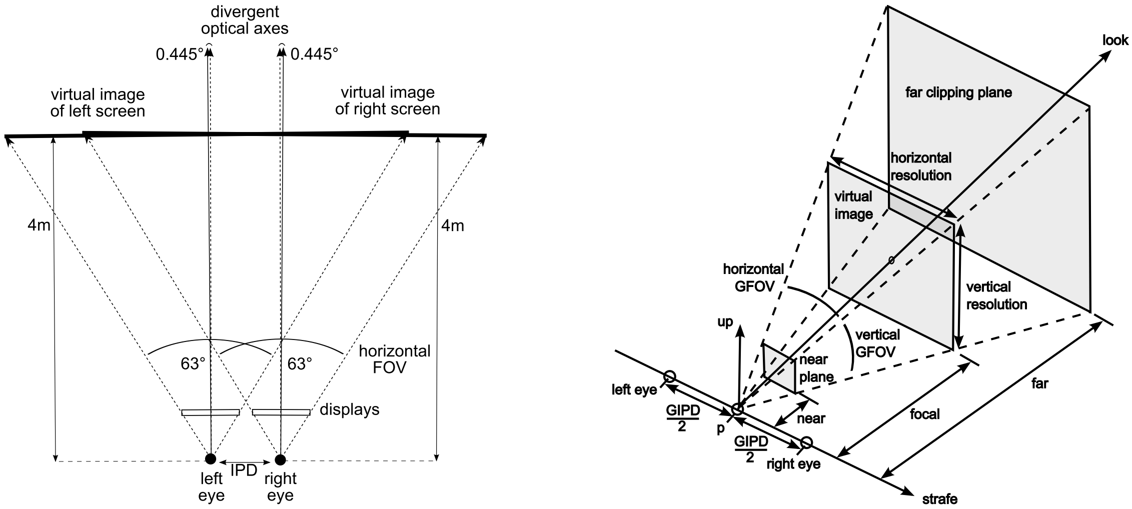
2 Stereoscopic Rendering on Head-mounted Displays

Due to a variety of different HMD designs, it is important to apply the correct stereoscopic rendering model to particular HMDs. However, due to the complex configurations of HMD optics (see Figure 1(b)), a number of generalizations and simplifications have gained a foothold in the computer graphics domain regarding stereoscopic rendering on HMDs. The different designs of HMDs allow a variety of different ways to provide overlapping visual information and a binocular view for a user, e. g., off-axis, on-axis, toe-in or toe-out [Bou99]. The challenge is to present three-dimensional content rendered using the correct model of the display optics, or otherwise a user may not be able to fuse the binocular information. Robinett and Holloway [RH94] presented a computational model for stereoscopic rendering on HMDs, which can describe most available HMD designs. Figure 2(a) shows a representation of the horizontal binocular configuration of a ProView SR80 HMD, with divergent optics and 4m accommodation distance to the perceived *virtual image* plane.

Geometric Interpupillary Distance

After measuring the user's individual IPD, for instance, using the approach described by Willemsen et al. [WGTCR08], this value has to be applied to the stereoscopic rendering model of the HMD. In general, specifying the *geometric interpupillary distance* (GIPD) (also referred to as *eye separation*) in a computer graphics environment depends on the virtual camera representation. In this paper we assume a typical coordinate system for defining a camera in a three-dimensional virtual environment consisting of the position $p \in \mathbb{R}^3$, normalized look-direction vector $look \in \mathbb{R}^3$, orthogonal up-vector $up \in \mathbb{R}^3$, and twice-orthogonal right-sided strafe-vector $strafe \in \mathbb{R}^3$. As illustrated in Figure 2(b), the camera model for HMDs consists of boundaries defined by the near and far clipping planes, as well as the size of the virtual image, which is located at accommodation distance from the eyes.

The camera position and orientation is usually updated according to the tracked position and orientation of a user's head in the HMD laboratory, specifically, the position of the center point between the user's eyes, and the main forward direction orthogonal to the axis defined by the eyes. Figure 2(b) illustrates the displacement of the eye points from the central camera position in strafe direction by $\pm\frac{GIPD}{2}$. Horizontal toe-in or toe-out rotations [Bou99] of the look- and strafe-vectors of the left and right eye camera can account for divergent and convergent HMD designs, whereas asymmetric frustums and off-axis rendering [Bou99] can be applied to compensate for off-center display configurations [RH94]. Assuming the binocular model of the HMD is correctly applied to the specification of the left and right eye camera frustums, differences between HMD users only occur in the GIPD between the centers of projection of the two cameras. If anthropometric population mean values are applied as GIPD to the rendering process, but deviate from a user's actual IPD, this either results in an increased or decreased GIPD relative to the user's IPD. This relative difference can be described via geometric interpupillary distance gains $g_I \in \mathbb{R}$ as $GIPD = g_I \cdot IPD$.



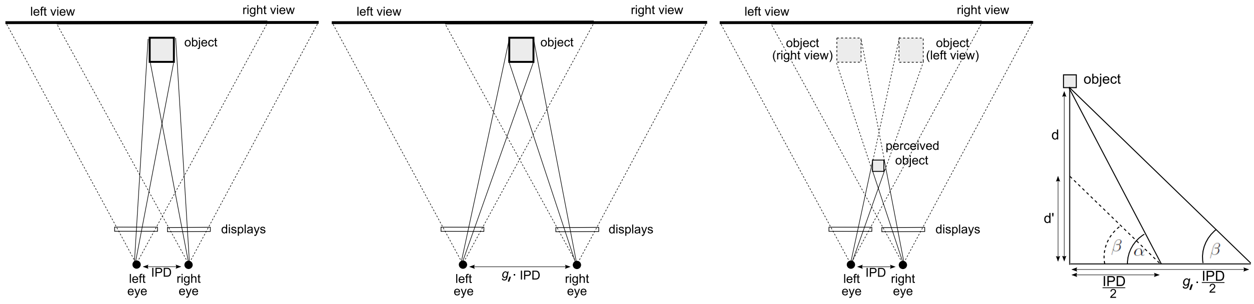
(a) (b)

Figure 2: (a) Binocular design of a ProView SR80 HMD: 63° monoscopic horizontal FOV, 64° total horizontal FOV, 63° or 99% binocular overlap, on-center optics, 0.445° divergent oculars. (b) Camera model for HMDs in three-dimensional computer graphics (adapted from [RH94]).

If the GIPD applied to the rendering process does not exactly match the user's IPD, stereoscopic display still provides relative depth cues for the HMD user. For instance, Hofsten [Hof76] observed for a polarization stereoscope that perceived distances were not based on the absolute convergence angles of the eyes, but rather on trained interpretations of relative differences in convergence angles. However, introducing a discrepancy between the GIPD for rendering and the user's IPD causes a difference in depth cues provided by the HMD, compared to viewing in the real world. In particular, a difference between the user's IPD and GIPD affects the accommodation-convergence problem [EBM95], e. g., when viewing monoscopic content on the HMD. Such an accommodation-convergence mismatch can cause eye strain and image blur, and may affect perception of object size, depth, velocity and distance [Pat07, PM92, Pel99, EBM95].

Mini- and Magnification

Applying different *geometric* fields of view (GFOVs) to the rendering system (which may deviate from the actual FOV of the HMD, see Figure 2) changes size and distance cues by mini- or magnification of the graphics. In particular, size mini- or magnification occurs if the distance correlating to the angular retinal size of an object deviates from the distance that object would have in a corresponding real-world viewing situation. For stereoscopic viewing conditions, size mini- or magnification can be observed when changing binocular depth cues by applying different GIPDs. In case of a mismatch between depth and size cues, this may lead to misperception of the distance to a virtual object, as well as objects appearing miniaturized, flat or "stretched" [BHG08].



(a) (b) (c) (d)

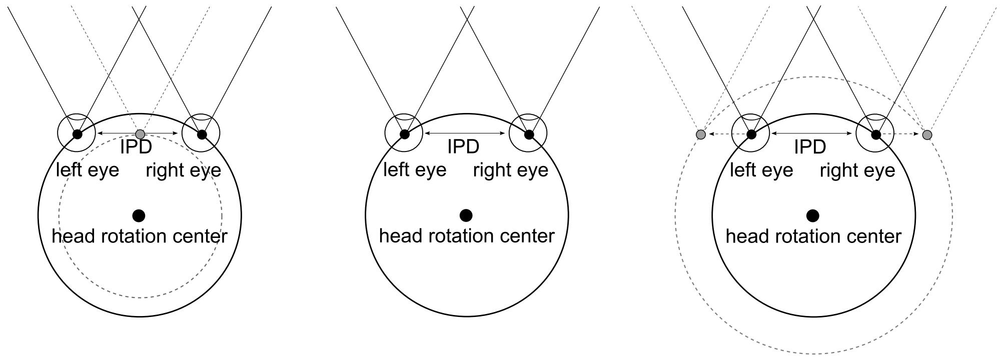
Figure 3: Illustration of depth minification.

The *puppet theatre effect* is one example for a mismatch between depth cues and perceived size of an object. This effect is characterized by apparent miniaturization of virtual scene objects, and caused by increasing the GFOV over the user's IPD [YOO06, MHE+06]. Figure 3(a) shows a top-down schematic of the binocular rendering frustums when viewing an object using the user's IPD, and (b) shows the differences in convergence angles for an increased IPD, whereas (c) illustrates the effect when presenting views rendered with the increased IPD of (b) for the user with smaller IPD in (a). In particular, Figure 3(c) shows that the size of the object appears minified, as well as an apparent decrease in the distance to the object. We can express the distance scaling effect for parallel on-center displays with the following relations (see Figure 3(d)):

$$(i)\ tan(\alpha) = \frac{2 \cdot d}{IPD}, \quad \text{and} \quad (ii)\ tan(\beta) = \frac{2 \cdot d}{g_I \cdot IPD} = \frac{2 \cdot d'}{IPD} \Rightarrow d' = \frac{d}{g_I},$$

with distance $d \in \mathbb{R}^+$ to the object for the user's IPD, and resulting distance d' when presenting the object rendered with $g_I \cdot IPD$, for $g_I \in \mathbb{R}^+$. For instance, applying a GIPD gain of $g_I = 2$ results in distances being halved by $d' = \frac{d}{2}$. Binocular convergence cues are usually limited to about $2-8$m from the observer in the real world [Mat09], with a potentially smaller range in HMD environments due to the reduced visual acuity (i. e., angular resolution) [RC05]. Increasing the GIPD over a user's IPD results in the user receiving binocular convergence cues over a larger range of distances in the VE, which may improve estimation of relative differences between objects, however, estimates are degraded by apparent minification of the displayed three-dimensional virtual content as shown in Figure 3.

The puppet theatre effect is named after the observation that people appear minified similar to puppets in a puppet theatre when displayed stereoscopically with increased GIPD or inconsistent camera convergence angles [YOO06]. Boev et al. [BHG08] state that when depth cues from binocular disparity and size do not match, usually disparity cues dominate, resulting in perceived size mini- or magnification, i. e., if two objects are displayed with the same angular retinal size, but different stereoscopic depths, the closer object appears smaller. Although usually this effect is reported for perceived size minification, cross-links with familiar size cues of objects may also result in size magnification [TSY01]. Researchers report a strong influence of the familiarity with displayed objects or subjects and their



(a) GIPD=0 (b) GIPD=IPD (c) GIPD>IPD

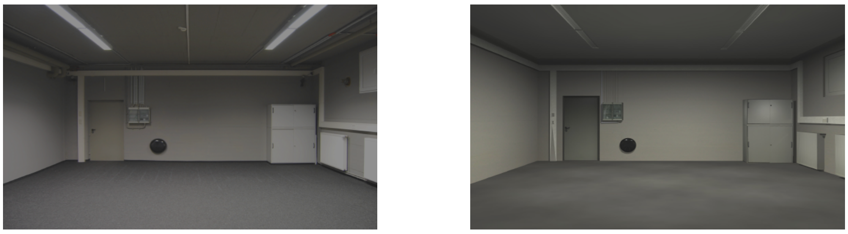
Figure 4: Head rotations with HMDs: head rotations for (a) monoscopic rendering, (b) the user's IPD, and (c) with an increased GIPD. The solid circles illustrate the natural rotation radius of the eyes around the center of rotation of the user's head, and the dashed circles illustrate the rotation radius of the left and right eye camera positions in the virtual scene.

susceptibility to the puppet theatre effect [BHG08]. Moreover, Tam et al. [TSY01] report an influence of display size on the effect, which was found for desktop screens, but may transfer to the FOV of a HMD, in particular, due to apparent size illusions found when occluding parts of stereoscopically displayed objects [PS09].

3 Estimation of Natural Interpupillary Distances

It is often assumed that the human visual system would be most comfortable with HMD viewing conditions that match natural viewing of the real world [RH94]. However, as found for GFOVs, subjects not always estimate calibrated perspective projections as most natural [SBL+11]. In particular, since distances are often underestimated in HMD environments, subjects estimated up to 50% increased GFOVs as most natural, which can alleviate observed underestimation effects [SBL+11, KTCR09]. The results motivate that subjects may estimate mini- or magnified stereoscopic renderings with increased or decreased GIPD as most natural, e. g., to compensate for distance underestimation [KTCR09].

The benefits of changing the GIPD are not clear [MHE+06]. For distance estimation tasks, binocular disparity has not been identified as major contributing factor [WGTCR08], in particular, for target distances greater than 2m viewing distance [Hof76]. However, perceptual observations, such as the puppet theatre effect [YOO06], motivate that significant cross-links between size and depth perception exist, with observable effects not limited to a 2m viewing distance. As discussed above, increasing the GIPD in a HMD environment augments the range of effective convergence cues for identifying object interrelations. Therefore, some researchers motivate that rendering VEs with task-dependent GIPDs may improve performance in tasks requiring relative depth discrimination [Ros93]. Stereoscopic depth also appears to be linked to the sense of presence [IdRF+01], which may be important for distance



(a) (b)

Figure 5: (a) View to the real laboratory, and (b) view to the virtual replica.

estimation. Moreover, changing the GIPD may change optic flow patterns as illustrated for the eye radius of head rotations in Figure 4. Increasing or decreasing the GIPD relative to the user's IPD may affect perception of head rotation angles in HMD environments. GIPD changes may also affect eye vergence induced by optic flow [BMM97]. Manipulation of the GIPD thus can affect visual-vestibular patterns during self-motion in immersive VEs.

In the following, we describe an experiment that we conducted to analyze how the GIPD should be specified for HMDs such that users judge real and virtual binocular perspectives to match, i. e., we determined the GIPDs that are identified as most natural by subjects for different HMDs. Therefore, subjects adjusted the GIPD for a rendered virtual replica of our real laboratory until perception of the virtual replica matched the real laboratory.

Participants

1 female and 7 male (age 23-37, ∅:27) subjects participated in the experiment. Subjects were students or members of the departments of computer science, mathematics or psychology. All subjects had normal or corrected to normal vision. We tested all subjects for stereoscopic vision before the experiment. Therefore, we asked subjects to order five stereoscopically rendered objects on the HMD regarding their depth. All subjects responded correctly in the stereopsis test. We measured the subjects' IPDs as 5.72, 6.01, 6.42, 6.52, 6.54, 6.62, 6.63 and 6.93 centimeters using the approach proposed by Willemsen et al. [WGTCR08]. All subjects had experience with walking in HMD environments. The total time per subject including pre-questionnaire, instructions, training, experiment, breaks, and debriefing was 1 hour. Subjects were allowed to take breaks at any time.

Experiment Setup

For this experiment we used the ProView SR80 HMD with a diagonal FOV of 76.88° [SBL+11]. On top of the HMD an infrared LED was fixed, which we tracked within the laboratory room (see Figure 5) with an active optical tracking system (WorldViz PPT), which provides sub-millimeter precision and sub-centimeter accuracy. The update rate was 60Hz, providing real-time positional data of the active marker. For three degrees of freedom orientation tracking we fixed an InterSense InertiaCube 2 with an update rate of 180Hz on the HMD.

The visual stimulus consisted of the virtual 3D model of our laboratory. The virtual scene was rendered on an Intel computer (dual-core processors, 4GB RAM, *n*Vidia GeForce 8800 GTX) using OpenGL and our own software, with which the system maintained a frame rate of 60 frames per second. We mapped the subject's tracked head movements from the real laboratory to the virtual replica using isometric one-to-one mapping, in which tracked linear and angular head movements are mapped to identical motions in the VE. In order to focus subjects on the tasks no communication between experimenter and subject was performed during the experiment. The subjects received instructions on slides presented on the HMD.

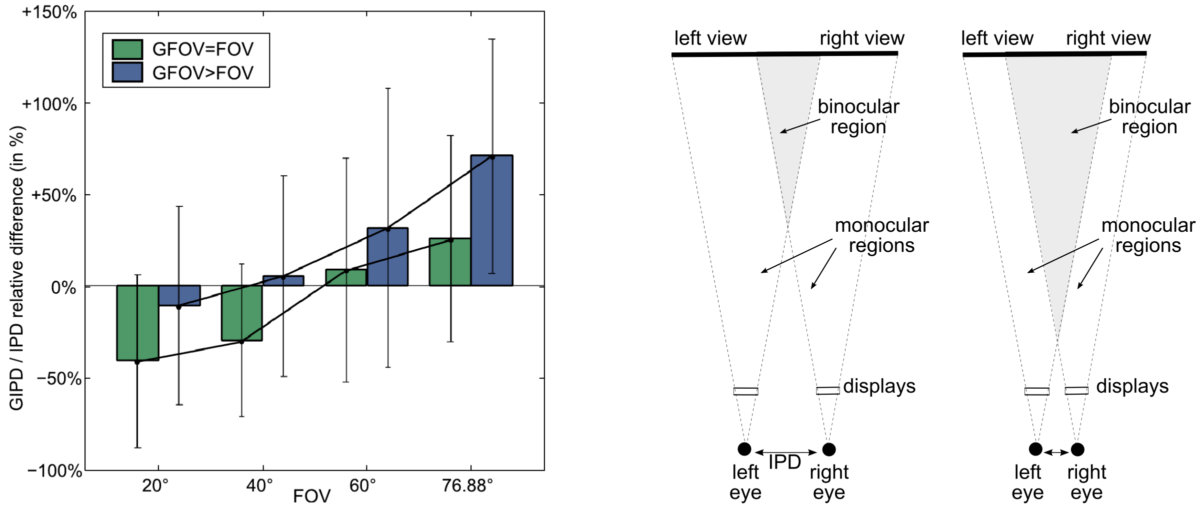
3.1 Material and Methods

We used a within-subject design for the experiment. At the beginning of the experiment, each subject was positioned in the center of the laboratory. Each subject was instructed to visualize and memorize the size, shape and binocular impression of the laboratory as well as objects within the laboratory, in particular, chairs, doors and cupboards. Therefore, subjects were allowed to move around the laboratory for 5 minutes. After this time, a subject had to put on the HMD, which immediately displayed a view to the virtual replica of the real laboratory with respect to the subject's tracked position and orientation in the laboratory.

In the subsequent trials a subject's task was to change the GIPD until the subject estimated the virtual view as most natural, i. e., that it matched the real laboratory. As illustrated in Figure 3, changing the GIPD affects the convergence demand of objects located in the virtual replica of our laboratory. In order to do so, subjects could adjust the $GIPD = g_I \cdot IPD$ with the gain $g_I \in \mathbb{R}_0^+$ for the subject's IPD. For $g_I = 1$ the GIPD corresponds to the subject's IPD. For $g_I = 0$ the virtual scene is viewed monoscopically.

To change the gain g_I, subjects used a Griffin PowerMate controller (see Figure 1(a)). Clockwise rotations of the wheel increased the gain g_I by 0.01 per 3 degrees, counterclockwise rotations decreased the gain by the same amount in the other direction. Subjects were instructed to walk around in the virtual replica and compare different cues until they were confident that the virtual view with the adjusted GIPD matched the real laboratory. Then subjects had to push the button on the PowerMate to indicate the end of the trial. We displayed a bright white image on the HMD, which faded to black in 3 seconds before the new trial started to prevent subjects from comparing visual stimuli of subsequent trials.

We simulated FOVs of different HMDs by scaling the viewport for each trial, i. e., a part of the display was blackened and the remaining area in the center of the display was used for rendering. Using this software-based approach we simulated HMDs with diagonal FOVs of 20°, 40°, 60° and 76.88° (the maximal FOV of the HMD [SBL+11]). For each of these simulated HMDs, we applied two different GFOVs to the rendering process: the correct GFOV of the simulated HMD and the GFOV that subjects reported as most natural for the HMDs in an experiment by Steinicke et al. [SBL+11], i. e., 29.53°, 53.85°, 72.33° or 88.34°. We tested these conditions to evaluate possible influences of a depth and size mismatch,



(a) (b) (c)

Figure 6: (a) Pooled results of the experiment showing the simulated FOVs on the horizontal axis plotted against the GIPD differences on the vertical axis. The green plots show the results for the matching diagonal FOVs and GFOVs of 20°, 40°, 60° and 76.88°, the blue plots show the results for the most natural diagonal GFOVs of 29.53°, 53.85°, 72.33° and 88.34°. Illustrations on the right side show binocular near-field regions for 20° HMDs with (b) user's IPD, and (c) decreased GIPD.

which is introduced due to the size minification caused by the increased GFOV for rendering the virtual scene [KTCR09]. Each of these GFOVs was tested 10 times in randomized order, of which five trials started with a GIPD gain $g_I = 1.5$ or $g_I = 0.5$, respectively.

3.2 Results

Figure 6(a) shows the relative deviation of the adjusted GIPDs from the subjects' IPDs. The x-axis shows the different tested diagonal FOVs, and the y-axis shows the GIPD responses. The green bars show the results of the trials in which we used the same GFOV for rendering the scene as the FOV of the HMD, whereas the blue bars show the results of the trials in which we applied the increased GFOVs. The black circles show the points of subjective equality (PSEs), i. e., the GIPDs that subjects judged as natural. The error bars show the standard errors. We found no difference between starting a trial with an initial gain $g_I = 1.5$ or $g_I = 0.5$, so we pooled the results for these two conditions.

The results show that the subjects' mean judgment of a "natural" GIPD varies significantly from their actual IPD. The mean PSEs in the experiment are given at GIPDs that are −41.50% compared to the real IPD for a diagonal GFOV of 20°, as well as −30.13% (40° GFOV), +8.46% (60° GFOV), and +25.29% (76.88° GFOV). For the conditions, in which we manipulated the GFOVs relative to the FOVs, we found PSEs at −10.87% (29.53° GFOV), +4.87% (53.85° GFOV), +30.95% (72.33° GFOV) and +70.46% (88.34° GFOV). Figure 6(a) shows that the GIPDs which appear most natural to subjects have to be decreased for smaller

GFOVs, and increased for larger GFOVs. However, the variance shown in Figure 6(a) illustrates that judgments of most natural GIPDs vary greatly within and between subjects.

3.3 Discussion

The results show that subjects often do not judge the GIPD as most "natural" that matches their actual IPD. In particular, we found a tendency that subjects judged a small GIPD as most natural for a HMD with a small FOV, and a large GIPD for a HMD with a large FOV.

For HMDs with a FOV of 20°, which supports only a very small portion of a subject's retina to be stimulated, subjects judged a GIPD as most natural that was decreased by 41.50% from the subject's IPD. Such HMDs provide only a limited binocular region in the near field, with large monocular regions at the sides. Decreasing the GIPD reduces the monocular regions at the sides, providing subjects with the ability to fuse objects in the near field (see Figure 6).

For HMDs with larger FOVs we found that this effect is reduced, i. e., subjects estimated GIPDs as most natural that are closer to their actual IPD. However, for a FOV of 76.88°, we found the opposite effect: subjects increased the GIPD on average by 25.29% over their IPD. Moreover, in the conditions, in which we applied the "most natural" GFOVs, which were always larger than the simulated FOVs, subjects tended to increase the GIPD over the responses found in the matching FOV and GFOV conditions. Increasing the GFOV over the FOV causes visual information to be minified, and apparent distances to increase, which can compensate for distance underestimation effects in VEs [KTCR09].

Since increasing the GIPD increases binocular disparity, which shifts objects towards the observer in depth, subjects may have compensated for minification. However, previous studies motivate that binocular depth cues play a minor role in distance estimation [WGTCR08, CRWGT05], and contribute more to shape perception [DKK01]. Increasing the GFOV over the simulated FOV introduces spatial distortions that affect shape perception, i. e., subjects may have compensated for such effects by increasing the GIPD. Conversely, consciously or subconsciously perceived advantages of a manipulated GIPD may also have influenced the results. For instance, the effective range of required binocular depth cues (i. e., arm-reach distance up to 10m distance between walls in the laboratory), may have caused subjects to optimize binocular disparity for the task (cf. [Ros93]).

4 Conclusion

In this paper we have presented an experiment that we conducted to evaluate effects of stereoscopic rendering on the user's estimate of "natural" viewing conditions in HMD environments. Our results motivate that accurate calibration of stereoscopic rendering is important. However, users not always estimate calibrated IPDs as most natural. The results show that subjects reduced the GIPD for HMDs with a small FOV, and increased the GIPD for larger FOVs. We found a similar tendency for the GFOV. The results illustrate the impact of stereoscopic rendering on perception in HMD environments, and motivate interrelations between size and depth mini- or magnification related to fields of view and binocular configurations.

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