

Natural Perspective Projections for Head-Mounted Displays

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Abstract—The display units integrated in today's head-mounted displays (HMDs) provide only a limited field of view (FOV) to the virtual world. In order to present an undistorted view to the virtual environment (VE), the perspective projection used to render the VE has to be adjusted to the limitations caused by the HMD characteristics. In particular, the *geometric* field of view (GFOV), which defines the virtual aperture angle used for rendering of the 3D scene, is set up according to the display field of view (DFOV). A discrepancy between these two fields of view distorts the geometry of the VE in a way that either minifies or magnifies the imagery displayed to the user. It has been shown that this distortion has the potential to affect a user's perception of the virtual space, sense of presence, and performance on visual search tasks.

In this article we analyze the user's perception of a VE displayed in a HMD, which is rendered with different GFOVs. We introduce a psychophysical calibration method to determine the HMD's *actual* field of view, which may vary from the nominal values specified by the manufacturer. Furthermore, we conducted two experiments to identify perspective projections for HMDs, which are identified as natural by subjects—even if these perspectives deviate from the perspectives that are inherently defined by the DFOV. In the first experiment, subjects had to adjust the GFOV for a rendered virtual laboratory such that their perception of the virtual replica matched the perception of the real laboratory, which they saw before the virtual one. In the second experiment, we displayed the same virtual laboratory, but restricted the viewing condition in the real world to simulate the limited viewing condition in a HMD environment. We found that subjects evaluate a GFOV as natural when it is larger than the actual DFOV of the HMD—in some cases up to 50%—even when subjects viewed the real space with a limited field of view.

Index Terms—Virtual reality, head-mounted displays, field of view.

1 INTRODUCTION

VIRTUAL reality (VR) environments provide the most sophisticated technology for human-computer interfaces developed so far. Because VR systems are able to present information as seen from a user's perspective, they have great potential as an enabling technology for immersive exploration in many domains, for instance they enable architects and engineers to experience virtual models at true scale. In general, for such systems one is often concerned with representing three-dimensional objects on a two-dimensional display screen.

1.1 Head-Mounted Displays

Immersive virtual environments (VEs) are often characterized by head-mounted displays (HMD) and a tracking system for measuring a user's position and orientation. Such head- or helmet-mounted displays are head-worn devices, which consist of either one or two small displays with lenses and semi-transparent mirrors that are

embedded in eye-glasses, a helmet, or a visor. These miniaturized display units consist of CRTs, LCDs, Liquid Crystal on Silicon, or OLEDs. Some vendors employ multiple micro-displays to increase the total resolution and display field of view. Applications can differ in whether HMDs display computer-generated images, images from the real world captured by cameras attached to the HMD, or a combination of both as used in augmented reality or mixed reality environments. The most rudimentary HMDs provide only an image which is not linked to a tracking system, i. e., the wearer's head position and orientation do not change the virtual view. However, most HMDs are commonly equipped with a tracking system, which measures the HMD's position and orientation. This information can be used to update the view of the virtual world according to the HMD's actual movements. This allows users to “look around” in a VR environment similar to the real world, i. e., turning the head leads to a rotation of the virtual camera without the need for additional input devices. In the scope of this paper we focus on immersive VEs and consider HMDs that display computer-generated images with respect to a user's head motions.

1.2 Geometric and Display Field of View

Besides high resolution one of the most often named requirements for a HMD is a large field of view (FOV).

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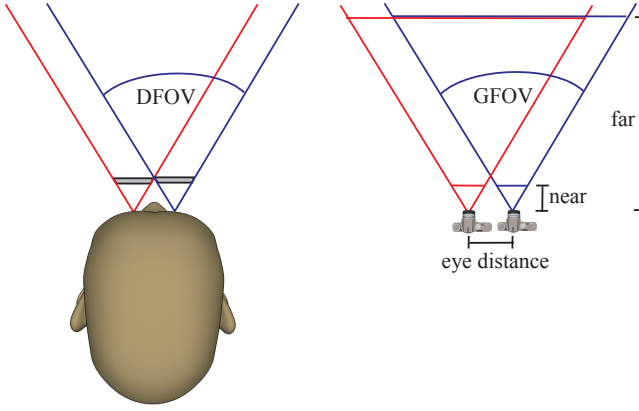


Fig. 1. Illustration of the relationship between (left) the DFOV of a HMD and (right) the GFOV used for perspective rendering. Together with the near and far plane the GFOV define the perspective view frustum.

This FOV refers to the horizontal and vertical angles subtended by the display—sometimes referred to as *display field of view* (DFOV) (see Figure 1 (left)). Usually a larger DFOV results in a greater sense of immersion and better situational awareness. However, most HMDs do not cover the entire visual field of the human eyes and support only a considerably smaller field of view. Commercially available HMDs typically have fields of view which range from 20 to 80 degrees diagonally—some even up to 150 degrees horizontal, whereas the effective visual field of humans is approximately 200 degrees horizontally and 150 degrees vertically [40]. In order for a virtual world to be displayed on a HMD, the computer graphics system must determine which part of the VE is to be viewed by the user.

In contrast to the DFOV, the *geometric field of view* (GFOV) defines the horizontal and vertical boundaries of the virtual viewing volume along with the aspect ratio (see Figure 1 (right).) With such a setup, user movements measured by the tracker are mapped to the position and orientation of the virtual camera. Usually, tracked head pose changes applied to the virtual camera by means of a one-to-one mapping define the camera’s position and orientation in the VE; the projection of the virtual camera defines the view frustum. In most VR applications a *perspective* projection is chosen such that depth cues are consistent with a user’s real-world view. Near and far clipping planes define the bounds of the visible scene. The horizontal and vertical geometric fields of view define the angles subtended by the viewport from the center of projection in virtual space or, equivalently, the angle subtended by the camera’s view frustum. As illustrated in Figure 1 (right) usually on-axis stereographic rendering is applied in HMD conditions. The image projected onto the viewport is displayed on both physical screens of the HMD.

If the GFOV matches the DFOV of the HMD, the viewport is mapped from virtual space onto the physical

display in such a way that users are presented with imagery that will have “correct” perspective as illustrated in Figure 2(b) (assuming that we neglect other distortions of the display device such as pincushion distortion). However, even if the fields of view of the display and the virtual camera frustum as well as the ratios of the display and the virtual viewport match, spatial perception of a virtual world through a HMD varies significantly from the real world. For example, several experiments provide evidence that egocentric distances are perceived as significantly compressed in immersive VEs—in some cases up to 50%—relative to distances perceived in the real world [11], [16], [23], [26], [38], [42], [44]. As experiments have shown, only a small portion of the observed compression can be caused by hardware issues, and an explanation for the larger portion of the effect remains unknown.

1.3 Mini- and Magnification

If the GFOV varies from the DFOV, this results either in *mini-* or *magnification* of the graphics [21] (cf. Appendix). As illustrated in Figure 2(a), if the GFOV is smaller than the DFOV of the HMD, the viewport image will appear magnified on the physical display because of the requirement for the image to fill a larger subtended angle in real space versus virtual space. Conversely, if the GFOV is larger than the DFOV of the HMD, a larger portion of the VE needs to be displayed in the image, which will appear minified (see Figure 2(c)). Depending on the distortion of the geometry of the VE the visual optical flow rate decreases or increases proportionately [6]. The optical flow rate is an essential visual motion pattern that in principle allows humans to extract self-motion information. Hence, manipulation of the GFOV provides a controllable optical distortion resulting in different visual-vestibular patterns in immersive VEs.

In this article we analyze how much mini- or magnification people prefer when they are able to adjust the perspective projection in a HMD environment. In particular, we determine how the geometric field of view needs to be specified in a HMD environment such that users have the impression that virtual and real perspectives match. The article is structured as follows. Section 2 summarizes work related to our approach. Section 3 introduces a psychophysical calibration method to identify the DFOV. In the first experiment described in Section 4 we used a virtual one-to-one copy of our real laboratory surroundings, and subjects had to adjust the perspective projection until they felt confident that the perspective of the displayed scene matched the perspective in the real laboratory. Section 5 presents a second experiment in which we analyzed the impact of a reduced field of view in the real-world on the subject’s judgement of a natural GFOV in a VE. Section 6 discusses the results

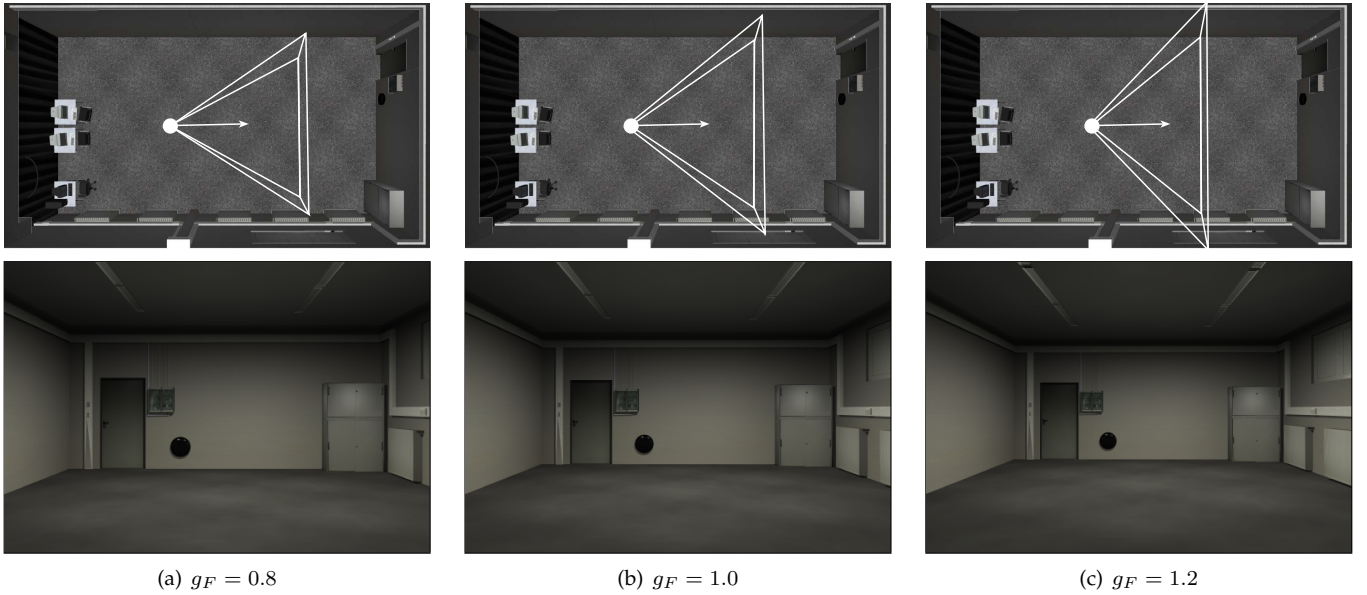


Fig. 2. Illustration of different perspective projections in a virtual 3D model of our laboratory: with a GFOV (a) larger than (b) identical to and (c) smaller than the DFOV. The top row shows the virtual laboratory and the camera frustums from a top-down view, the bottom row shows the corresponding renderings of the laboratory with GFOVs which have been manipulated with gains of (a) $g_F = 0.8$, (b) $g_F = 1.0$ and (c) $g_F = 1.2$.

of the experiments as well as implications about how to set up the virtual perspective in HMD environments. Section 7 concludes the paper and gives an overview about future work. Some of the results presented in this article have been presented in [37].

2 RELATED WORK

It is a challenging task to project virtual objects on a planar display surface in such a way that metric properties of objects are perceived correctly by human observers. In order to extract three-dimensional depth, size and shape cues about virtual objects from planar representations, the human visual system combines various different sources of information [27]. Since two-dimensional pictorial or monocular depth cues, e.g., linear perspective, are interpreted by the visual system as three-dimensional depth, the information they present may be ambiguous [18]. These ambiguities make it difficult to extract correct depth cues and are intentionally introduced in many common optical illusions [9].

View Frustums

The perspective view frustum defines the three-dimensional volume in space, which is projected to the image plane. As illustrated in Figure 1 (right), a view frustum can be specified in view space by the distances of the near ($near \in \mathbb{R}^+$) and far ($far \in \mathbb{R}^+$) clipping planes, and the extents of the projection area on the near plane ($left, right, top, bottom \in \mathbb{R}$) [35]. Alternatively, a symmetrical view frustum can be specified using only the vertical angle of the geometric field of view:

$$GFOV = 2 \cdot \text{atan} \left(\frac{\text{top}}{\text{near}} \right) \in]0, 180[, \quad (1)$$

and the image ratio ($ratio \in \mathbb{R}^+$).

The nominal DFOV of a HMD can be derived by the width (w) and the height (h) of the displays specified by the manufacturers, and the distance (d) of the eyes to the displays. Assuming a symmetrical view frustum, the vertical DFOV can be calculated with the following equation:

$$DFOV = 2 \cdot \text{atan} \left(\frac{h}{2 \cdot d} \right), \quad (2)$$

and the horizontal DFOV can be calculated by replacing h by w in equation (2).

Since most commercially available HMDs have relatively narrow fields of view in comparison to the effective visual field of humans, HMD users can see only a rather restricted portion of the virtual world if the GFOV matches the DFOV of the HMD. In the real world, a narrow field of vision has been shown to degrade spatial awareness and human performance in navigation and manipulation tasks [17], [13] as well as visual search tasks [3]. There has been much evidence that a restricted FOV in the virtual world may lead to perceptual, visual, and motor decrements in various kinds of performance tasks [1], [12].

Mini- and Magnification

As mentioned in Section 1.2, if the GFOV matches the DFOV, the viewport is mapped directly from virtual space onto the physical display, and therefore users

are presented with imagery that will have a “correct” perspective. However, a deviation between the GFOV and the DFOV occurs, for example, when the actual DFOV varies from the nominal values specified by the HMD manufacturers. A deviation can also be induced intentionally. Sometimes VR application developers use a larger GFOV in order to provide a wider view to the virtual world. Such deviations result in minification of the graphics (cf. Appendix). Choosing an extremely large field of view may not always be optimal, since the required GFOV for a HMD mainly depends on the application under consideration. If the GFOV is larger than the DFOV of the HMD, any given object drawn to the screen will cover fewer pixels in the screen as the GFOV is increased. Furthermore, a large GFOV may be unnecessary for tasks, which are localized within a small spatial region of interest [13], and it may aggravate simulator sickness effects, particularly those caused by vection and visual-vestibular mismatch [34], [36].

However, an increased GFOV allows for the inclusion of more information in the 3D view like a larger physical display would. A larger DFOV is essential in some applications and has the potential to improve and increase the user’s sense of presence [2], [34]. Similar benefits may also occur if a large GFOV is used with a display that has a small DFOV. Several works have introduced these deviations in order to address limitations of small display spaces in two-dimensional desktop environments, for example using Fish-Eye views [8].

Scene Perception

Mini- or magnification changes several visual cues that provide information about metric properties of objects such as distances, sizes, shapes and angles [18]. However, even if the GFOV and DFOV match, people’s perceptions and actions in the VE may differ from their perceptions and actions in an equivalent real environment. Many studies that compared distance perception of static targets in immersive VEs and in the real world found evidence that distances are perceived as compressed in VEs relative to the real world [11], [26], [42], [43]. It has been shown that as long as HMD users look around in a real or virtual environment, a restricted field of view (e.g., a 60 degree diagonal DFOV) did not change their behavior on blind walking distance estimation tasks [4], [19]. However, previous studies have suggested that physical factors related to the ergonomics of head-mounted displays may account for some of the apparent compression [19], [22], [21], [38], [41].

However, an explanation for the larger portion of the observed compression effects remains unknown. Given that underestimation has been found in a number of studies using HMDs and that HMDs typically have a reduced FOV, the restricted field of view has been suspected as a factor influencing distance perception [30], [43]. Increasing the GFOV of a VE may be one way to compensate for the restricted DFOV.

Although researchers have investigated the effects of the GFOV on performance and level of presence experienced [15], few studies have explicitly considered the relationship between GFOV and the DFOV of HMDs [45]. In the experiments described by Kuhl et al. [21] subjects saw the virtual world with a FOV that was larger (20%) than the one provided by the HMD resulting in minification of the graphics. In this case, the typical spatial compression effects in direct blind walking tasks in VEs were reduced, i.e., subjects walked significantly farther to previously seen targets when the graphics were minified. On the other hand, magnification changes these cues in the opposite direction and can potentially decrease perceived distance. The benefits of distorting the GFOV are not clear [37]. A series of studies were conducted to evaluate the role of the GFOV in accurate spatial judgments. It has been shown that when subjects perceive proprioceptive and tactile feedback, the GFOV can be increased without causing a significant distortion in the user’s distance perception [45]. Relative azimuth and elevation judgments in a perspective projection were less accurate for GFOVs greater than the DFOV [25]. This effect has been noted in see-through stereoscopic displays that match real-world viewing with synthetic elements [32]. Alternatively, room size estimation tasks and distance estimation tasks were aided by a larger GFOV [28]. The sense of presence also appears to be linked to an increased GFOV [14]. For other tasks, like estimating the relative skew of two lines, a disparity between DFOV and GFOVs was less useful [33].

3 PSYCHOPHYSICAL CALIBRATION OF GFOV

As mentioned in Section 2, the DFOV of a HMD may vary from the nominal values specified by the manufacturer. In this section we describe a psychophysical calibration method for HMDs that allows to determine the DFOV. Usually, the nominal DFOV for HMDs is specified as visual angle across the diagonal of a display.¹

Since most graphics systems require the horizontal and vertical (instead of the diagonal) fields of view of the display, almost all HMD users convert the nominal diagonal DFOV into geometric horizontal and vertical fields of view, often assuming a square-pixel aspect ratio. However, according to Kuhl et al. [21], the horizontal and vertical geometric fields of view determined in such a way can fail to match the DFOV of the HMD for three reasons:

- 1) The nominal diagonal DFOV may differ from the display’s actual diagonal DFOV.
- 2) The actual aspect ratio of the display may not match the ratio of horizontal to vertical pixel counts.
- 3) Pincushion distortion may lead to different FOV values.

1. For simplicity, we refer to GFOV and DFOV as the diagonal fields of view, if not stated otherwise.

In order to account for the three sources of error, different calibration methods have been proposed to identify the DFOV of a HMD [24]. Ellis and Nemire [7], [29] displayed vertical poles in the HMD. When wearing the HMD, subjects had to point at the perceived location of the poles in the real world. This allowed the researchers to calculate how the GFOV has to be specified so that the virtual angles and pointed angles match. Another method [31] uses a strobe light to provide subjects with an afterimage of a known visual angle. When wearing the HMD, subjects used this afterimage to measure the FOV of the display. It may also be possible to calibrate non-see-through HMDs by adapting methods used for see-through display calibration [10]. Another simple calibration approach requires VR users to adjust the GFOV by comparing a real object with a virtual object by constantly raising and lowering the HMD [21]. In the following we describe a psychophysical calibration method to identify the DFOV of a HMD in a more precise way in comparison to previously described methods.

Psychophysics is an area of perceptual psychology that employs specific behavioral methods to study the relation between stimulus intensity and perception reported by a human observer. The amount of change in a stimulus required to produce a noticeable sensation is defined as the *just noticeable difference* (JND). In the calibration process discussed here, subjects had to report their judgments of different GFOVs based on a *two-alternative forced-choice task* (2-AFCT). In order to manipulate the GFOV we apply *field of view gains* $g_{F[x]} \in \mathbb{R}^+$ and $g_{F[y]} \in \mathbb{R}^+$ to the virtual camera frustum by replacing the horizontal angle fov_x and the vertical angle fov_y of the geometric field of view by $g_{F[x]} \cdot fov_x$ and $g_{F[y]} \cdot fov_y$, respectively.

In the psychophysical calibration process described in this section, we used the method of constant stimuli, i.e., the presented stimuli were not related from one trial to the next, but presented randomly and uniformly distributed. After the visual stimuli had been presented, a participant had to choose between one of two possible responses, i.e., “Do you think the virtual world is *minified* or *magnified*?”; responses like “I can’t tell.” were not allowed. In this method, when the participant cannot detect the signal, he must guess, and on average he will be correct in 50% of the trials. Participants were trained as to what “minified” and “magnified” means in this context.

The gain at which a subject responds “minified” in half of the trials is taken as the *point of subjective equality* (PSE), at which the subject perceives both stimuli as identical. As the gain decreases or increases from this value the ability of the subject to detect a difference between both stimuli increases, resulting in a psychometric curve for the discrimination performance. Thresholds are those points of intensity at which subjects can just detect a discrepancy between physical and virtual stimuli. Usually the points at which the curve reaches the middle between the chance level and 100% correct estimations

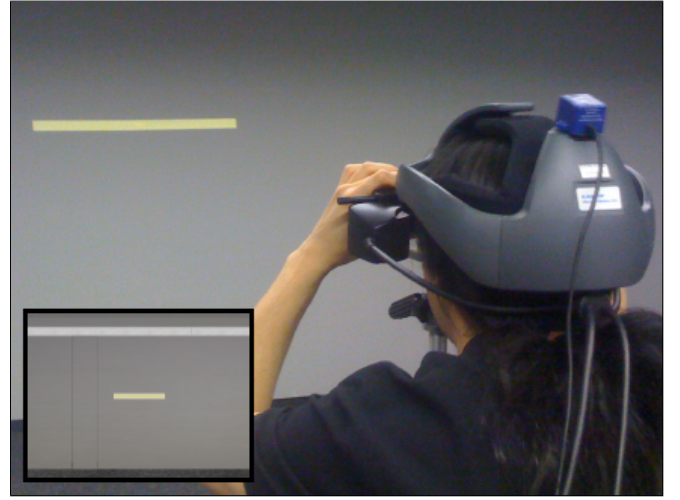


Fig. 3. Picture taken during the psychophysical calibration process. A participant at a fixed position compares the size of the horizontal stripe in the real world with the virtual stripe displayed on the HMD (see inset).

are taken as thresholds. We define the *detection threshold* (DT) for gains smaller than the PSE to be the value of the gain at which the subject has 75% probability of choosing the “magnified” response correctly, and the detection threshold for gains greater than the PSE to be the value of the gain at which the subject chooses the “magnified” response in only 25% of the trials. The correct response “minified” was then chosen in 75% of the trials.

3.1 Material and Methods

Two members of the computer science department with much HMD experience participated in the calibration process. Both had normal or corrected to normal vision. The total time per participant took 1 hour. We performed the calibration process in a 10m×7m darkened laboratory room. We used two HMDs for the stimulus presentation: (1) Rockwell Collins ProView SR80 (1280 × 1024 @ 60Hz, 80° diagonal DFOV), and (2) eMagin Z800 (800 × 600 @ 60Hz, 40° diagonal DFOV). On top of each HMD an infrared LED was fixed. We tracked the position of the LED within the room with an active optical tracking system (Precise Position Tracking of World Viz), which provides sub-millimeter precision and sub-centimeter accuracy. The update rate was 60Hz providing real-time positional data of the active markers. For three degrees of freedom orientation tracking we used an InertiaCube 2 (InterSense) with an update rate of 180Hz. The InertiaCube was also fixed on top of the HMD. An Intel computer (dual-core processors, 4GB RAM, nVidia GeForce 8800) displayed the VE and was used for system control and logging purposes. The virtual scene was rendered using OpenGL and our own software with which the system maintained a frame rate of 60 frames per second. In order to focus participants on the tasks no communication between experimenter and

participant was performed during the experiment. The participants received instructions on slides presented on the HMD. A Nintendo Wii remote controller served as an input device via which the participant judged his comparison between virtual and real perspective.

The visual stimuli consisted of a virtual 3D model of the real laboratory (see Figure 2). We modeled this virtual replica as a set of texture-mapped polygons. The texture maps were obtained from a mosaic of digital photographs of the walls, ceiling and floor of the laboratory. All floor and wall fixtures were represented true to original as detailed, textured 3D objects, e.g., door knobs, furniture and computer equipment.

During the calibration procedure, the participants faced a wall of the laboratory with their heads mounted in a fixed position at a distance of 3m from the wall (see Figure 3). In the virtual world we displayed consecutively a horizontal respectively vertical $1\text{m} \times 0.05\text{m}$ stripe on the wall, in the real world we taped corresponding stripes onto the wall. The participants compared the real-world stripes with the stripes displayed in the HMD by repeatedly raising and lowering the HMD on their head. Then the participants had to judge whether the virtual stripe was displayed minified or magnified compared to the real-world stripe based on a 2-AFCT. We tested both the ProView and the eMagin HMD with a horizontal and a vertical stripe consecutively. We manipulated the GFOV with different gains $g_{F[x]}$ and $g_{F[y]}$ ranging between 0.90 and 1.10 in steps of 0.01 applied to the horizontal and vertical angles of the HMDs, which we computed from the diagonal DFOV specified by the manufacturers (cf. Appendix). We presented the gains in randomized order, each gain occurring 10 times. Figure 3 shows a participant in the physical laboratory, who compares the horizontal virtual stripe in the 3D model with the stripe in the real world.

3.2 Results

Figure 4 plots the mean probability for a participant's estimation that the virtual horizontal/vertical stripe was displayed minified against the tested gains for the ProView SR80 HMD. The solid lines show the fitted psychometric functions of the form $f(x) = \frac{1}{1+e^{a \cdot x+b}}$ with real numbers a and b . The green line corresponds to the participants' pooled results for the ProView SR80 for the vertical FOV, the blue line corresponds to the participants' results for the horizontal FOV. The error bars show the standard errors. The results show that participants are quite good at discriminating between vertical and horizontal real and minified/magnified virtual stripes. The PSEs in the experiment approximate $g_{F[x]} = 0.9548$ and $g_{F[y]} = 0.9562$ for the ProView HMD. This means that the aspect ratio of the display as perceived by the participants approximates the ratio of horizontal to vertical pixel counts, i.e., a ratio of 1.243 instead of $1280/1024=1.25$. Furthermore, the results show that the DFOV perceived by the participants is slightly

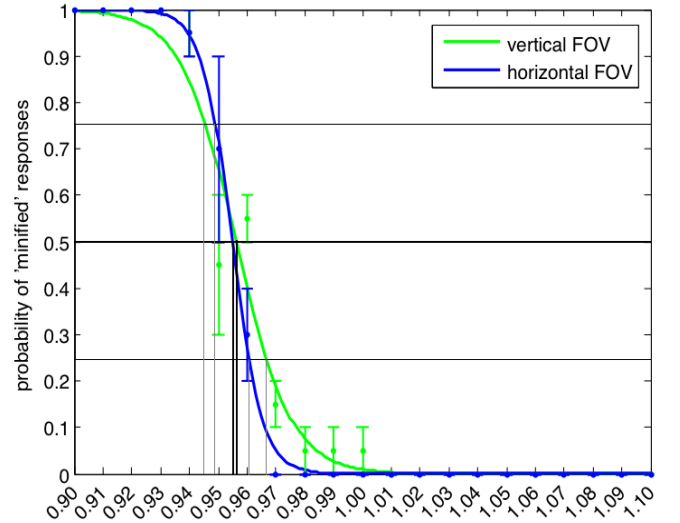


Fig. 4. Pooled results of the discrimination between the DFOV of the HMD's and the GFOV. The horizontal axis shows the gains applied to the GFOV, the vertical axis shows the probability that subjects estimate the virtual world to be minified compared to the real world.

smaller than the FOV specified by the manufacturers, i.e., 76.88° instead of 80° for the ProView SR80.

Lower and upper detection thresholds for the ProView are given for gains at $g_{F[x]} = 0.9491$ and $g_{F[x]} = 0.9606$, and $g_{F[y]} = 0.9457$ and $g_{F[y]} = 0.9666$. This means that participants cannot notice when the GFOV varies between 76.35° and 77.41° for the 80° diagonal ProView. The results for the eMagin were similar. The PSEs approximate $g_{F[x]} = 0.9708$ and $g_{F[y]} = 0.9602$, resulting in a FOV of 38.72° instead of the specified 40° , and a ratio of 1.264 instead of $800/600 \approx 1.333$. Lower and upper detection thresholds for the eMagin are given for gains at $g_{F[x]} = 0.9639$ and $g_{F[x]} = 0.9776$, and $g_{F[y]} = 0.9518$ and $g_{F[y]} = 0.9687$.

The small JND intervals around the PSEs for both displays show that the participants were quite accurate in detecting a manipulated field of view, so that this calibration method appears reliable to determine a DFOV. Hence, we assume the native DFOV of the ProView SR80 HMD to be 76.88° with a native aspect ratio of 1.243. We use these values to define the perspective projection in the experiment described in Section 4.

In most graphics systems only the vertical field of view is specified in order to set up the perspective projection; the horizontal angle is derived using the aspect ratio. Hence, in the following we will focus on *fovy*, and for simplicity we will denote the gain applied to the vertical field of view of the display by $g_F \in \mathbb{R}^+$, if not stated differently. Hence, in order to manipulate the perspective projection, we render the scene with a GFOV defined by the display's actual vertical FOV multiplied with the gain g_F . If $g_F = 1$ the DFOV of the HMD and the GFOV used for rendering are identical (cf. Figure 2(b)), if $g_F < 1$ the used GFOV is smaller than the DFOV and the virtual



Fig. 5. Photo from the experiment showing a subject with the ProView SR80 HMD adjusting the GFOV with the PowerMate.

world is magnified (cf. Figure 2(a)), and if $g_F > 1$ the GFOV is increased and the virtual world is minified (cf. Figure 2(c)).

4 EXPERIMENT 1 (E1): JUDGMENT OF NATURAL PERSPECTIVE PROJECTIONS

In this section we describe the experiment that we conducted to identify the geometric field of view, which subjects reveal as most natural, i.e., the GFOV from which they estimate that it matches the real-world perspective. We performed the experiment in almost the same setup as described in Section 3. For the experiment E1 we used the ProView SR80 HMD with the results from the calibration process, i.e., we assumed an actual diagonal DFOV of 76.88 degrees and an actual aspect ratio of 1.243. In order to determine the most natural perspective projection, subjects could change the GFOV of the virtual scene by changing the gain g_F that we applied to the actual vertical geometric field of view, while preserving the aspect ratio as described in Section 3.2. Hence, for $g_F = 1.0$ the horizontal and vertical GFOV correspond to the display's actual fields of view that we have identified using the psychophysical calibration method (cf. Section 3).

Participants

2 female and 9 male (age 23-46, \bar{x} : 28.8) subjects participated in the experiment E1. Subjects were students or members of the computer science, mathematics, psychology, geoinformatics, and physics departments. All had normal or corrected to normal vision; three wore glasses or contact lenses. Five of the subjects had experience with walking in VR environments using a HMD setup. Four had much video game experience, four some,

and three none. Two of the authors participated in the study, all other subjects were naive to the experimental conditions. The total time per subject including pre-questionnaire, instructions, training, experiment, breaks, and debriefing took 1 hour. Subjects were allowed to take breaks at any time.

4.1 Material and Methods

We used a within-subject design in this 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 of the laboratory as well as the sizes of objects within the laboratory, e.g., chairs, doors and cupboards. Therefore, subjects were allowed to move around the laboratory for a short period of time. After two minutes, a subject had to put on the HMD which immediately displayed a virtual view of the one-to-one virtual replica of the real laboratory with respect to the subject's tracked position and orientation in the real laboratory. In the subsequent trials a subject's task was to adjust the geometric field of view until the subject evaluated the GFOV as most natural, i.e., that it matched the real perspective. In order to do so, subjects could adjust the gain g_F , which we used as a factor for the display's vertical FOV to compute the vertical GFOV, from which in turn we computed the horizontal GFOV using the display's aspect ratio (cf. Section 3.2). To change the gain g_F , subjects used a PowerMate USB multimedia controller manufactured by Griffin Technology (see Figure 5). Clockwise rotations of the wheel increased the gain g_F by 0.01 per 3 degrees, counterclockwise rotations decreased the gain by the same amount in the other direction. Subjects were allowed to walk around in the virtual replica and compare different cues until they were confident that the adjusted GFOV matched the real-world perspective. Then they had to push the button on the PowerMate to indicate the end of the trial. After that we displayed a bright white image on the HMD, which faded to black in 3 seconds before the new trial started. We used this transition effect to prevent subjects from comparing the visual stimuli of two subsequent trials, for example, by comparing borders or edges of the virtual laboratory.

We simulated fields of view of different HMDs by scaling the viewport during the rendering process, 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 DFOVs of 20, 40, 60 and 76.88 degrees (the ProView's DFOV as derived from the calibration process). Each of these DFOVs was tested 10 times in randomized order, of which five trials started with a gain $g_F = 1.5$ and five trials with a gain $g_F = 0.5$.

4.2 Results

Figure 6(a) plots the DFOVs against the subjects' adjustment for the most natural geometric fields of view.

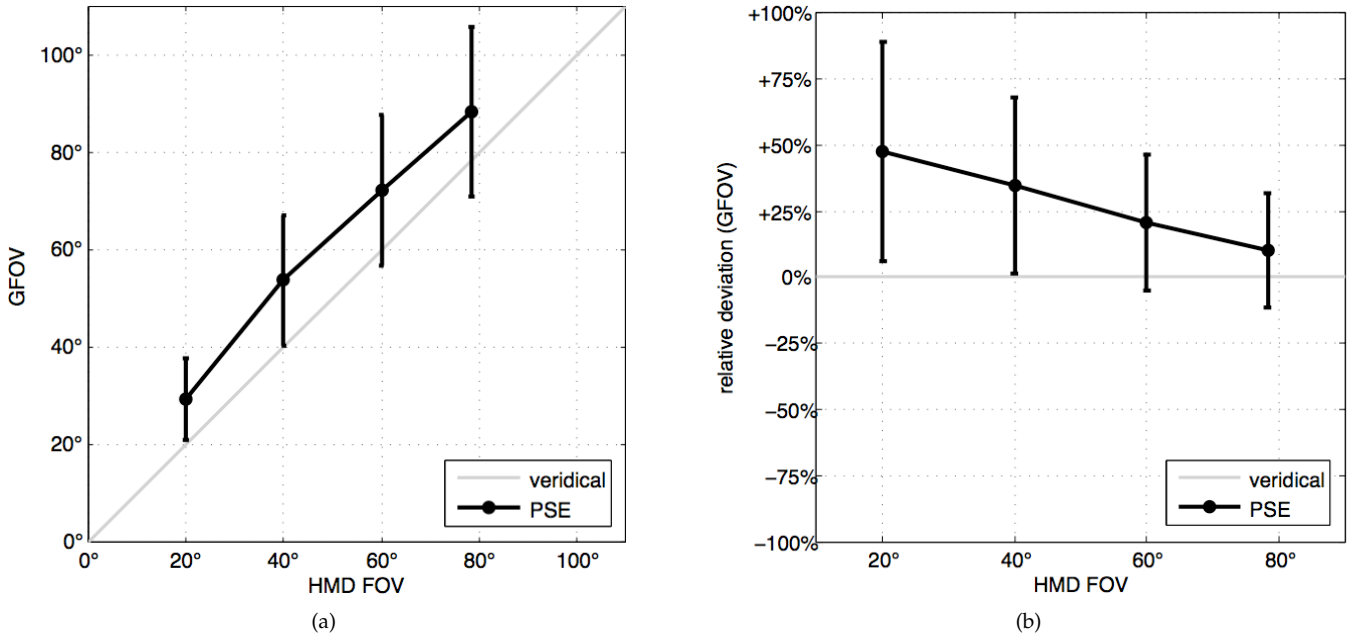


Fig. 6. Pooled results of the experiment showing the different simulated displays' fields of view on the horizontal axis plotted against (a) the absolute GFOVs and (b) the relative deviation of the GFOVs from the display's FOV on the vertical axis.

Figure 6(b) shows the relative deviation of the GFOVs from the displays' actual fields of view. The black circles represent the PSEs, i.e., the GFOVs that subjects perceived as natural. The error bars show the standard errors pooled over all subjects. There was no difference between starting a trial with an initial gain $g_F = 1.5$ or $g_F = 0.5$, so we pooled the results for these two conditions. The results show that the subjects' average judgment of a "natural" GFOV deviates significantly from the actual display's FOV, especially for small FOVs. The PSEs in the experiment are given at a diagonal geometric field of view of 29.53° for a HMD with a diagonal DFOV of 20°, 53.85° (40°), 72.33° (60°), and 88.34° (76.88°). The results show that the geometric field of view which appears most natural to the subjects is larger than the display's field of view. In Figure 6(b) it is pointed out that subjects adjusted the GFOV approximately 47.66% larger than the display's field of view in the case that the HMD's DFOV equals 20°. In the other cases the geometric fields of view were adjusted 34.63% (40°), 20.55% (60°), and 12.68% (78.4°) larger than the DFOV.

From the subjects' answers we computed lower and upper thresholds at the points of intensity around the PSEs where subjects answered with 75% probability that the presented perspective projections were natural. These thresholds define a range of gains which appear natural to users in 75% of the time. Hence, gains within this range can be applied in HMD environments without subjects noticing a discrepancy between the display's FOV and the GFOV used for rendering the VE. For a HMD with 20° diagonal field of view the lower and

upper thresholds for GFOVs are 23.40° and 34.20°. For the other simulated fields of view the lower and upper thresholds are 45.40° and 59.40° (40°), 60.00° and 80.40° (60°), and 77.60° and 98.40° (78.4°). The intervals around the PSEs for the different FOVs show that the subjects' judgment of a "natural" FOV shifts towards larger GFOVs for HMDs with a small FOV. The results further show that the subjects' judgment of a natural GFOV approximates the DFOV for HMDs with a larger FOV. The results for the two expert users who performed the calibration (as described in Section 3) did not vary significantly from the other subjects.

In summary, the results motivate that the GFOV should be increased for HMDs with a small geometric field of view in order to appear more natural to users. Even when the geometric field of view is further increased within the gain interval of the detection thresholds the corresponding perspective projection appears still natural.

We measured the subjects' self-reported sense of presence in the displayed virtual world using the Slater-Usuh-Steed (SUS) presence questionnaire [39]. Subjects rated their sense of presence on average with a SUS score of 4.52. Subjects further judged the difficulty of the task with 0.75 on average on a 5-point Likert-scale (0 corresponds to very easy, 4 corresponds to very difficult). On a comparable Likert-scale subjects reported their fear of colliding with physical objects during immersion on average as 0.5, which shows that subjects felt quite safe, probably because the virtual scene showed a co-located and detailed virtual replica of the subjects' physical surroundings. Draper et al. [6] have reported increased

simulator sickness when manipulating GFOVs. Hence we also considered effects of the different gains on simulator sickness. Simulator sickness is an important, but common issue of VR systems, in particular in HMD experiments over a long period of time. We measured simulator sickness by means of Kennedy's Simulator Sickness Questionnaire (SSQ). The pre-experiment SSQ score averages to 4.86 and the Post-SSQ score to 13.09. There was no significant increase on simulator sickness caused by the experimental task and manipulated GFOVs in comparison to HMD experiments that we have previously performed in our laboratory. The pre-recorded panorama images used by Draper et al. [6] as visual stimulus instead of a visually faithful virtual scene may have led to the increase observed in their experiments.

5 EXPERIMENT 2 (E2): INFLUENCE OF FIELD OF VIEW DISCREPANCIES

During the real-world situation at the beginning of the experiment E1 described in Section 4 and [37] subjects could use the entire visual angle of their eyes to view the real-world laboratory. Afterwards, when wearing the HMD this field of view was limited due to the properties of the HMD. The subjects' overestimations of a natural FOV might have been effected by this difference since they compared the limited view to the virtual laboratory with an unlimited view to the real laboratory. In order to examine if this unlimited view has affected the subjects' judgements we performed a second experiment.

5.1 Material and Methods

We used the same within-subject design in the experiment E2. In contrast to the experiment E1 (described in Section 4) subjects were equipped with a physical view restriction to simulate a limited field of view in the real world. Therefore, we disassembled a pair of passive stereo glasses and adapted them in such a way that subjects were able to view the laboratory through a peephole with an effective vertical field of view of 20 degrees for each eye (see Figure 7) and a ratio of 4/3. We tested only a view restriction of 20 degrees since this was the largest difference between the visual angle of the eyes and the limited viewing condition in our experiment. For this experiment we chose only subjects who had not seen the VR laboratory before the experiment. They were equipped with the view limiting glasses outside the laboratory. We calibrated the glasses for each subject by positioning subjects at a distance of 2m from a wall. We attached a stripe to the wall with a length of 1.73m and told the subjects to adjust the glasses until the stripe fitted entirely into the view. Then, a subject was guided to the center of the real laboratory. The remainder of this experiment was performed similar to the experiment E1 described in Section 4. Each subject was instructed to visualize and memorize the size of



Fig. 7. Photo of a user with a view restriction. The glasses limit the field of view to 20°. During the experiment a cloth was attached to the glasses to avoid that subjects could perceive visual information from beyond the glasses.

the laboratory as well as the sizes of objects within the laboratory, e. g., chairs, doors and cupboards. Therefore, subjects were allowed to move around the laboratory for 2 minutes.

Afterwards, each subject was guided outside the laboratory and had to put on the HMD which displayed a virtual view of the one-to-one virtual replica of the real laboratory with respect to the subject's tracked position and orientation in the real laboratory. Hence, we ensured that the subjects were able to view the real laboratory only with a restricted field of view.

As described in Section 4.1 subjects were equipped with a PowerMate input device to adjust the geometric field of view until they thought the view matched the view to the previously experienced real-world situation with a limited field of view. We tested the smallest GFOV of 20 degrees. We tested this FOV 10 times, five trials started with a gain $g_F = 1.5$ and five trials with a gain $g_F = 0.5$.

Participants

10 male (age 23-38, \bar{x} : 28.5) subjects participated in the experiment E2. None of the subjects had seen the laboratory before the experiment. Subjects were students or members of the computer science, mathematics, psychology, geoinformatics, and physics departments. All had normal or corrected to normal vision; three wore glasses or contact lenses. Four of the subjects had experience with walking in VR environments using a HMD setup. Three had much video game experience, four some, and three none. All subjects were naïve to the experimental conditions. The total time per subject including pre-questionnaire, instructions, training, experiment, breaks, and debriefing took one hour. Subjects were allowed to take breaks at any time.

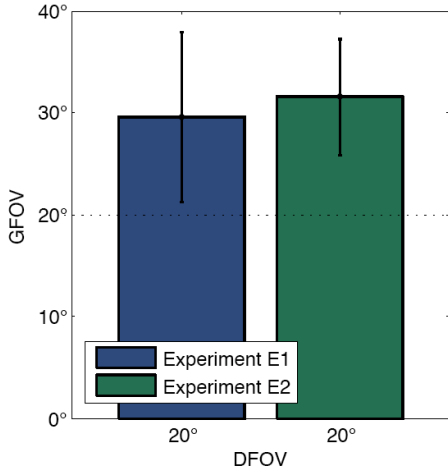


Fig. 8. Pooled results of experiments E1 and E2 showing the displays' fields of view (20°) on the horizontal axis plotted against the GFOVs on the vertical axis.

5.2 Results

Figure 8 plots the DFOV of 20° against the subjects' adjustment for the most natural geometric field of view (left) for the unlimited real-world viewing condition (cf. experiment E1) and (right) the limited real-world viewing condition. The bars represent the PSEs, i.e., the GFOVs that subjects perceived as natural. The error bars show the standard errors pooled over all subjects. There was no difference between starting a trial with an initial gain $g_F = 1.5$ or $g_F = 0.5$, so we pooled the results for these two conditions.

The results show that the subjects' average judgment of a "natural" GFOV deviates significantly from the tested DFOV of 20°. The PSE in this experiment is given at a diagonal geometric field of view of 31.5360° for a HMD with a diagonal DFOV of 20°. This corresponds to an overestimation of 57.6799% ($SD = 28.53$, $SE = 9.02$). The results show that the geometric field of view which appears most natural to the subjects is larger than the display's field of view.

From the subjects' answers we computed lower and upper thresholds at the points of intensity around the PSEs where subjects answered with 75% probability that the presented perspective projections were natural (cf. Section 4.2). In this experiment for a HMD with 20° diagonal field of view the lower and upper thresholds for GFOVs are 23.70° and 38.80°.

We used a t-test analysis to reveal whether or not the results from this experiment significantly deviate from the findings of the experiment E1 described in Section 4. There was no statistically significant difference in the judgements between subjects, who inspected the real laboratory with a limited field of view and those subjects, who viewed the laboratory without view restriction ($p > 0.46$).

In summary, the results of this experiment indicate that the deviation between the real-world visual angle

and the limited field of view caused by the viewing condition in an IVE system cannot explain the subjects' overestimation of the natural GFOV.

6 DISCUSSION

The psychophysical calibration method described in Section 3 shows that subjects are quite accurate at discriminating the DFOV of a HMD from the GFOV used for rendering of the virtual scene when they can compare the virtual view directly with the corresponding view to the real world. However, the experiments described in Section 4 and Section 5 shows that subjects do not necessarily estimate a GFOV that is identical to the DFOV as most natural. Subjects tended to judge a significantly larger geometric field of view as natural in case the DFOV was rather small; in some cases up to 50%. This observation was confirmed even when the subject's view to the real laboratory was reduced according to the field of view of the DFOV. One reason for this bias might be that users in HMD environments in general tend to underestimate distances to scene objects visible on the HMD. Since a GFOV that is larger than the DFOV leads to minification of scene objects (cf. Appendix), users might estimate objects to be farther away. Therefore, an increased GFOV may appear more natural in contrast to a GFOV that is identical to the DFOV. When subjects have to judge natural perspectives, another reason for the deviation between the display and a geometric field of view might originate in various consciously or subconsciously perceived advantages of a large FOV. As stated above, humans have a much larger field of vision than most HMDs support. With a larger FOV it is easier for humans to detect, localize and acquire visual information about the environment compared to a situation with a more restricted FOV, in which humans have to observe different regions of interest using head movements. The "unnatural" need to rotate the head in order to see objects that would have been in their normal field of vision in the real world also might have influenced their answers. Furthermore, fatigue due to continuously required head movements as well as simulator sickness introduced by latency or inaccuracies in head-tracking may have affected the results and have to be considered carefully. Those influences are underlined by the fact that the deviation between the DFOV and the GFOV adjusted by the subjects increases even more for displays with small FOVs.

In summary, increasing the GFOV by the amount determined in our experiments causes the rendering system to display more information in a user's view, and furthermore, the user perceives such a distorted perspective projection as more natural in contrast to the situation when the GFOV is identical to the field of view of the display. This result suggests that if a GFOV, which is larger than the DFOV, is intentionally used in some application (for example, to reduce compressed distance judgments [22]), some amounts of distortion will likely go unnoticed by subjects.

7 CONCLUSION AND FUTURE WORK

In this article we have presented a psychophysical calibration method that allows to determine the DFOV of a HMD as perceived by users, and we have conducted two experiments to identify geometric fields of view that appear most natural to users in such a HMD environment. We found that the GFOVs users judge as most natural are not identical to the FOVs supported by the HMDs; for all tested FOVs subjects reported a larger geometric than display's FOV as natural. We determined how much a GFOV has to deviate from a DFOV in order for subjects to estimate the virtual perspective projection as natural. We believe that increasing the GFOV to the point where users perceive the perspective as most natural—though this may lead to perspective distortions that influence the perceived size of objects, distances and optical flow patterns—has the potential to enhance the overall VR experience. Increased GFOVs afford more information into the limited field of view of a HMD, which leads to more visual information in a user's view. Furthermore, it has been shown that a larger field of view (resulting in an increased overlap of visual information during camera motions) supports a user's ability to form a cognitive map of unknown virtual worlds [5]. Kuhl et al. [21] further showed that slightly increased GFOVs and the resulting minification of the displayed graphics (compared to a view from the real world) reduces the distance compression effects in VEs. We compared the results of different tested FOVs, and we found that the PSEs between a DFOV and GFOV are shifted towards increased GFOVs for HMDs with a small FOV. The results provide interesting insights for the specification of GFOVs in HMD environments. In order to render a VE so that the scene appears most natural to users, for HMDs with 20° diagonal DFOV the GFOV should be set to 29.53°, respectively 53.85° for HMDs with 40° diagonal DFOV, 72.33° for HMDs with 60° DFOV, and 88.34° for HMDs with 76.88° DFOV (the largest DFOV we have tested). However, in certain situations the geometric field of view desired by users may be much larger in order to get a better impression of an unknown VE or even smaller, since in this case the display resolution is increased because less pixels are mapped to the same display area. It is a challenging question whether the display's optimal field of view for arbitrary environments and situations can be predetermined. In the future we will pursue these questions more deeply and explore the effects of geometric fields of view, which deviate from displays' FOVs, on spatial perception in VEs. In particular, we will examine in how far the increased geometric fields of view, which appear natural to VR users, reduce distance compression effects, when the virtual world is displayed with a corresponding perspective projection.

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APPENDIX

The nominal field of view for most HMDs is specified by the manufacturers as visual angle α across the diagonal of the screen with a given aspect ratio in screen space denoted by *ratio*. Assuming a symmetrical view frustum, the horizontal and vertical fields of view *fov_x* and *fov_y* can then be calculated with equations (3) and (4):

$$fov_x = 2 \cdot \operatorname{atan} \left(\frac{\tan(\alpha/2)}{\sqrt{1 + \frac{1}{ratio^2}}} \right) \quad (3)$$

$$fov_y = 2 \cdot \operatorname{atan} \left(\frac{\tan(\alpha/2)}{\sqrt{1 + ratio^2}} \right) \quad (4)$$

In a computer graphics system usually only the vertical geometric field of view (*fov_y*) has to be specified from which the vertical extent of the near plane is calculated, and then the horizontal extent of the near plane is derived using the *ratio*. Mini- or magnification of the graphics is caused by changing the size of the near plane, e. g., by adjusting the vertical and horizontal geometric field of view (see Figure 9). As stated above such a mini- or magnification changes several visual cues that provide distance information. In particular, minification changes three specific cues in a way that can potentially increase perceived distances to objects [20]: (1) it reduces the visual angle, (2) familiar size cues may make objects appear more distant, and (3) minification causes binocular convergence to indicate that objects are more distant. On the other hand, magnification changes these cues in an opposite direction and can potentially decrease perceived distance.

The described mini- and magnification can be implemented as follows. Let *fov_y* denote the vertical geometric field of view before mini- or magnification. We assume that the horizontal geometric field of view *fov_x* is defined according to the *ratio*. If *fov_y* is scaled by a gain g_F (and *fov_x* is modified accordingly using *ratio*), we can determine the amount m of mini- respectively magnification with the following equation:

$$m = \frac{\tan(fov_y/2)}{\tan((g_F \cdot fov_y)/2)} \quad (5)$$

As illustrated in Figure 9, the mini-/magnification m denotes the amount of uniform scaling that is required to map the viewport (rendered with a certain GFOV) to the display (defined by its DFOV and *ratio*). If this mini-/magnification equals 1.0, a person will perceive a

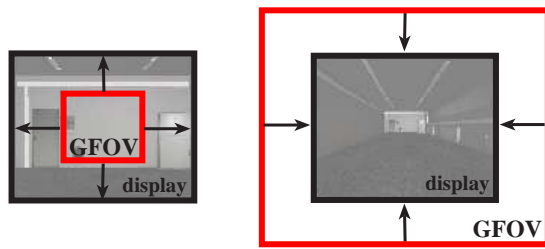


Fig. 9. Illustration of the relationship between the display's FOV and the viewport, and the GFOV used for perspective rendering. The left image illustrates a magnification ($m > 1$), the right image illustrates a minification ($m < 1$).

spatially accurate image, as defined by the spatial dimensions of the virtual space model. When the geometric field of view is increased ($g_F > 1$), the resulting image is minified ($m < 1$), whereas a decreased geometric field of view ($g_F < 1$) results in a magnified image ($m > 1$).

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