# Judgment of Natural Perspective Projections in Head-Mounted Display Environments

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## Abstract

The display units integrated in todays 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's field of view. A discrepancy between these two fields of view distorts the geometry of the VE in such a way that objects and distances appear to be "warped". Although discrepancies between the geometric and the HMD's field of view affect a person's perception of space, the resulting mini- and magnification of the displayed scene can be useful in some applications and may improve specific aspects of immersive virtual environments, for example, distance judgment, presence, and visual search task performance.

In this paper we analyze if a user is consciously aware of perspective distortions of the VE displayed in the HMD. 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 an experiment to identify perspective projections for HMDs, which are perceived as natural by subjects-even if these perspectives deviate from the perspectives that are inherently defined by the display's field of view. We found that subjects evaluate a field of view as natural when it is larger than the actual field of view of the HMD; in some case up to $50\%$.

**CR Categories:** H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems—Artificial, augmented, and virtual realities; I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Virtual reality

**Keywords:** Virtual reality, head-mounted displays, field of view

## 1 Introduction

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 [Burdea and Coiffet 2003]. Some vendors employ multiple of such micro-displays to increase the total resolution and 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. Sophisticated HMDs are equipped with a tracking system that determines the wearer's head position/orientation, so that a tracked motion of the HMD leads to a corresponding change of the virtual view. This allows to "look around" in a virtual reality (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.

The most often named requirements for a HMD are a high resolution and a large field of view (FOV). This FOV refers to the horizontal and vertical angles subtended by the display. In comparison to the effective visual field of humans, which approximates 200 degrees horizontally and 150 degrees vertically [Warren and Wertheim 1990], many commercially available HMDs have relatively narrow fields of view, ranging roughly from 20 to 80 degrees diagonally. 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 display's FOV, the *geometric* field of view (GFOV) defines the horizontal and vertical boundaries of the virtual viewing volume along with the aspect ratio. With such a setup user movements tracked in the laboratory are mapped to position, orientation and/or projection changes of a virtual camera. Usually, tracked head pose changes are applied to the virtual camera by means of a one-to-one mapping, and 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. The image projected onto the viewport is displayed on the physical screen of the HMD.

If the GFOV matches the field of view of the HMD, the viewport is mapped from virtual space onto the physical display in such a way that users perceive a "correct" perspective (assuming that we neglect other distortions of the display device such as pincushion distortion). On the other hand, if the GFOV varies from the display's FOV, it results either in mini- or magnification of the graph-

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ics [Kuhl et al. 2008] (cf. Appendix). As illustrated in Figure 1(a), if the GFOV is smaller than the FOV 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 FOV of the HMD, a larger portion of the VE needs to be displayed in the image, which will appear minified (see Figure 1(c)). Depending on the distortion of the geometry of the VE the visual optical flow rate decreases or increases proportionately [Draper et al. 2001]. 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 paper we analyze how much perspective distortion caused by a deviation between the GFOV and display's FOV is unnoticeable to HMD users. 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 paper is structured as follows. Section 2 summarizes work related to our approach. Section 3 introduces a psychophysical calibration method to identify the display's actual FOV. In the 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 discusses the results of the experiments as well as implications about how to set up the virtual perspective in HMD environments. Section 6 concludes the paper and gives an overview about future work.

## 2 Related Work

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 portion of the virtual world if the GFOV matches the display's FOV. In the real world, a narrow field of vision has been shown to degrade human performance in navigation and manipulation tasks [Jansen et al. 2008; Hassan et al. 2007], spatial awareness, and visual search tasks [Arthur 1996]. 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 [Alfano and Michel 1996; Hagen et al. 1978].

As mentioned in Section 1, if the GFOV matches the display's FOV, the viewport is mapped directly from virtual space onto the physical display, and therefore users perceive a “correct” perspective. However, a deviation between the GFOV and the FOV of the HMD occurs, for example, when the display's actual field of view 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 mini- or magnification of the graphics (cf. Appendix). Choosing the largest field of view possible may not always be optimal, since the required size of the GFOV for a HMD mainly depends on the application under consideration. If the GFOV is larger than the display's FOV, the display resolution decreases because the same pixels are mapped to a larger display area. Furthermore, a large FOV may be unnecessary for tasks, which are localized within a small spatial region of interest [Hassan et al. 2007], and it may aggravate simulator sickness effects, particularly those caused by vection and visual-vestibular mismatch [Stanney and Kennedy 1997; Seay et al. 2002].

However, an increased GFOV affords the inclusion of more information in the 3D view, and for a broad class of applications a larger field of view is essential, since it has the potential to improve immersion and to increase the user's sense of presence [Seay et al. 2002; Allison et al. 1999]. 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 [Furnas 1986].

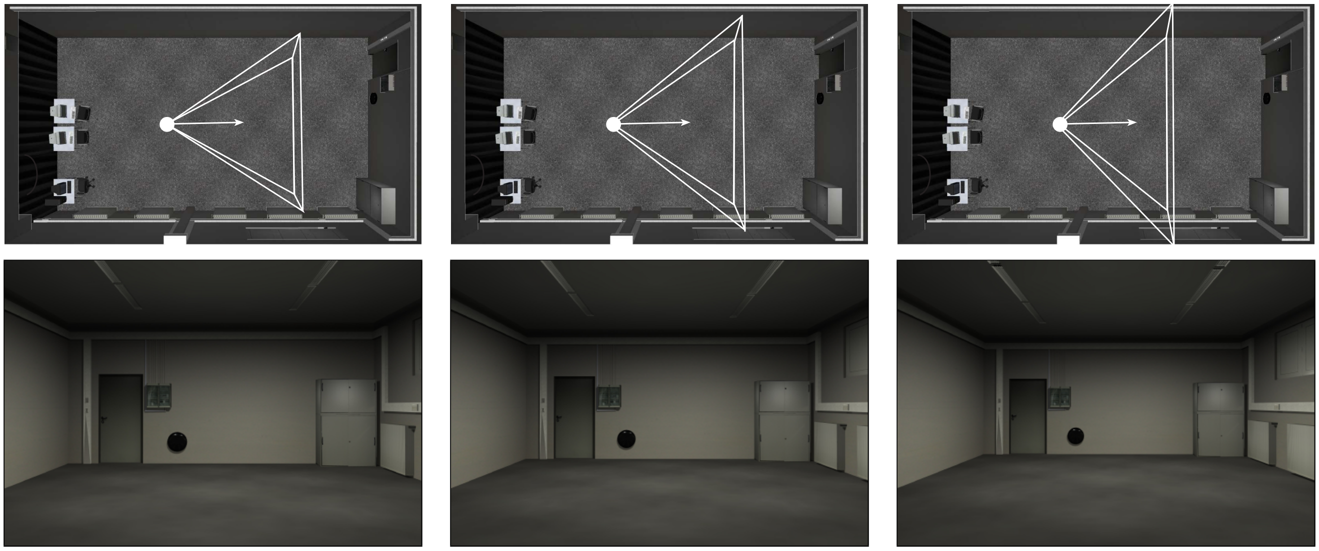
Even if GFOV and display's FOV match, viewing the real world varies significantly from viewing a virtual world through a HMD. Many studies that compared distance perception of static targets in immersive VEs and in the real world found evidence that distances are perceived as compressed in VEs relative to the real world [Witmer and Kline 1998; Willemsen and Gooch 2002; Messing and Durgin 2005; Gooch and Willemsen 2002]. It has been shown that as long as HMD users look around in a real or virtual environment, a restricted field of view (like a 60 degree diagonal FOV) did not change their behavior on blind walking distance estimation tasks [Creem-Regehr et al. 2005; Knapp and Loomis 2004; Loomis and Knapp 2003]. However, previous studies have suggested that physical factors related to the ergonomics of head-mounted displays may account for some of the apparent compression [Willemsen et al. 2009; Kuhl et al. 2006; Kuhl et al. 2008; Thompson et al. 2004; Knapp and Loomis 2004].

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 HMD displays typically have a reduced FOV, the restricted field of view has been suspected as a factor influencing distance perception [Witmer and Kline 1998; Psotka et al. 1998].

Although researchers have investigated the effects of the GFOV on performance and level of presence experienced [Hendrix and Barfield 2000], few studies have explicitly considered the relationship between GFOV and the display's FOV. In the experiments described by Kuhl et al. [Kuhl et al. 2008] 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 was reduced, i. e., subjects walked significantly farther to previously seen targets when the graphics were minified. The work primarily focused on measuring the effects of mini- and magnification on distance judgments instead of measuring if subjects were consciously aware of the distortion. Since subjects had to walk without vision, they did not perceive any visual flow information. As explained above, mini- or magnification strongly affects the visual optical flow rate, which is an essential visual motion pattern that allows humans to extract self-motion information. Therefore, we are interested in analyzing how much deviation between GFOV and the display's FOV is unnoticeable for users and which GFOV is perceived as most natural.

## 3 Psychophysical Calibration of GFOV

As mentioned in Section 2, a HMD's actual FOV 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 a display's actual FOV. Usually, the nominal FOV for HMDs is specified as visual angle across the diagonal of the screen. 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 FOV into geometric horizontal and vertical fields of view, often assuming a square-pixel aspect ratio. However, according to Kuhl et al. [Kuhl et al. 2008], the horizontal and vertical geometric fields of view determined in such a way can fail to match the FOV of the HMD for three reasons:



(a) $g_F = 0.8$ (b) $g_F = 1.0$ (c) $g_F = 1.2$

**Figure 1:** *llustration of different perspective projections in a virtual 3D model of our laboratory: (a) with a GFOV, which is larger than, (b) identical to and (c) smaller than the display's actual FOV. 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)* $g_F = 1.2$*.*

1. The nominal diagonal FOV may differ from the display's actual diagonal FOV.
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.

In order to account for the three sources of error, different calibration methods have been proposed to identify the actual FOV of a HMD [McGarrity and Tuceryan 1999]. Ellis and Nemire [Ellis and Nemire 1993; Nemire and Ellis 1993] 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 allows to calculate how the GFOV has to be specified so that the virtual angles and pointed angles match. Another method [Rinalducci et al. 1996] uses a camera flash 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 [Gilson et al. 2008]. 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 of the HMD [Kuhl et al. 2008]. In the following we describe a psychophysical calibration method to identify the actual FOV 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 *fovx* and the vertical angle *fovy* of the geometric field of view with $g_{F[x]} \cdot fovx$ and $g_{F[y]} \cdot fovy$ respectively.

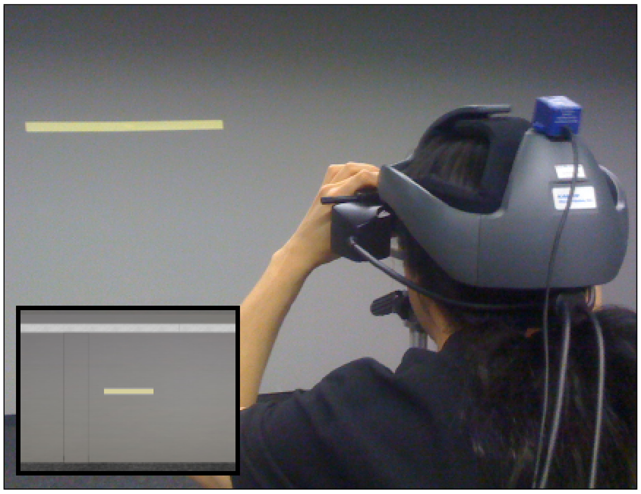


**Figure 2:** *Picture taken during the psychophysical calibration process. A participant at a fixed position compares the size of the horizontal stripe in the real world with the virtual stripe displayed on the HMD (see inset).*

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 chose 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 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 $10m \times 7m$ darkened laboratory room. We used two HMDs for the stimulus presentation: (1) ProView SR80 (1280 × 1024 @ 60Hz, 80° diagonal FOV), and (2) eMagin Z800 (800 × 600 @ 60Hz, 40° diagonal FOV). 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, *n*Vidia 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 1). 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 2). In the virtual world we displayed consecutively a horizontal respectively vertical $1m \times 0.05m$ 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 FOV specified by the manufacturers (cf. Appendix). We presented the gains each 10 times in randomized order. Figure 2 shows a participant in the physical laboratory, who compares the horizontal virtual stripe in the 3D model with the stripe in the real world.

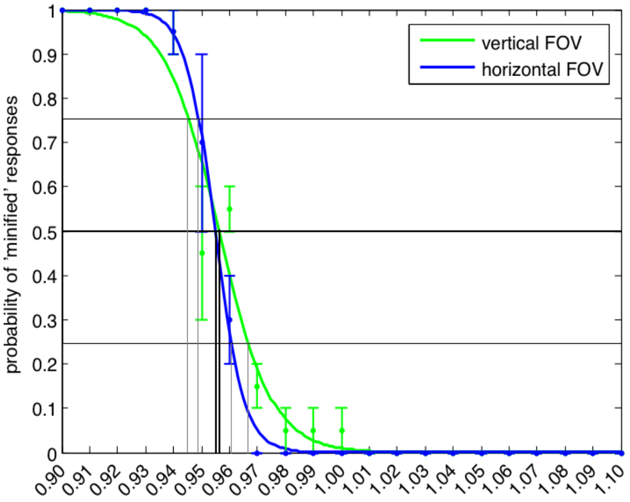


**Figure 3:** *Pooled results of the discrimination between the HMD's and the geometric FOV. The horizontal axis shows the gains applied to the geometric FOV, the vertical axis shows the probability that subjects estimate the virtual world to be minified compared to the real world.*

## 3.2 Results

Figure 3 shows the mean probability for a particpant'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 in discriminating between real and virtual as well as vertically and horizontally 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 actual field of view perceived by the participants is slightly smaller than the FOV specified by the manufactures, 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 de-

**Figure 4:** *Photo from the experiment showing a subject with the ProView SR80 HMD adjusting the GFOV with the PowerMate.*

termine a display's actual FOV. Hence, we assume the native FOV of the ProView SR80 HMD to be $76.88^\circ$ 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 calculated with respect to 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 FOV of the HMD and the GFOV used for rendering are identical (cf. Figure 1(b)), if $g_F < 1$ the used GFOV is smaller than the display's FOV and the virtual world is magnified (cf. Figure 1(a)), if $g_F > 1$ the GFOV is increased and the virtual world is minified (cf. Figure 1(c)).

## 4 Experiment

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 this experiment we used the ProView SR80 HMD with the results from the calibration process, i. e., we assumed an actual diagonal FOV of 76.88 degrees and 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

9 male and 2 female (age 23-46, $\varnothing : 28.8$) subjects participated in 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. Five of the subjects had experience with walking in VR environments using a HMD setup. Four had much game experience, four some, and three none. Two of the authors participated in the study, all other subjects were naïve 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.

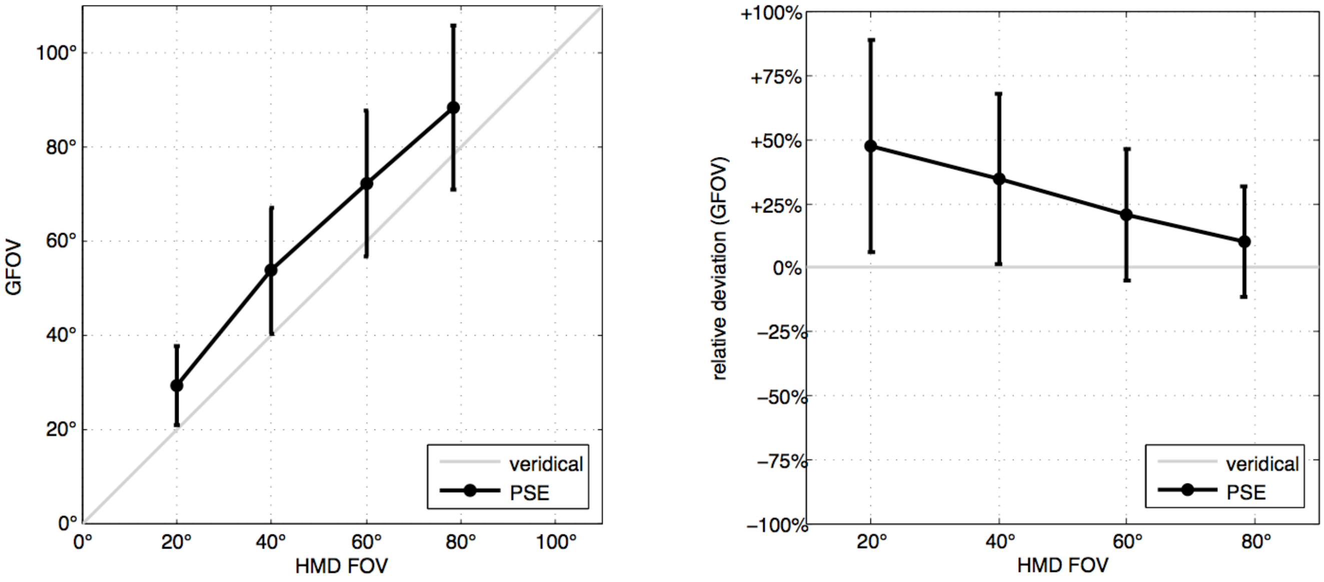
### 4.1 Material and Methods

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 geometric FOV, from which in turn we computed the horizontal geometric FOV using the display's aspect ratio (cf. Section 3.2). To change the gain $g_F$, subjects used a PowerMate manufactured by Griffin Technology (see Figure 4). 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 FOVs of 20, 40, 60 and 76.88 degrees (the ProView's actual FOV as derived from the calibration process). Each of these FOVs 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

In Figure 5(a) we plotted the FOVs against the subjects' adjustment for the most natural geometric fields of view. Figure 5(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. We could not find a 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" geometric FOV 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 $29.53^\circ$ for a HMD with a diagonal FOV of $20^\circ$, $53.85^\circ$ ($40^\circ$), $72.33^\circ$ ($60^\circ$), and $88.34^\circ$ ($76.88^\circ$). The results



(a) (b)

**Figure 5:** *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 actual display's FOV on the vertical axis.*

show that the geometric fields of view which appear most natural to the subjects are larger than the actual displays' fields of view. In Figure 5(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 FOV 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 display's FOV.

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 greater GFOVs for HMDs with a small FOV. The results further show that the subjects' judgment of a natural GFOV approximates the actual FOV for HMDs with a larger FOV. 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-Usoh-Steed (SUS) presence questionnaire [Usoh et al. 1999]. 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. [Draper et al. 2001] 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 $13.09$. We could not find a 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. [Draper et al. 2001] as visual stimulus instead of a visually faithful virtual scene may have led to the increase observed in their experiments.

## 5 Discussion

The psychophysical calibration method described in Section 3 shows that subjects are quite accurate at discriminating the FOV 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 experiment described in Section 4 shows that subjects do not necessarily estimate a GFOV that is identical to the display's FOV as most natural. Subjects tended to judge a significantly larger geometric field of view as natural in case the display's FOV was rather small; in some cases up to $50\%$. 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 display's FOV 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 display's actual FOV. When subjects have to judge natural perspectives, another reason for the deviation between the display's 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 display's FOV 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 affords more information into 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 display's FOV. This result suggests that if a GFOV, which is larger than the display's FOV, is intentionally used in some application (for example, to reduce compressed distance judgments [Kuhl et al. 2008]), some amounts of distortion will likely go unnoticed by subjects.

## 6 Conclusion and Future Work

In this paper we have presented a psychophysical calibration method that allows us to determine the display's actual FOV as perceived by users and we have conducted an experiment 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 display's FOV 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 [Dolezal 1982]. Kuhl et al. [Kuhl et al. 2008] 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 display's FOV and GFOV are shifted towards increased GFOVs for HMDs with a small FOV. The results provide important guidelines for the specification of GFOVs in HMD environments. For HMDs with $20^\circ$ diagonal FOV the GFOV should be set to $29.53^\circ$ to appear most natural to users, respectively $53.85^\circ$ for HMDs with $40^\circ$ diagonal FOV, $72.33^\circ$ for HMDs with $60^\circ$ FOV, and $88.34^\circ$ for HMDs with $76.88^\circ$ FOV (the largest FOV 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.

## Appendix

The nominal field of view for most HMDs is specified by the manufacturers as visual angle $\alpha$ 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 *fovx* and *fovy* can then be calculated with equations (1) and (2):

$$fovx = 2 \cdot atan\left(\frac{tan(\alpha/2)}{\sqrt{1+\frac{1}{ratio^2}}}\right) \tag{1}$$

$$fovy = 2 \cdot atan\left(\frac{tan(\alpha/2)}{\sqrt{1+ratio^2}}\right) \tag{2}$$

In a computer graphics system usually only the vertical geometric field of view (*fovy*) has to be specified from which the extent of the near plane is calculated; the horizontal extent of the near plane is calculated with respect to 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 6). 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 [Kuhl et al. 2006]: (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 *fovy* denote the vertical geometric field of view before mini- or magnification. We assume that the horizontal geometric field of view *fovx* is defined according to the $ratio$. If *fovy* is scaled by a gain $g_F$ (and *fovx* is modified accordingly using $ratio$), we can determine the amount $m$ of mini- respectively magnification with the following equation:

$$m = \frac{tan(fovy/2)}{tan((g_F \cdot fovy)/2)} \tag{3}$$

As illustrated in Figure 6, 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 FOV and ratio). If this mini-/magnification equals $1.0$, a person will perceive a 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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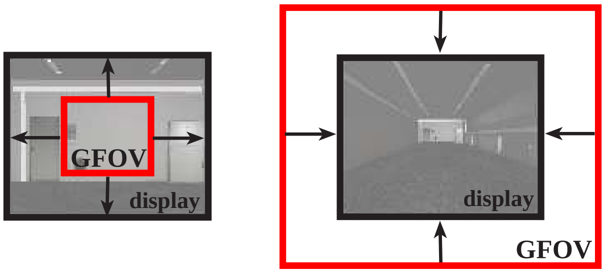

**Figure 6:** *Illustration of the relationship between the display's FOV and the viewport, and the GFOV used for perspective rendering.*

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