Simulating Lens Distortion in Virtual Reality

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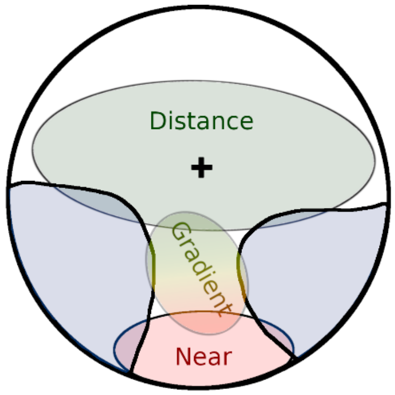
ABSTRACT

Modern progressive lenses are widely used to allow distance and near-view within one lens. Novice users experience motion sickness during adaptation and have problems performing everyday tasks when first using progressive lenses. To evaluate the effects of progressive lens distortion in psychophysical experiments these need to be simulated in real-time. We present a method to generate the distortion pattern of a progressive lens in virtual reality that allows testing perceptual distortions and behavioural consequences of exposure to such distortions. A user study showed that the heading angle on the horizontal axis was significantly underestimated through implemented distortion.

1. INTRODUCTION

All people develop presbyopia with age, and increasing amount of the population correct their myopia, hyperopia or astigmatism using spectacles. Ageing populations all over the world lead to more people needing spectacles to correct conjunctions of multiple corrections. A common approach in lens design for this problem is progressive additive lenses (PAL), which have a distance and a near view zone (see Fig. 1).). In PALs both zones are connected through a gradient corridor in which the magnification changes smoothly in contrast to bifocals with a hard border between the far and near zone. This allows having a lens with correction for near sightedness, refractive errors and without perceiving sudden displacements. Since PALs are used in most spectacles for presbyopia, PAL design has evolved dramatically during the last 40 years (Meister & Fisher, 2008). Although lens-design allows individual lenses created through free-form lens surfacing, some wearers experience motion sickness through their spectacles and most need time to adapt to it. Elderly bifocal, trifocal, and PALs wearers have been found to fall significantly more likely than wearers of single-vision lenses (Lord et al., 2002).



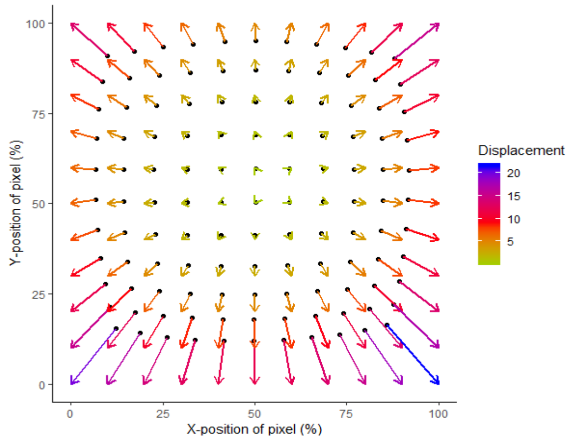


Figure 1. *Schematic of a progressive additive lens and its distortion vectors in the FOV. The gradient corridor between the distance (green) and near view (red) zones leads to unavoidable side-effects in the periphery e.g. skew on both sides of the lens (blue).*

PALs distort the image that reaches the retina differently in different image areas, creating a new mapping between the world and the retinal image. Following Sheedy et al. (2005) this mapping includes astigmatism like distortions in more peripheral areas that follow the physical limitations described in the Minkwitz-theorem (1963) and appear through creating the gradient area. These distortions are a likely source of discomfort and disorientation during locomotion in novel wearers. Faubert & Allard (2004) used a multi-screen system to investigate the effects of a PAL-like distortion on the perception of forward movements. They measured the leaning angle of subjects standing on one foot and found that the distortions generated significant instability. The reason behind this instability may be that distortions produced by a PAL continuously change the optic flow field, i.e. the motion field experienced on the retina during self-motion (Gibson, 1950). Optic flow is used, among other things, for the control of stance (Lee, 1980) and the perception of the direction of self-motion, or heading (Lappe et al., 1999). Habtegiorgis et al. (2017) showed that adaptation effects on PAL-like distortion through display presentation is possible. It thus seems possible to use VR to simulate and investigate the perceptual and behavioural modifications that occur in novel wearers of PALs, since the complete FOV can be distorted in real-time and according to self-motion.

We present a VR method to investigate and compare the possible effects of optical lens designs on visual perception. As a proof of concept we created a user study in which distortion was applied on the field of view (FOV) of a virtual environment in which users were asked to estimate their heading direction.

2. SIMULATION OF PAL DISTORTION IN HMD

All stimuli were presented with the HTC Vive, a Head Mounted Display (HMD) with 2 OLED screens with 1080 x 1200 Px at 90 Hz and a FOV of 110°. A Vive controller was as input device. To track position and orientation we used the lighthouse tracking system. To present the experiment we used Unity3D and the SteamVR asset on a computer with a NVIDIA GeForce RTX 2060 graphics card, an Intel Core i7-8750 CPU with 2.2 GHz, 16 GB of RAM running Microsoft Windows 10.

In an optical lens, light-rays that enter the lens are refracted and thus reach the retina at a different location than in normal viewing. To create a similar effect in a digital image, each pixel position is replaced by a source pixel at a different location in the undistorted image. To simulate a given distortion pattern of a progressive lens in VR, we applied a custom pixel shader on a virtual camera object in Unity3D. By accessing the render pipeline of the graphics processor, shaders can be applied fast on any given environment. Our shader redefined the pixel positions on the x and y axis of both displays in the HMD. For the simulation we used a typical PAL design. The distortion map of a grid of the example lens design was generated through raytracing using a grid consisting of 50 x 50 grid points with an inter grid point distance of 41 mm, seen at a distance of 2 m. To simplify this distortion matrix, we used the curve fitting toolbox of MatLab 2018b to fit two derivable polynomial-functions (see equation 1) to predict the distortion-shift f in x and y-direction for each x and y position ($rmse_x = 0.0021$, $rmse_y = 0.0027$). The fitted 11 parameters of both functions were then passed to the pixel shader. All defined pixels were replaced by source pixels at the calculated x- and y-positions of the undistorted image.

$$f(x,y) = \sum_{i+j=5} (p_{ij} x^i y^j) \qquad\qquad i,j,x,y \geq 0 \qquad\qquad (1)$$

3. User Study of Heading Perception in Simulated PAL Viewing

3.1 Procedures

Eleven subjects (4 female, aged 23 - 30) took part in a user study with 264 trials. Seven subjects were naive to the hypotheses of the experiment. Ethical approval for the testing of all subjects was obtained from the ethics board of the Department of Psychology of the University of Münster prior to testing. The experiment was done in accordance with the 1964 Helsinki Declaration and its later amendments. Informed, written consent was obtained from all participants.

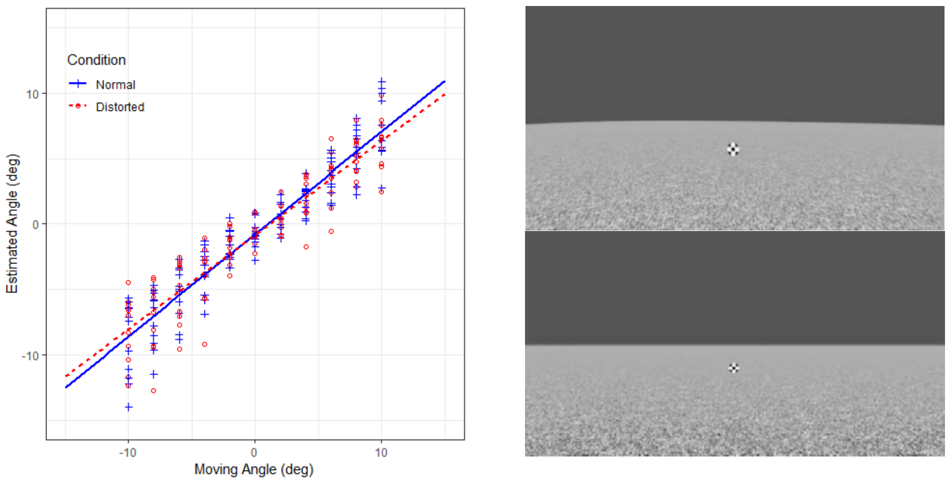


Figure 2. *Left: Underestimation of the heading angle. Through the PAL distortion the heading angle is slightly underestimated. The effect is dependent on the true heading angle. Lines show a linear fit. Right: Distorted (above) and non-distorted FOV at the starting position of the experiment.*

All subjects were asked to sit down. The virtual environment was presented in stereo, although the same distortion was applied to both displays in the HMD. Each subject was asked to adjust the HMD until all edges of a head-fixed aligning-texture were visible and the texture was centred correctly. Then the approximately 15 minutes long experiment started. To estimate distortions of self-motion perception in simulated PAL viewing we conducted an experiment that tested perceived heading direction following established procedures of heading perception research (Warren et al., 1988; Royden et al., 1992; Lappe et al., 1999). In two conditions participants either experienced a distorted or a non-distorted FOV (see Fig. 2), and were instructed to look at a fixation target (diameter of 1 m, positioned 10 m in front of the subject at the height of 0.5 m). The display then simulated forward motion at 2 m/s in one of a set of 11 heading angles (-10, -8, -6, -4, -2, 0, 2, 4 6, 8, 10) for 0.5 seconds. Heading direction and distortion condition varied in a pseudorandom order that was different for each participant. After the motion stopped, participants were asked to indicate their perceived heading direction. A thin vertical red bar was placed on a red circle with a radius of 10 m around the participant. Participants placed the bar in the perceived heading direction by pointing with the controller in their right hand and confirmed by pulling a trigger. To mask the change of distortion between trials the screen greyed out for 0.5 seconds between trials.

Table 1. *Influence of Distortion on Heading:*

	Baseline Model	Comparison Model
(Intercept)	−0.01 (3.86)	−0.01 (3.86)
True Heading	0.75 (0.01)***	0.78 (0.01)***
Distortion	−0.04 (0.10)	−0.04 (0.10)
Rotation y-Axis	−0.06 (0.05)	−0.06 (0.05)
Vision corrected	−0.36 (0.73)	−0.37 (0.73)
Hypothesis	−0.27 (0.72)	−0.26 (0.72)
Age	−0.02 (0.14)	−0.02 (0.14)
Gender	−0.13 (0.71)	−0.13 (0.71)
True Heading*Distortion	-	−0.06 (0.02)***
AIC	13965.27	13959.22
BIC	14048.67	14048.57

Table 1. *Beta weights are shown for all factors (standard errors in brackets). Only the factors True Heading and True Heading* Distortion had a significant influence on the estimated heading direction. Factors with beta weights of 0.00 in both models and were not included (*** $p < 0.001$).*

3.3 Results

We calculated the perceived heading angle by using the final tracking positions of the controller and the HMD, when the trigger was pulled. The mean perceived heading angles of all participants can be seen in Fig. 2. The lines indicate regressions for the distorted and the non-distorted condition. The regression line for the distorted view is shallower than that for the non-distorted view indicating a misperception of heading induced by the distortion. To analyse the data statistically we defined a mixed effect model to predict the perceived heading angles using the control variables *True Heading*, *Gender*, mean *X-*, *Y-* and *Z-Rotation Angle*, *Trial length*, *Trial number* and *Distortion* as fixed effects. The factor *Subject* was added as a random effect. To test if the simulated PAL distortion in interaction with the *True Heading* had an influence on the perceived heading angle, a second model including this interaction was fitted (see Table 1). The second model including the interaction *True Heading*Distortion* was significantly better ($\chi^2 = 14.512$, $p < .001$). The random factor *Subject* explained 13.3 % of the variance in Model 2 ($p < .001$).

4. CONCLUSIONS

We demonstrated that VR can be used to simulate and measure the distortion effects of PALs. The method offers a simple, fast, and efficient opportunity to investigate the distortion created by different lens designs. This is achieved by mimicking and displaying the outgoing image of a PAL, to generate a comparable retinal image. Since the object's distance can be optically translated into size, the distortion map is valid for all distances. In order to show the applicability of the method we conducted a user study comparing self-motion perception with distorted and non-distorted views. As in many studies before (Warren & Hannon, 1988; Royden et al, 1992), subjects were able to estimate their heading direction from the non-distorted visual input. The negative beta coefficient of the interaction of -0.06, suggests that the PAL-distortion led to an underestimation of the heading angle during the experiment. Since the motion vectors of the FOV are asymmetrically changed through the applied distortion a difference in heading estimation seems plausible. In the real wearing of PAL glasses, the observed underestimation may lead to slightly wrong expectations about distance and position of visible objects during self-motion. Thus, distortion may be a factor wearers may need to adapt to. We introduced a method to use cost-efficient hardware to display optical effects of complex progressive lenses and showed in a user study that the PAL-distortion applied through a custom shader led to an underestimation of the heading angle.

Acknowledgements: This work was supported by the German Research Foundation (DFG La 952-4-3) and has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skodowska-Curie grand agreement No. 734227.

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