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Influence of display device and screen curvature on perceiving and controlling simulated ego-rotations from optic flow

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Influence of display device and screen curvature on perceiving and controlling simulated ego-rotations from optic flow

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Abstract. This study investigated how display parameters influence humans' ability to control simulated ego-rotations from optic flow. The literature on visual turn perception reports contradictory data, which might be partly due to the different display devices used in these studies. In this study, we aimed at disentangling the influence of display devices, screen curvature, and field of view (FOV) on the ability to control simulated ego-rotations solely from visual information. In Experiment 1, FOV and display device (projection screen vs. head-mounted display (HMD)) was manipulated. In Experiment 2, screen curvature and FOV were varied. Subjects' task was to perform visually simulated self-rotations with target angles between 45 and 270°. Stimuli consisted of limited lifetime dots on a dark background, and subjects used a joystick to control the turning angle of the visual stimulus. In Experiment 1, performance was tested in a within-subject design, using a curved projection screen (FOV 84°×63°), a HMD (40°×30°), and blinders (40°×30°) that restricted the FOV on the screen. Performance was best with the screen (gain factor 0.77) and worst with the HMD (gain 0.57). We found a significant difference between blinders (gain 0.73) and HMD, which indicates that different display devices can influence ego-motion perception differentially, even if the physical FOVs are equal. In Experiment 2, screen curvature was found to influence the perception of ego-rotations: At identical FOVs of 84°, participants undershot target angles on the curved screen (gain 0.84), while they overshot target angles on the flat screen (gain 1.08). Perceptual mechanisms that may underlie these results will be discussed. We conclude the following: First, differences between display devices (HMD vs. curved projection screen) are more critical than the FOV for the perception of ego-rotations, with projection screens being better than HMDs. Second, screen curvature significantly influences performance for visually simulated ego-rotations: Compared to the flat screen, the curved screen enhanced the perception of ego-rotations. These findings have relevant implications for the design of motion simulators.

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1 INTRODUCTION

It is known that observers typically misperceive simulated turning angles in Virtual Reality (VR) if only visual information is available. In almost any VR simulations, observers have problems to estimate how far they have turned while navigating in a virtual environment. In general, the literature suggests that proprioceptive and vestibular cues are essential for spatial orientation when rotations of the observer are involved, and that visual stimuli alone are insufficient (Bakker, Werkhoven, & Passenier, 1999). However, many different display devices and field of views (FOV) have been used (see Figure 1), and the data are highly inconsistent (Bakker et al., 1999; Bakker, Werkhoven, & Passenier, 2001; Kearns, Warren, Duchon, & Tarr, 2002; Péruch, May, & Wartenberg, 1997; Riecke, 1998; Riecke, van Veen, & Bülthoff, 2002).

The present study aims to disentangle the influence of display devices, screen curvature, and FOV on the ability to control simulated ego-rotations solely from visual information.

Bremmer and Lappe (1999) have shown that humans can use optic flow to perceive and control translational ego-motion with high accuracy, even if no landmark information is available. However, for the special case of ego-rotations, observers' ability to estimate ego-motion from visual information alone becomes very inaccurate: In one study, Bakker et al. (1999) asked participants to perform visually simulated ego-rotations at specific turning angles (e.g., 45° left, 90° right etc.). Participants were seated and viewed a virtual scene using a head-mounted display (HMD, FOV 24°×18°). They used a joystick to control the turns: When they pulled the joystick to the side, the visual scene moved as if the participant was turning around his vertical axis. In this condition, it was found that when only visual information was presented, participants undershot target angles for requested ego-rotations by nearly 60%. Performance improved when participants turned physically on their

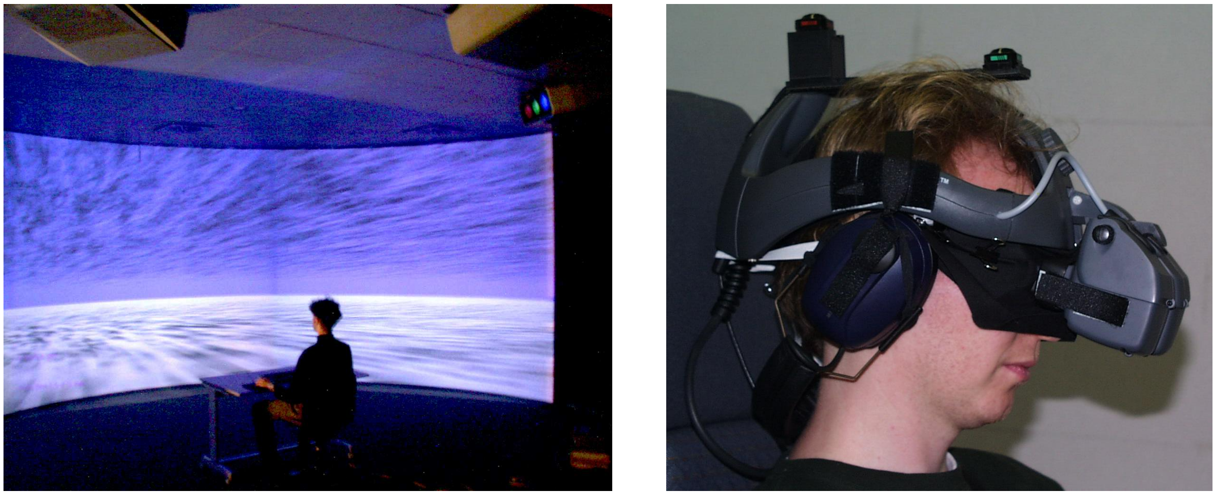

Figure 1: **Left**: 180°×50° FOV half-cylindrical projection screen. **Right**: Subject wearing HMD, FOV 40°×30°.

feet, thus adding proprioceptive and vestibular cues to the visual cues, but undershooting still occurred. Strikingly, performance was best when participants turned blindfolded. The authors conclude that ... "orientation based on visual flow alone is most inaccurate and unreliable".

On the other hand, using a large, half-cylindrical projection screen with a large FOV of 180° (see Figure 1, left), Riecke et al. (2002) found that participants were able to perform instructed rotations with remarkable accuracy from visual flow alone. In a comparable task, turning performance was nearly perfect, with a gain factor of 0.99 and errors more than ten times smaller than in the Bakker et al. (1999) study.

So far, to our knowledge no study has systematically examined whether this contradiction is attributable to the different display devices (HMD vs. projection screen), the difference in screen curvature (cf. Péruch et al., 1997; Riecke et al., 2002), or the different FOVs used in these experiments.

To investigate this question, we performed two psychophysical experiments. Participants were requested to perform visually simulated ego-rotations for specific target angles, similarly to the study by Bakker et al. (1999) as described above. In Experiment 1, FOV (84°×63° vs. 40°×30°) and display devices (HMD vs. curved projection screen) were varied. In Experiment 2, screen curvature (flat vs. curved) and FOV (84°×63° vs. 40°×30°) were manipulated.

2 HYPOTHESES

Experiment 1: If only FOV matters for accurate ego-rotation perception, one would expect a performance difference only between the large screen (84°×63°) and the two conditions with restricted FOVs of 40°×30° (HMD and "blinders"), and no difference between the latter two. If the display device matters, one might expect a difference between HMD and blinders at the identical FOV. Experiment 2: If screen curvature affects turning accuracy, one would expect different results between flat and curved projection screens at identical FOVs.

3 EXPERIMENT 1

3.1 Design & apparatus

In a within-subject repeated-measures design, 18 participants performed visually simulated ego-rotations. In a full factorial design, five turn angles (45° to 225°, steps of 45°) were crossed against four turning velocities (20, 27, 34, and 42°/s), two directions (left/right) and three visualization conditions (curved projection screen: FOV 84°×63°, HMD: 40°×30°, blinders: 40°×30°). The blinders restricted the FOV on the projection screen to the same FOV that was visible in the HMD. The screen resolution was set to 1024×768 pixels on all display devices. To provide only optic flow information without any landmarks, a starfield of limited lifetime dots (dot lifetime = 650 ms) on a dark background was used. The three conditions were presented in balanced order between subjects. Each of the six possible permutations was performed by three participants.

Participants were seated in front of the projection screen, with the head position stabilized by a chin rest (see Figure 2). Viewing distance was 106 cm to the center of the curved screen, which had a curvature radius of 2 m (see Figure 5). Participants viewed the stimulus with both eyes. Target angles were instructed via headphones, e.g. "Turn 90° to the left", and participants used a joystick to control the simulated turns:

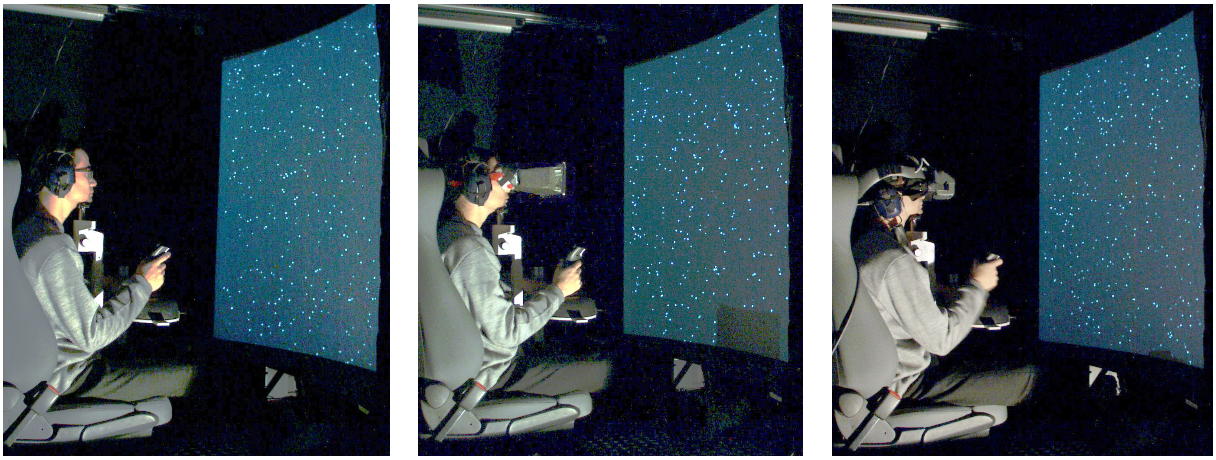

Figure 2: Experimental setup. **Left:** Screen FOV 84° × 63°; **center:** blinders FOV 40° × 30°; **right:** HMD FOV 40° × 30°

When they pulled the joystick to the side, the visual scene turned around the observer as if he or she was turning around the vertical axis. After 8 practice trials without feedback, participants performed 40 trials in randomized order in each of the three visualization conditions. No training or feedback about performance was provided at any stage of the experiment.

3.2 Results & Discussion

Generally, all turning angles were undershot (see Figure 3). The presentation order of the three conditions had no significant effect (F(5,12) = 0.75, p=0.604). For turn error as the dependent measure, a 3 (visualization conditions) × 5 (target angles) × 4 (velocities) × 2 (turn directions) repeated-measures ANOVA with all factors as within-subject factors showed the following results: The effect of visualization condition was significant, as well as target angle (F(2,24) = 13.3, p<0.001 and F(4,48) = 45.1, p<0.001, respectively). Bonferroni-corrected post-hoc tests revealed significant differences between the full screen and HMD (p<0.001), and also between HMD and blinders (p<0.01). The interaction between visualization condition and target angle was also significant (F(8,96) = 6.3, p<0.001). Figure 3 illustrates the ranked order of the three conditions and the interaction. With a value of 0.77, the gain of the curved screen lies closest to 1, and the gain of the HMD diverges most with a value of 0.57. That is, with the HMD, undershooting of target angles was largest. The magnitude of undershooting with the HMD is consistent with values found in Bakker et al. (1999). Mean subjective ratings about task difficulty were highest for the blinders (3.6 on a 5-point Likert-scale), as opposed to values of 2.7 for the screen and 2.9 for the HMD (see Figure 4, left). This is remarkable because performance with the blinders was much superior to the HMD and did not differ significantly from the full screen condition. While performance was worst with the HMD, the task was perceived as rather easy.

In summary, the effect of display device appears to be more critical than the FOV for the present task. However, it is worthwhile mentioning that in a post-test interview, the FOV of the HMD was estimated more than twice as large on average than the actual FOV (see Figure 4, right). In contrast, estimates for the FOV on the screen and the blinders was very accurate. Participants also reported that the dots appeared to be farther away in the HMD than on the screen, even though dot size in terms of visual angle was equated between the two conditions. There is evidence from Wist, Diener, Dichgans, and Brandt (1975) that, with the angular speed of a visual surround held constant, observers' perceived speed of rotary self-motion increases linearly with increasing perceived distance of this surround. This means that for the special case of self-rotation, human observers seem to mistakenly use linear velocity on the screen instead of angular velocity to estimate rotation speed. Therefore, it is possible that both altered apparent distance to the stars and the largely misperceived size of the FOV in the HMD contributed to the large performance deterioration for the HMD.

4 Experiment 2

4.1 Design & apparatus

In Experiment 2, screen curvature and FOV were manipulated. The design and task was almost identical to Experiment 1, except that turns of 270° were added and velocities were slightly modified to 28, 33, 38, and 43°/s. This was done because in Experiment 1, slow turns of 20°/s yielded higher variability and larger

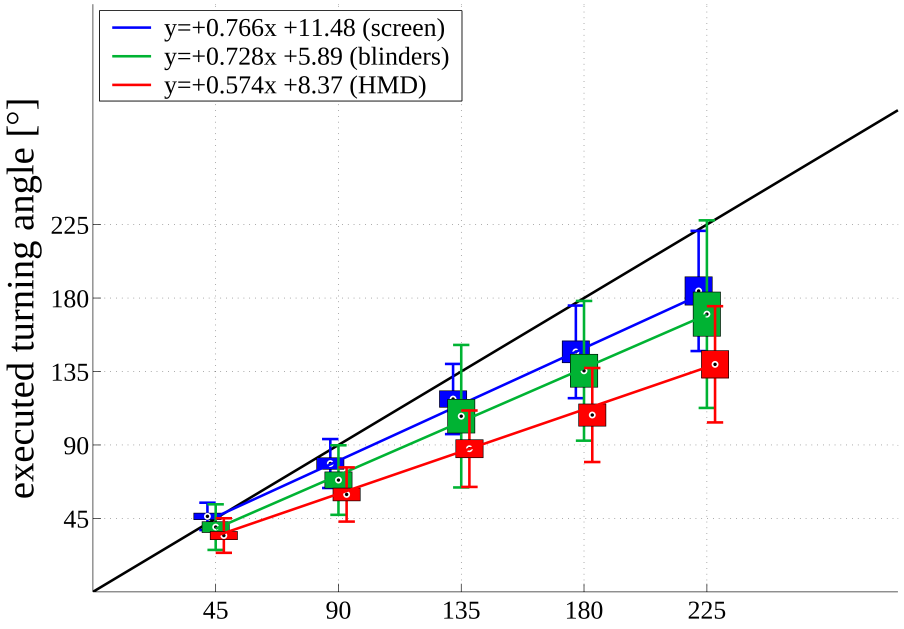

Figure 3: Experiment 1: Means of turned angles per visualization condition plotted against the correct target angles. Boxes show one standard error of the mean, whiskers indicate one standard deviation. The slopes of the fitted lines correspond to the gain factors. The equations for the linear fit are shown in the inset on top. A gain factor of 1 (black line) describes perfect performance. Notice that all turning angles are undershot.

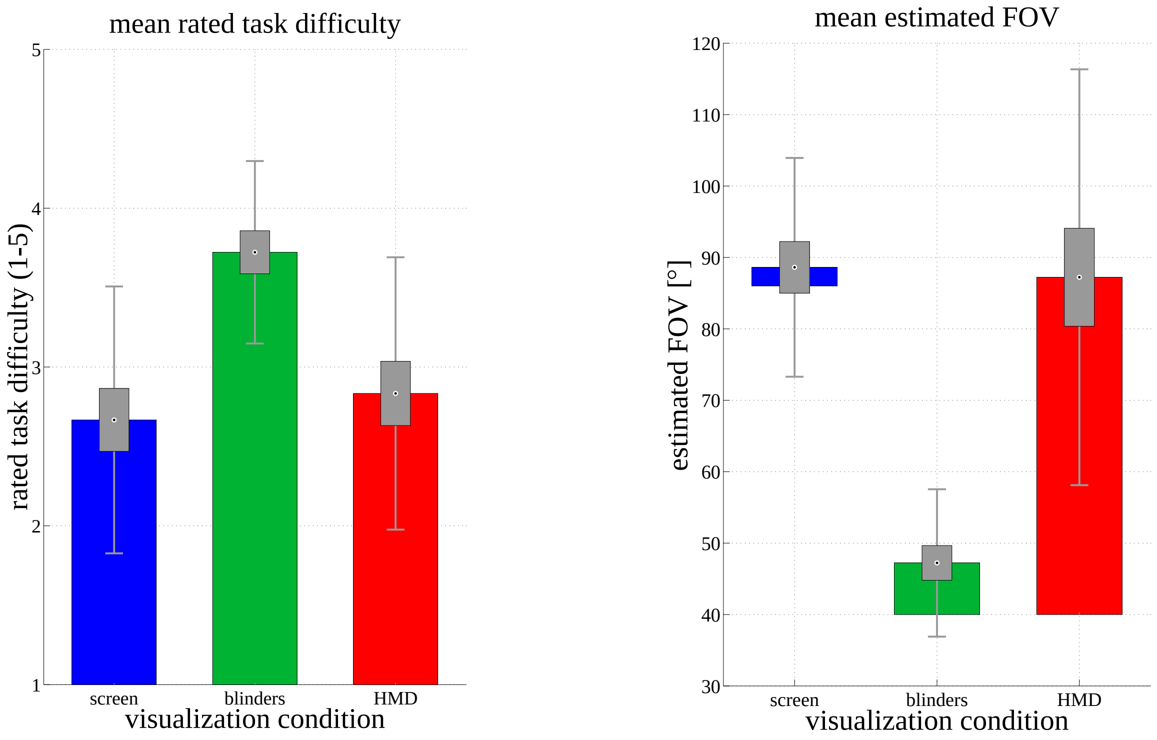

Figure 4: **Left:** Mean rated task difficulty. Boxes show one standard error of the mean, whiskers indicate one standard deviation. Note that task difficulty for the HMD was rated as almost as easy as the full screen condition, even though the HMD yielded the worst turning performance. **Right:** Mean estimated FOV. The heights of the colored boxes indicate the amount of deviation from the actual FOV. Notice the large over-estimation of FOV for the HMD.

turning errors than the faster velocities. Sixteen observers who had not participated in Experiment 1 performed the task using a flat projection screen and a curved screen (curvature radius = 2m; FOV = $84^\circ \times 63^\circ$ for both, see Figure 5) in two separate blocks on two different days. FOV was also varied ($84^\circ \times 63^\circ$ vs. $40^\circ \times 30^\circ$) in each session using blinders. Presentation order of the blocks was fully balanced across participants.

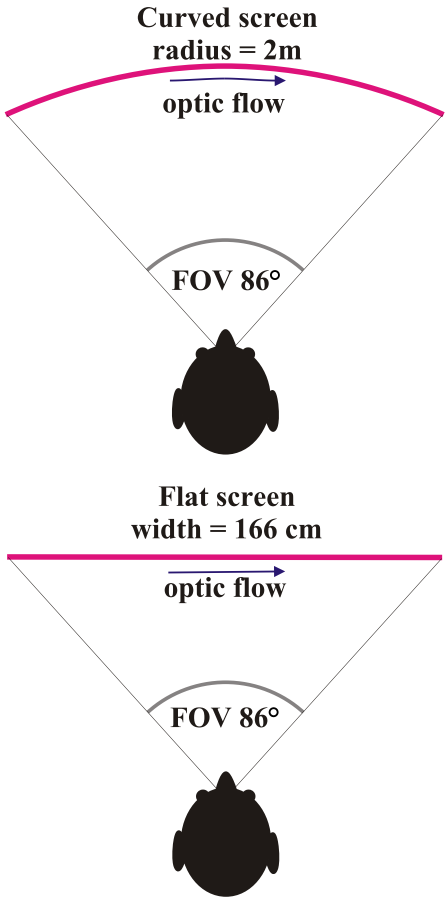

Figure 5: Schematic drawing of Experiment 2: **Top:** Curved screen; **Bottom:** Flat screen; FOV = $84^\circ \times 63^\circ$ for both. Viewing distance was 89 cm to the flat screen and 106 cm to the center of the curved screen. The identical stimuli from Experiment 1 were used for both conditions in Experiment 2.

4.2 Results & Discussion

A repeated-measures ANOVA with turn error as the dependent variable revealed a significant effect of screen curvature, turning velocity, and also an interaction between curvature and turn angle: While target angles were undershot in the curved screen (gain factor 0.84), a surprising overshoot was observed for the flat screen (gain factor 1.08, see Figure 7, bottom). The presentation order of the randomized blocks (flat vs. curved screen) had no significant effect (see Table 1 for F-values).

Factor	***df* and F-value**	**Significance**
Visualization condition	F(1.95,15.6) = 8.21	p<0.001
Velocity	F(1.22,9.75) = 9.32	p <0.01
Visualization condition × Target angle	F(2.96,23.65) = 6.79	p<0.002
Presentation order	F(1,7) = 0.13	p=0.993

Table 1: F-Table of ANOVA results. Note: df and F-values for repeated-measures tests are Greenhouse-Geisser corrected.

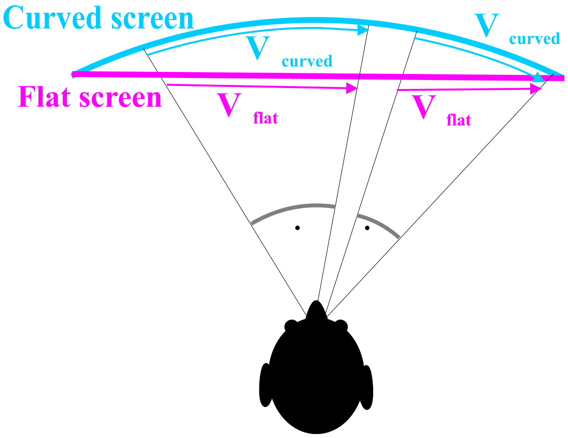

Figure 6: Optical difference of rotational optic flow viewed on the flat and the curved screen. Due to the fact that the FOV was kept constant, the center of the curved screen is farther away from the observer than the flat screen. While the angular velocity ($\dot{\alpha}$ and $\dot{\beta}$) of optic flow is unaffected, the linear velocity ($V\alpha$and $V\beta$) on the projection screen is both dependent on the distance to the observer and on curvature: Vectors of linear velocity are longer in the center of the curved screen than on the flat screen, while the difference becomes less towards the periphery.

Figure 7 (bottom) summarizes the results. For comparison, results from Experiment 1 are plotted again in the top part. Bonferroni-corrected post-hoc tests showed a significant difference for gain factors between the flat and curved screen in the full view condition (p<.05). There was, however, no significant difference for the reduced FOV for both the curved and the flat screen (p=.82 and p=.14, respectively).

In the experiment, participants had been instructed to trust their sense of ego-motion to estimate their

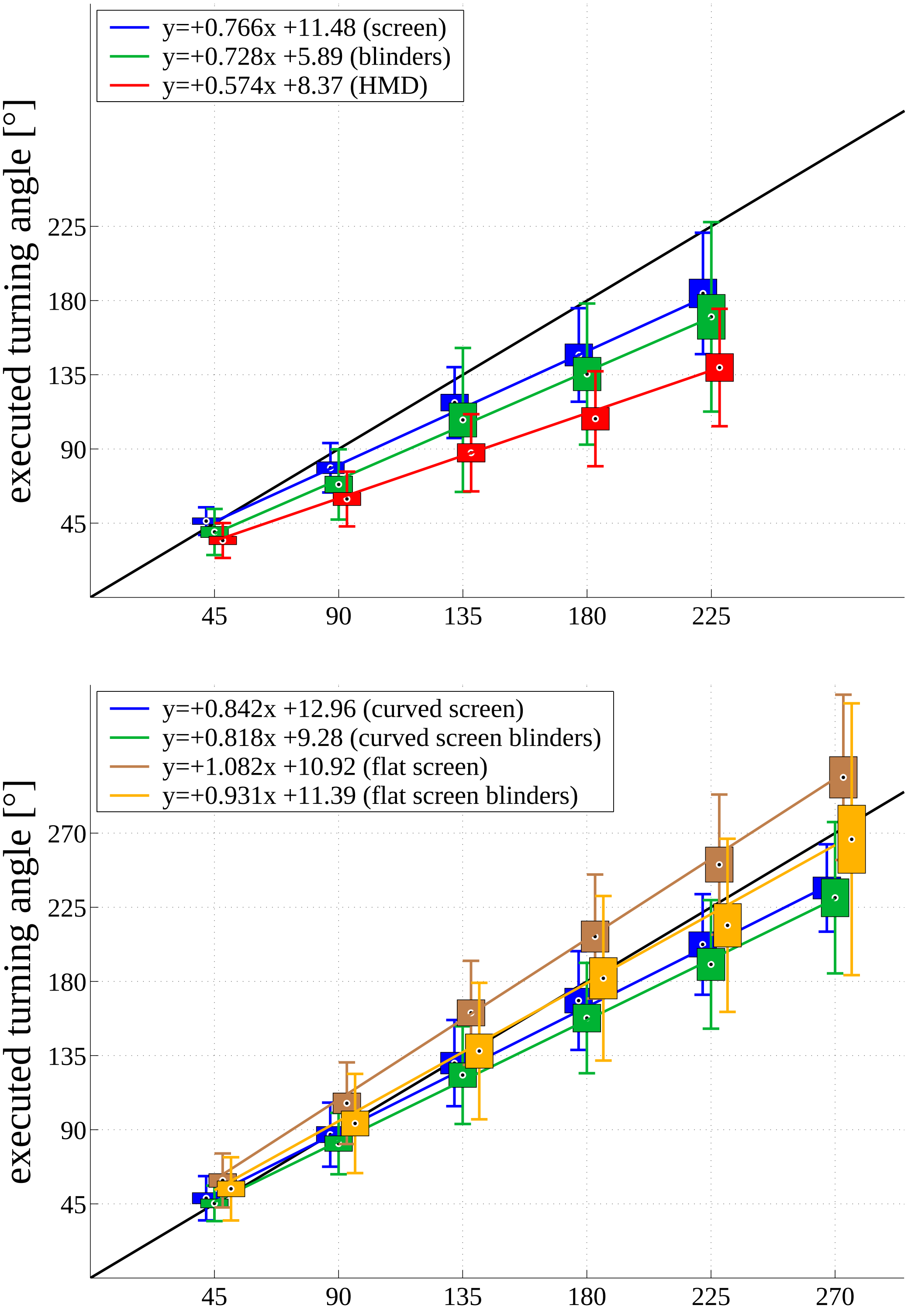

Figure 7: Means of turned angles per visualization condition plotted against the correct target angles. For comparison, results from Experiment 1 (top) and Experiment 2 (bottom) are plotted above one another. Boxes show one standard error of the mean, whiskers indicate one standard deviation. The slopes of the fitted lines correspond to the gain factors. The equations for the linear fit are shown in the inset on top. A gain factor of 1 describes perfect performance, as indicated by the black diagonal line. Notice that in both experiments, turning angles were undershot on the curved screen, whereas overshooting occurred on the flat screen.

turn angles. Interestingly, some observers' verbal reports after the experiment indicated that on the curved screen, the simulated self-rotations looked "more realistic" than on the flat screen. This may have led them to overestimate turns on the curved screen (thus to undershoot target angles) and to underestimate turns on the flat screen (and thus to overshoot target angles). Figure 6 illustrates the optical difference of the stimuli on the two screens. The longer vector on the curved screen for stimuli with the same angular velocity predicts that turns should be overestimated on the curved screen compared to the flat screen if the linear velocity rather than the angular velocity is used to estimate turning angles. Indeed, this pattern of results was found in our study. Some participants also reported after the experiment that rotational optic flow on the flat screen looked like translational lamellar flow (e.g., like looking sideways when walking forward).

5 GENERAL DISCUSSION

In this study, we investigated the influences of display devices, FOV, and screen geometry on the perception and control of visually simulated ego-rotations. In Experiment 1, we found that turning accuracy with the HMD (FOV $40^\circ \times 30^\circ$) was significantly worse than on a projection screen with a FOV of $84^\circ \times 63^\circ$. Importantly, reducing the FOV on the projection screen from $84^\circ \times 63^\circ$ to the same $40^\circ \times 30^\circ$ as on the HMD did not affect performance at all, although this significantly increased perceived task difficulty. Furthermore, performance on the projection screen was significantly better than on the HMD even when the FOV was equal to the HMD ($40^\circ \times 30^\circ$). Previous research has mainly attributed reduced perceptual performance of HMDs to their reduced FOV, and also to the predominantly low resolution and their weight (Arthur, 2000). Our results question this hypothesis. In the present study, the resolution was kept constant at 1024×768 pixels for all display devices, and the additional weight of the HMD was supported by a chin rest. We identified two other factors that might have affected performance on the HMD: First, observers overestimated the FOV on the HMD by a factor of 2.2 on average, while they were very accurate at judging the FOV on the screen for both the full view and the reduced view conditions with the blinders (cf. Figure 4). Second, most observers reported that on the HMD, the visual stimuli appeared to be at a farther distance than on the screen, even though stimulus size in terms of visual angle was kept constant. Findings from Wist et al. (1975) suggest that this overestimation of distance leads observers to overestimate ego-rotation speed, as discussed in section 3.2.

The open question is why observers largely overestimated the FOV with the HMD, but not with the blinders. One difference is that with blinders, there were distance cues available for both the distance of the viewing aperture and the projection screen (cf. Figure 2, center). Additionally, minimal head movements might have provided parallax information. Participants had explicitly been instructed not to move their head during the trials, and their head was always stabilized in the chin rest, but it cannot be ruled out that some observers did move their head minimally. With the HMD, on the other hand, the black rim of the viewing aperture is not clearly visible since it is very close to the eyes, and the distance to the LCD screens is not directly perceivable because they are viewed through optical lenses. Furthermore, the HMD was not position-tracked in this study. This means that if observers moved their head, they did not get any visual feedback from their motion. In summary, viewing conditions with HMDs are rather unnatural, which can result in distorted perception of distance, FOV, and turning angles(see also Kearns et al., 2002).

It seems likely that both misperceived FOV and distance have contributed to the large performance deterioration for the HMD. Further investigation is needed to identify the source of the distorted distance-perception and estimated FOV for HMDs.

6 CONCLUSIONS

In this study we intended to disentangle the influence of display devices, screen curvature, and FOV on the ability to control simulated ego-rotations solely from visual information. We found that display devices had a strong influence on the ability to control simulated ego-rotations: Performance was better when a projection screen was used (gain 0.77), and performance dropped drastically when a HMD was used (gain 0.57). Surprisingly, we did not find any effect when the FOV was reduced: With a reduced FOV of $40^\circ \times 30^\circ$, performance was as accurate as when a large FOV of $84^\circ \times 63^\circ$ was available. Furthermore, in Experiment 2, we found an effect of screen curvature: While participants undershot target angles for visually simulated ego-rotations on the curved screen (gain 0.84), they overshot target angles on the flat screen (gain 1.08).

Using a HMD with a FOV of $24^\circ \times 18^\circ$, Bakker et al. (1999) also found large undershooting of intended turn angles. However, in a follow-up study, where a new HMD with a larger FOV of $48^\circ \times 36^\circ$ was used, they found overshooting for the same task using the identical stimuli (Bakker et al., 2001). The authors attribute the difference to the increased FOV, since it was the only parameter changed in their experiment. The results of our study, however, suggest another view on this issue: We could show that FOV alone is not the crucial parameter, because reducing the FOV on the projection screen from 84°×63° to the same 40°×30° as the HMD resulted in far superior performance compared to the HMD. Therefore, FOV cannot be the only issue with HMDs that limits perceptual performance. We identified two other potential sources for perceptual distortions in HMDs: First, participants largely overestimated the size of FOV in the HMD by a factor of 2.2 on average. Second, participants reported that the perceived distance of the visual stimuli was largely increased compared to the projection screen, even though the size in terms of visual angle had been kept constant. It remains to be clarified how these different factors contribute to the distorted perception in HMDs. In conclusion, care should be taken when using HMDs to investigate basic perceptual processes at the current stage of knowledge.

From our results from Experiment 2, we can conclude that curved projection screens seem to be more appropriate than flat screens to simulate rotational egomotion. Still, even on the curved screen, participants generally undershot turning angles (gains 0.77 and 0.84 in Experiments 1 and 2, respectively). In a comparable study, Riecke et al. (2002) asked participants to perform a similar task as in our experiment, but using a 180° half-cylindrical projection screen (see Figure 1, left). They found almost perfect performance with a gain factor of 0.99 and only minimal errors.

There are two critical differences between the Riecke et al. (2002) and the current study that might explain the different results. First, the larger FOV might have improved turn performance, even though no effect of FOV between 84°×63° and 40°×30° for the projection screen was found in the present study. Second, the curvature radius in the Riecke et al. (2002) study was equal to the distance of the observer to the screen (both 3.5m), such that the projected stimulus rotated at a constant physical distance around the observer. In the present study, the screen curvature of 2m was larger than the distance of the observer to the screen (1.06m), such that the stimulus did not rotate at a constant physical distance around the observer but had also some lamellar component.

Future work will aim to identify the parameters that underlie the performance differences between these two screens. The contributions of FOV, peripheral vision, and the reference frame provided by the screen geometry will be investigated.

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