Perceiving Simulated Ego-Motions in Virtual Reality - Comparing Large Screen Displays with HMDs

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ABSTRACT

In Virtual Reality, considerable systematic spatial orientation problems frequently occur that do not happen in comparable real-world situations. This study investigated possible origins of these problems by examining the influence of visual field of view (FOV) and type of display device (head-mounted display (HMD) vs. projection screens) on basic human spatial orientation behavior. In Experiment 1, participants had to reproduce traveled distances and to turn specified target angles in a simple virtual environment without any landmarks that was projected onto a 180° half-cylindrical projection screen. As expected, distance reproduction performance showed only small systematic errors. Turning performance, however, was unexpectedly almost perfect (gain=0.97), with negligible systematic errors and minimal variability, which is unprecedented in the literature. In Experiment 2, turning performance was compared between a projection screen (FOV 84°×63°), an HMD (40°×30°), and blinders (40°×30°) that restricted the FOV on the screen. Performance was best with the screen (gain 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. We conclude that the type of display device (HMD vs. curved projection screen) seems to be more critical than the FOV for the perception of ego-rotations. Furthermore, large, curved projection screens yielded better performance than HMDs.

Keywords: Virtual Reality, psychophysics, navigation, spatial cognition, motion simulator, self-motion, HMD, projection screen

1. INTRODUCTION

Even though Virtual Reality (VR) technology has advanced with an amazing pace over the last decades, there still seem to be some rather fundamental unsolved issues when simulated ego-motions are involved. Whenever users cannot rely on salient landmarks for orienting themselves in a visually presented virtual environment, they tend to become disoriented and get lost very easily while navigating. Often, users produce strikingly large errors even for simple spatial orientation tasks in VR, especially when simulated ego-rotations are involved. Only few studies have addressed this problem directly so far. In these studies, participants are typically presented with a simple virtual environment and requested to perform for example simulated upright rotations for a given angle, e.g. "Turn 90° to the right". Even though this is a trivial task for anyone in the real world (even with eyes closed), most studies report very poor performance for this task when it is carried out in VR. Typically, a considerable variability in users' turn responses is found, accompanied with a regression towards stereotyped turn responses. Moreover, many studies also report systematic errors in participants' spatial orientation or navigation performance. The type and amount of systematic errors, however, seem to differ considerably between different studies, especially when different visualization setups are used.

When participants were asked to perform visual turns in a simple virtual environment presented via head-mounted display (HMD), Bakker, Werkhoven, and Passenier (2001)[1] reported systematic *overshooting* of the turns for a field of view (FOV) of 48°×36°, i.e., participants turned further then instructed. Conversely, a different HMD with smaller FOV of 24°×18° resulted in systematic *undershooting* of about twice the amount.[2] The FOV alone, however, is not sufficient to fully explain the observed systematic turn errors. Visual 180° turns displayed on a flat projection screen subtending a FOV of 45° were for example *undershot* by 16% in a study by Péruch, May, and Wartenberg (1997).[3] Based on their finding that spatial orientation ability increased when visually simulated motions presented via HMD were accompanied by physical motions, Chance, Gaunet, Beall, and Loomis (1998)[4] suggest *"the advisability of having subjects explore*

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virtual environments using real rotations and translations in tasks involving spatial orientation" (p. 168). The overall poor performance for visually presented turns in VR lead Klatzky, Loomis, Beall, Chance, and Golledge (1998)[5] to conclude that "*optic flow without proprioception, at least for the limited field of view of our virtual display system, appears not to be effective for the updating of heading*" (p. 297).

These problems associated with updating rotations from visual cues alone are corroborated by triangle completion studies in a simple virtual environment void of any landmarks which was presented via HMD[6] (FOV: $60° \times 40°$): When asked to return to the starting point after traveling two legs of a triangular excursion, participants essentially rotated by the same amount in order to face the origin, regardless of the angles turned during the excursion, and hence independent of the correct turning angle. This surprising result suggests that participants had no obvious sensitivity to turning angles. Adding kinesthetic and vestibular cues through physical walking reduced overall response variability, but did not eliminate the lack of stimulus response for rotations. The striking conclusion from this experiments seems to be that even when physical motion cues from free walking are included, this is not necessarily sufficient to enable good spatial orientation in VR. Comparable blind walking triangle completion experiments, however, indicate a clear sensitivity to rotations,[7–9] even though there were still considerable systematic errors. Hence, we posit that the visual presentation via HMD itself might have somehow caused the insensitivity to turning angles in the study by Kearns, Warren, Duchon, and Tarr (2002).[6] Considerable spatial orientation problems associated with HMDs were also reported in other studies using different methodologies. For example, when Bakker et al. (1999)[2] asked standing participants to perform simple upright physical turns by physically stepping around, adding visual stimuli of a simple scene through an HMD (FOV: $24° \times 18°$) did not increase performance, but rather showed a tendency towards *decreasing* performance (i.e., undershooting), compared to simple blindfolded rotations without the HMD.[2]

Taken together, these results suggests that we cannot simply assume that any given VR setup that is sufficiently sophisticated and/or costly will automatically allow for natural spatial orientation performance. But what are the critical parameters that might allow for accurate and precise spatial orientation performance in VR without landmarks?

2. EXPERIMENT 1 - TURN EXECUTION AND DISTANCE REPRODUCTION USING A PANORAMIC 180° PROJECTION SCREEN

As all navigation behavior can essentially be decomposed into combinations of elementary translations and rotations, we set off to investigate those basic spatial orientation tasks in Experiment 1. Participants were asked to reproduce distances traveled and to execute ego-rotations for given angles in a simple virtual environment without any landmarks*. The experiment was similar to the translation experiments by Bremmer and Lappe (1999)[11] and the rotation experiments by Bakker et al. (1999, 2001),[1,2] respectively, but a different VR setup involving a half-cylindrical 180° projection screen with three projectors was used instead of a flat projection screen ($90° \times 90°$) and HMD, respectively.

The study by Bremmer and Lappe (1999)[11] demonstrated that optic flow information from visually simulated translations is essentially sufficient for accurate distance reproduction, and only minor systematic errors in terms of a slight general overshoot were observed. Experiments on turn execution in VR, however, report rather inconsistent findings, typically involving noticeable systematic errors, large variability, and a strong regression towards stereotyped turn responses.

In Experiment 1, a high-end VR setup including a half-cylindrical 180° projection screen was used to investigate whether (a) we could replicate the good distance reproduction performance observed by, e.g., Bremmer and Lappe (1999),[11] and (b) whether the large field of view (FOV) and reference frame provided by the half-cylindrical projection screen can help to overcome the systematic errors often associated with simulated turns. The poor turning performance was often attributed to the limited size of the FOV of the HMDs used in most of the studies, which typically ranges from 24° to 60° horizontally (cf., e.g.,[1,2,12]).

2.1. Methods

Participants were seated in the center of a half-cylindrical projection screen of 3.5m radius and 3.15m height (see Fig. 1). Computer-generated images of a simple virtual environment were projected non-stereoscopically using three CRT projectors. The resulting panoramic image had a resolution of about 3500×1000 pixels and subtended a field of view of $180° \times 50°$. To provide optic flow information only, a simple virtual environment without any landmarks was used (see Fig. 1).

*Experiment 1 is a re-analysis of the first experiment of a study by Riecke et al. (2002).[10]

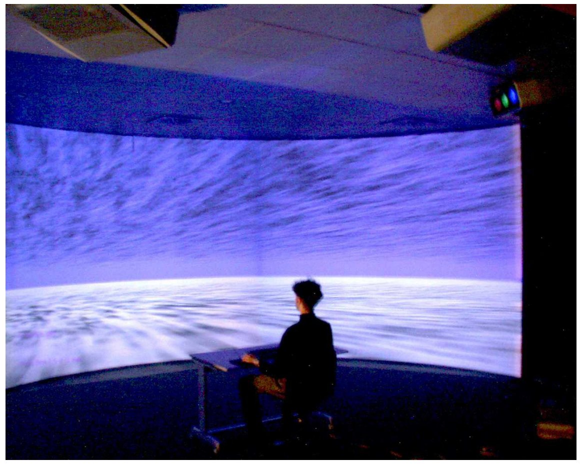

Figure 1. Participants in Experiment 1 were seated in the center of a 180°×50° half-cylindrical projection screen displaying the optic flow stimulus.

The environment consisted of a ground plane and several layers of simulated blobs that were placed both on the ground and floating in the air. This ensured that participants had to resort to path integration by optic flow and could not use any landmark-based strategies.

In a repeated-measures within-subject design, nine participants were asked to turn by specific target angles and reproduce distances traveled using randomized velocities and a simple button-based motion model with fixed movement velocity. In the first (**distance encoding**) phase, participants were moved a given distance upon pressing a designated button. In the second (**turn execution**) phase, participants were requested to visually turn by an angle displayed on the screen. Visually simulated turns were initiated by pressing the left or right button and lasted as long as the button was pressed. In the third (**distance reproduction**) phase, participants were asked to reproduce the initial (encoded) distance in the current direction. Apart form a short acceleration and deceleration phase, movement velocity was constant and randomly selected for each trial phase within a range of [3.75m/s, 7.5m/s] for translations and [20°/s, 80°/s] for rotations. After six practice trials, each participant completed 96 trials in randomized order, corresponding to a factorial combination of 8 distances (20m, 28.3m, 36.6m, 44.9m, 53.1m, 61.4m, 69.7m, 78m) × 6 turning angles (45°, 90°, 135°, 180°, 225°, 270°) × 2 turning directions (left/right). No training or feedback about performance was provided at any stage of the experiment. Head movements and response times were not restricted.

2.2. Results

2.2.1. Turn execution

Figure 2 (left top) shows almost perfect turning performance with negligible systematic errors: The gain factor for turns (slope of the linear regression) of 0.97 was very close to perfect performance (gain=1), and turns were only minimally undershot by 1.8°±1.0° on average. Furthermore, between-subject variability (indicated by the whiskers) was quite small. Within-subject turning variability showed an interesting pattern (cf. Fig. 2, left bottom): Apart from the smallest turning angle (45°), within-subject turning variability scaled quite linearly with the turning angle, and was at a level of just 5% of the angle to be turned. The mean absolute turning error was merely 6.2°±1.6° and at a level of 3%-5% of the target angle for all but the smallest turning angle (13% for the 45° turns). Taken together, we conclude that the half-cylindrical projection screen allowed for an unexpectedly high turning accuracy and precision that is to the best of our knowledge unprecedented in the literature.

2.2.2. Distance reproduction

Distance reproduction performance was somewhat less accurate and precise than turn execution performance (see Fig. 2, right). The slope (gain factor) of the linear regression fit was 0.91 ± 0.05, indicating a slight regression towards stereotyped responses. Furthermore, participants tended to overshoot shorter distances in the reproduction phase by about 15%,

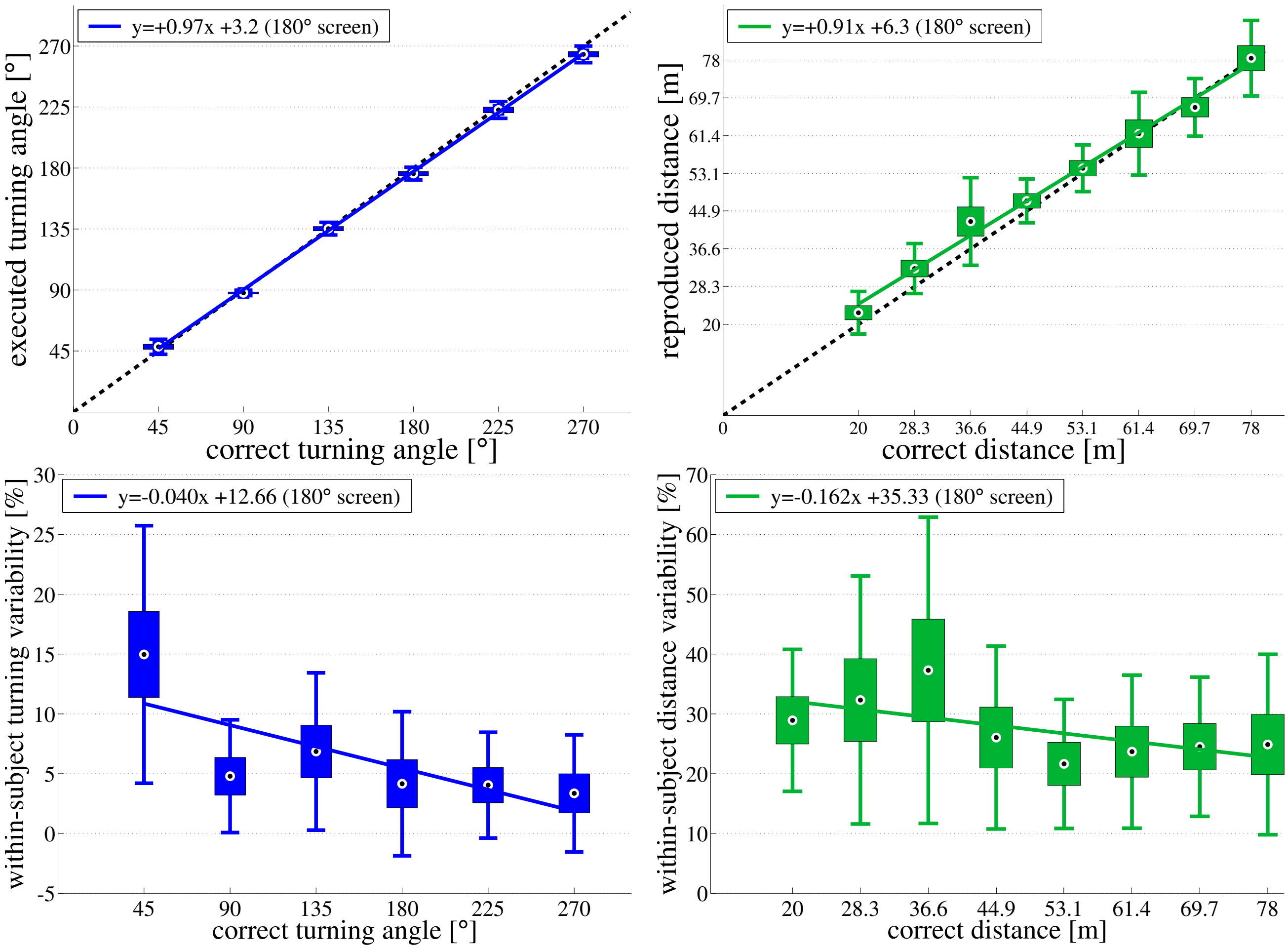

Figure 2. Mean turn execution and distance reproduction performance (left and right, plots respectively). Boxes and whiskers depict one standard error of the mean and one standard deviation, respectively. Turning and distance variability was computed as the within-subject standard deviation per turning angle and distance, respectively, scaled by the correct value. The linear fit equation is shown in the top inset and depicted as a solid line in the graph. Note that the gain factor, which we defined as the slope of the linear regression in the top plots, is for both tasks close to perfect performance (gain=1, as indicated by the dashed line).

whereas larger distances were reproduced correctly on average. Distances were on average overshot by 1.8m $\pm$ 1.7m, and the mean absolute error was 10.6m $\pm$ 1.7m. Between-subject variability (indicated by the whiskers in Figure 2, right top) was considerably larger than for turns. Figure 2 (right bottom) indicates a linear relationship between within-subject distance variability and distance to-be-reproduced, similar to the results for turns. The amount of variability was, however, with a value of 25% around five times larger than for rotations.

A correlation analysis showed no significant influence of movement velocity on rotation or translation errors. This suggests that participants did not use a simple, time-based strategy (e.g., counting seconds) to estimate angles turned or distances traveled, but that they did instead integrate the optic flow to estimate the angle/distance moved.

2.3. Discussion

2.3.1. Distance reproduction

As expected, participants were able use optic flow to reproduce distance with decent accuracy, irrespective of movement velocity. Compared to the study by Bremmer and Lappe (1999),[11] we observed a distance overshoot only for small distances - larger distances were reproduced accurately on average. That is, performance in our experiment seems to be at least equally accurate, even though one might argue that the task used by Bremmer and Lappe[11] was, if anything, rather easier than ours: Participants in their study were allowed to actively control translation speed in the reproduction phase, thus offering the possibility to match the speed from the encoding phase. Furthermore, they had more exposure to simulated translations as they had previously accomplished a distance discrimination task. Finally, Bremmer and Lappe[11] did not use an intervening turning task which might have increased memory load in our study. Hence, one might conclude that the large, curved projection screen used in Experiment 1 allows for comparable, if not better distance reproduction performance than the flat projection screen (90°×90° FOV) used in the study by Bremmer and Lappe.[11]

2.3.2. Turn execution

The turn execution data from Experiment 1 did not show the large systematic errors and high variability that is typically observed in the literature using HMDs or flat projection screens.[1–6, 13] Rather, presenting optic flow on a half-cylindrical projection screen allowed participants to perform simulated ego-rotation with amazing accuracy and precision. Both systematic errors and turning variability were typically less than 5%, without any feedback training. We conclude that our VR setup which includes a half-cylindrical projection system and a large (180°×50°) FOV was indeed sufficient to overcome the systematic errors often associated with visually simulated ego-rotations.

Using a head-mounted display in two otherwise comparable visual rotation tasks, Bakker et al.[1, 2] observed turning errors that were more than ten times larger than in the current experiment (for signed error, absolute error, and between-subject variability). Only within-subject variability was at a comparable level. Using explicit feedback training, Bakker et al. (2001)[1] were able to reduce turning errors significantly. Even after training, however, turning errors were still around three times larger than in the current study, and increased again on the following day.

Where do these huge performance differences between our study and the studies by Bakker et al.[1, 2] originate from? The main difference seems to be the display setup used. The current study used a semi-cylindrical projection screen with a large FOV of 180°×50°, whereas Bakker et al.[1, 2] used two different HMDs with rather small FOVs. Using an HMD with a FOV of 48°×36° resulted in a systematic overshooting of visually simulated ego-rotations,[1] whereas a smaller FOV of 24°×18° yielded strong systematic undershooting.[2] That is, the FOV seems to play a considerable role for perceiving rotations, whereas translations do not seem to depend as critically on the FOV. Consequently, we focused solely on rotations in the following experiment. The two studies by Bakker et al.[1, 2] demonstrated a considerable change in turning performance when using a different HMD with twice the FOV. But is it merely the size of the FOV that determines ego-rotation performance, or does the display device itself also affect it?

3. EXPERIMENT 2 - DISAMBIGUATING THE EFFECT OF DISPLAY DEVICES (HMD VS. PROJECTION SCREEN) AND FOV FOR TURN EXECUTION

The surprising result from Experiment 1 was that participants were able to perform simulated turns with remarkable accuracy when using a half-cylindrical 180° projection screen, an accuracy far better than in any other study we are aware off. Since most of the studies which reported poor performance used HMDs or smaller projection screens, we designed a second experiment to disambiguate the effect of display device and FOV. Here, we compared turn execution performance in a within-subject design using three visualization conditions: Participants performed the rotation task using (a) a projection screen with a FOV of 84°×63° (cf. Fig. 3, left), (b) the same projection screen, but participants wore cardboard blinders that restricted the FOV to 40°×30° (cf. Fig. 3, middle), and (c) an non-headtracked HMD with the same FOV as the blinders condition (40°×30°) (cf. Fig. 3, right). If FOV is the main determining factor 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 (40°×30°), and no difference between the latter two. If the display device matters, one might expect a difference between the HMD and the projection screen condition for the identical FOV of 40°×30°.

3.1. Methods

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° in steps of 45°) were crossed against four turning velocities (20, 27, 34, and 42°/s), two turning directions (left/right), and three visualization conditions (curved projection screen: FOV 84°×63°, blinders: 40°×30°, HMD: 40°×30°). The inside of the blinders was covered with light absorbing black material, so that only the stimuli projected onto the screen were visible. The resolution was set to 1024×768 pixels on all display devices. To provide only optic flow information without any landmarks, a star-field of limited lifetime dots (dot lifetime = 650 ms) on

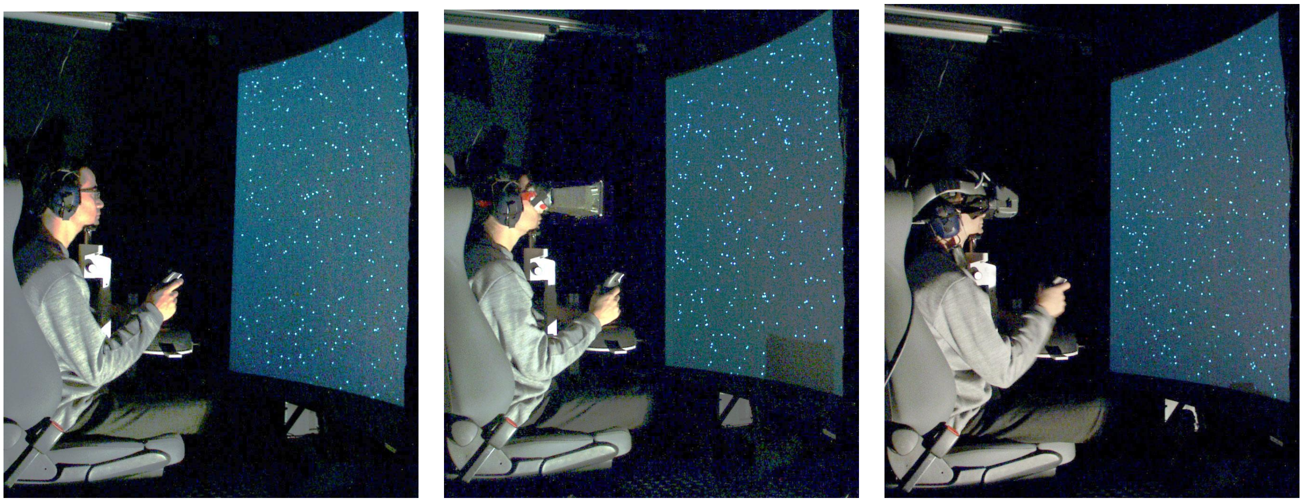

Figure 3. Experimental setup for Experiment 2 showing the star-field stimulus for the three visualization conditions. **Left:** Projection screen subtending a FOV of $84°\times63°$; **Center:** Cardboard blinders limiting the FOV on the screen to that of the HMD ($40°\times30°$); **Right:** Non-stereoscopic HMD (FOV $40°\times30°$).

a black 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 Fig. 3). Viewing distance was 106 cm to the center of the curved screen, which had a curvature radius of 2m. Participants viewed the stimulus with both eyes. A computer-generated voice was used to indicate target angles and turning directions via headphones (e.g., "Turn 90° to the left"). Participants used a joystick to control the simulated turns: When they pulled the joystick to the side, the visual scene turned with constant velocity 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

Turning angles were generally undershot (see Fig. 4, left). 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) $\times$ 5 (target angles) $\times$ 4 (velocities) $\times$ 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 $84°\times63°$ screen and HMD ($p<0.001$), and also between the blinders and HMD ($p<0.01$). The interaction between visualization condition and target angle was also significant ($F(8,96) = 6.3$, $p<0.001$). Figure 4 (left) 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 (perfect performance), and the gain of the HMD diverges most with a value of 0.57. That is, the undershooting of target angles was most pronounced in the HMD condition. The magnitude of undershooting in the HMD condition is consistent with values found in the study by Bakker et al. (1999)[2] using an HMD as well.

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 full screen and 2.9 for the HMD (see Fig. 5, left). This is remarkable, because performance with the blinders was superior to the HMD condition and did not differ significantly from the large FOV condition. Conversely, the HMD condition was rated as rather easy, even though actual performance with the HMD was worst. Hence, participants' subjective ratings of task difficulty reflected by no means their actual performance in the task.

In summary, the type of display device appears to be more critical for estimating upright rotations than the visual field of view of the display. Note, however, that participants were not able to estimate the horizontal FOV of the HMD correctly in a post-test interview (see Fig. 5, right). Instead, they overestimated the horizontal FOV as being more than twice as large on average (88°) than it actually was (40°). In contrast, estimates for the FOV of the screen and the blinders were

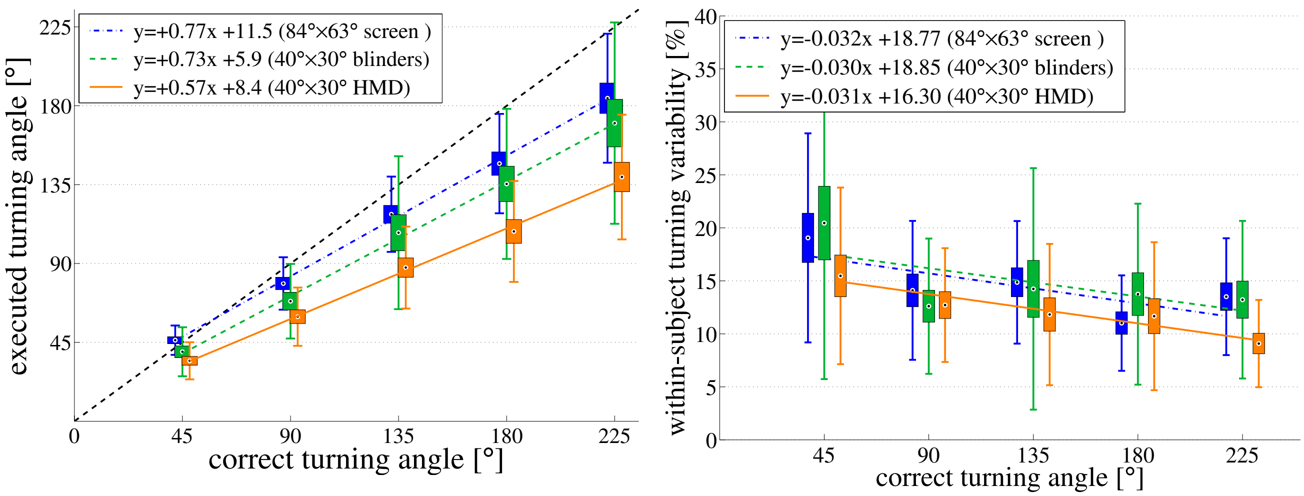

Figure 4. Turn execution performance for Experiment 2: **Left:** Means of angles turned per visualization condition, plotted against the correct target angles. Boxes show one standard error of the mean, whiskers indicate one standard deviation. The slopes of the fitted lines correspond to the gain factors. The equations for the linear fit are shown in the inset on top. A gain factor of 1 (black dashed line) describes perfect performance. Notice that almost all turning angles were undershot. **Right:** Within-participant turning variability for all conditions and turning angles.

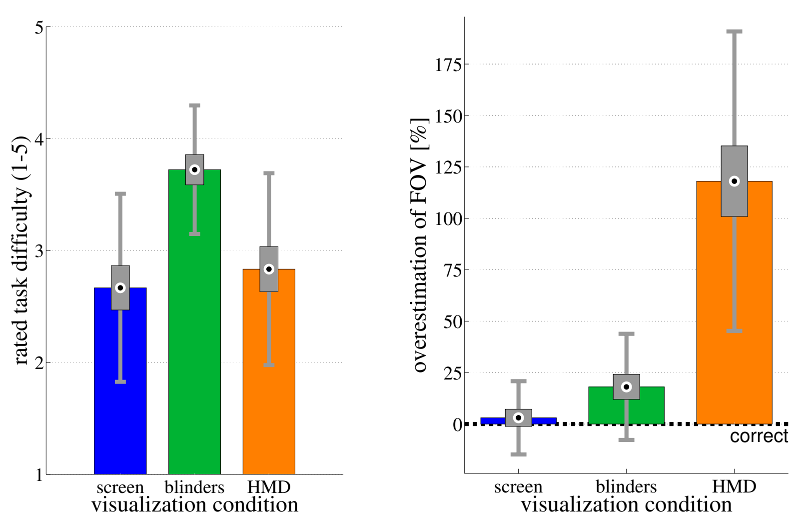

Figure 5. Subjective ratings for Experiment 2. **Left:** Mean rated task difficulty. Note that task difficulty for the HMD was rated as almost as easy as the full screen condition, even though the HMD yielded the worst turning performance. **Right:** Mean estimated horizontal FOV for all three conditions, plotted as %-overestimation relative to the correct FOV. Note that participants on average estimated the horizontal FOV of the HMD as being more than twice as large (almost 90°) as it actually was (40°).

quite accurate. Participants also reported consistently that the simulated white dots appeared to be farther away in the HMD than on the screen, even though dot size was equated in terms of visual angle between all conditions. This effect might be caused by the optical lenses in the HMD which introduce a mismatch between the accommodative distance and the simulated distance of an object. There is evidence from Wist, Diener, Dichgans, and Brandt (1975)[14] that observers' perceived speed of rotary self-motion increases linearly with increasing perceived distance of the visual surrounding, even though the actual angular speed of the visual surrounding, which is distance-independent, is held constant. This means that for the special case of visually simulated self-rotation, human observers seem to mistakenly use aspects of the linear velocity of stimuli on the screen surface instead of just angular velocity to estimate self-rotation speed. Taken together, one might argue that both the increased apparent distance to the star-field and the largely overestimated FOV in the HMD condition contributed to the performance deterioration observed for the HMD.

4. GENERAL DISCUSSION & CONCLUSIONS

The studies presented in this paper were designed to investigate the influence of display devices and FOV on basic spatial orientation tasks in VR. The Experiment 1 provided first results for turn execution and distance reproduction performance when displaying an optic flow stimulus on a half-cylindrical 180° projection. Distance reproduction performance showed a slight tendency towards overshooting for smaller distances. Larger distances, however, were reproduced with negligible systematic errors, irrespective of movement velocity and without any feedback training. The variability of participants' responses scaled linearly with distances and was at a level of about 25% of the to-be-reproduced distances.

This overall good performance is comparable to distance reproduction results by Bremmer and Lappe (1999),[11] where participants were seated at a distance of 57cm from a back-projection screen subtending a FOV of 90°×90°. This suggests that the geometry and FOV of the projection screen might not be too critical for the distance reproduction task. Using a 2 AFC distance discrimination task and the same 90°×90° back-projection screen, Frenz, Bremmer, and Lappe (2003)[15] demonstrated that optic flow is indeed under a wide range of stimulus conditions and depth cues sufficient to discriminate distances traveled. Parameters varied included movement velocity, simulated eye height above ground, visibility range, and simulated gaze angle. Frenz et al. concluded that observers did not use image velocity itself to estimate distances traveled, but rather the inferred self-motion speed. Note that both the distance reproduction and distance discrimination tasks used by Bremmer and Lappe (1999),[11] Frenz et al. (2003),[15] and also Experiment 1 of this study did not require the observer to be able to estimate distances or movement velocity on an *absolute* scale. Rather, being able to estimate distances traveled on a *relative* basis was sufficient to solve the task. This might explain the good overall performance observed for those tasks, compared to studies that required participants to estimate distances on an absolute scale for example by blind walking to targets previously presented using a VR display. While distance estimations using this method in the real world is typically rather accurate and without systematic errors for distances up to 20m,[16–21] comparable experiments where the visual stimuli were presented in VR typically report compression of distances as well as a general underestimation of egocentric distances, especially if HMDs are used[22].[23–25] Even a wide-FOV (140°×90°) HMD-like Boom display resulted in a systematic underestimation of about 50% for simulated distances between 10 and 110 feet.[26]

The only study we are aware of that found comparable distance estimation in real world and a VR replica was performed using a large, 270° CAVE-like three-walled backprojection setup.[27] This lead Plumert, Kearney, and Cremer (2004)[27] to conclude that "distance perception may be better in virtual environments involving large screen immersive displays than those involving head mounted displays (HMDs)". A similar advantage of using a large projection system instead of an HMD was found in the turn execution studies of Experiments 1 and 2 of this manuscript and will be discussed in the following.

In the turn execution part of Experiment 1, participants were able to use the optic flow presented on a half-cylindrical 180° projection screen to perform simulated upright rotations with extremely high accuracy and precision, independent of turning velocity and without any feedback training. The gain factor of 0.97 and the overall undershooting of merely 1.8°±1.0° indicate that systematic errors were negligible. Response variability both between- and within subject was also remarkably low. The high accuracy and precision observed in the current experiment was all the more remarkable as the literature typically reports considerable systematic errors and/or high variability for visually simulated upright rotations when no landmarks are available.[1–6, 13] All these studies used either HMDs or flat projection screens with horizontal FOVs well below 180°, which suggests that the considerable systematic turning errors often observed in VR can indeed be overcome by using a large FOV and a curved projection screen. We can, of course, only speculate about the underlying mechanisms, but we can assume that the half-cylindrical reference frame provided by the 180° projection screen played a critical role and allowed participants to estimate egocentric angles and thence also turning angles more easily than when using flat displays that are not curved around the observer. The half-cylindrical screen suggests a polar coordinate system, in which the cardinal directions front-left-back-right are easily accessible and angles in between can be estimated rather easily by subdividing. This hypothesis would predict that the FOV itself is not the only critical parameter for estimating simulated rotations properly, but that also the reference frame of the physical display setup plays a considerable role by allowing for an easy estimation of egocentric angles. In an earlier pilot study using a triangle completion paradigm and the same 180° projection setup (Riecke, 1998, Exp. 4),[28] we found indeed that systematically reducing the displayed horizontal size of the the screen (hFOV) while leaving the borders (reference frame) of the half-cylindrical projection screen visible did not decrease homing performance drastically. Further experiments are, however, needed to clearly determine and disambiguate the effects of FOV and reference frame for simulating ego-rotations in VR properly. Experiment 2 of this manuscript was such a first step, and we attempted to disentangle the effect of FOV and display device by comparing turn execution performance between an HMD, a projection screen with the same FOV as the HMD ($40° \times 30°$) and a projection screen with more than twice the FOV ($84° \times 63°$). Distance reproduction performance did not seem to depend as critically on the FOV and display type used and was consequently not investigated further.

Experiment 2 revealed that turning accuracy using an HMD (FOV $40° \times 30°$) was significantly worse than for a projection screen with a FOV of $84° \times 63°$. Importantly, using blinders to reduce the FOV on the projection screen from $84° \times 63°$ to the same $40° \times 30°$ as for the HMD did not decrease performance at all, although it significantly increased perceived task difficulty. Furthermore, performance for the projection screen was significantly better than for the HMD, even when the FOV equaled that of the HMD ($40° \times 30°$).

Previous research has attributed the reduced perceptual performance of HMDs mainly to their reduced FOV, the relatively low resolution, and their weight.[29] All of these parameters were, however, controlled for in Experiment 2 of the current study: Screen resolution was the same for the screen and the HMD (1024×768 pixels), the additional weight of the HMD was supported by a chin rest, and the FOV between HMD and blinders was matched. As the blinders condition of Experiment 2 yielded performance superior to the HMD condition, this suggests that the FOV and weight of the HMD are at least not the only critical parameters, as those were equated between the blinders and HMD condition. We identified, however, two perceptual factors that might have affected performance in the HMD condition: First, observers overestimated the horizontal field of view (hFOV) of the HMD by a factor of 2.2 on average, while they were quite accurate at judging the hFOV on the screen for both the full view and the blinders-reduced view conditions (cf. Fig. 5). An overestimation of the hFOV should correspond to an overestimation of the angle turned if the hFOV is used to estimate egocentric angles turned: For example, a 180° turn can be expressed in multiples of the hFOV, resulting in 4.5 times the actual hFOV of 40°, but only about 2.05 times the mean estimated hFOV (88°). Hence, overestimating the hFOV of the HMD can result in an undershooting of intended turning angles as observed in Experiment 2. The difference between the HMD and blinders condition was, however, less than predicted solely by the errors in the estimated hFOVs, suggesting that the estimated hFOV is at least not the only parameter affecting turn perception.

A second factor that might be related to the performance decrease for the HMD is related to the perceived distance of the star-field stimulus: Most observers reported that with the HMD, the visual stimuli appeared to be further away than for the screen, even though stimulus size in terms of visual angle was kept constant for all conditions. Findings from Wist et al. (1975)[14] suggest that an overestimation of distance would indeed lead observers to overestimate ego-rotation speed, as discussed in section 3.2. This, in turn, might have contributed to the observed undershooting of targets in the HMD condition, where the apparent distance to the stimulus was overestimated with respect to the projection screen.

It remains, however, an open question why observers largely overestimated the FOV of the HMD, but not of the blinders. One difference is that the blinders provided distance cues for both the viewing aperture and the projection screen (cf. Fig. 3, center). Additionally, minimal head movements might have provided parallax information for the blinders. Participants had explicitly been instructed not to move their head during the trials, and their head was always stabilized by the chin rest, but it cannot be ruled out that some observers did move their head minimally. With the HMD, though, 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 easily perceivable because they are viewed through optical lenses which introduce a mismatch between the accommodation distance and the distance of simulated objects. 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 seem to be rather unnatural, which might contribute to the distorted perception of distance, FOV, and turning angles.[6]

In the present study, it seems likely that the misperception of both the FOV and the distance to the visual stimulus have contributed to the performance deterioration observed for the HMD. The exact origins of the distorted perception of distances and the misestimation of FOVs of HMDs remain unclear, though, and await further investigation. Most studies agree that simulated distances in VR are compressed and underestimated, i.e., that objects appear to be much closer to the observer than the simulated distance (see, e.g., Creem-Regehr, Willemsen, Gooch, and Thompson (2003)[30] for and excellent overview). Such systematic misperceptions, however, pose a considerable problem for many applications and the usability of VR in general, as a veridical perception of the simulated space is important for natural and effortless interaction with the virtual environment. Recent studies managed to isolate and exclude several parameters that were previously thought to be related to the distance perception problem in HMDs:

A recent study by Knapp and Loomis (2004)[31] argues that the limited FOV of HMDs is, in fact, not the cause of the often observed distance underestimation in VR: Blindfolded participants were able to walk accurately to previously seen targets in real environments even when their FOV was limited to $58° \times 43°$ by goggles that simulated the situation when one is wearing an HMD. Using a similar blind walking paradigm, Creem-Regehr et al. (2003)[30] demonstrated that the distance errors typically observed for HMDs are most likely not caused by the hFOV, the lack of visibility of one's own body, or the lack of distance cues from binocular viewing. Only when participants' head movements were restricted did distance estimation performance degrade.

Similarly, a study by Thompson, Willemsen, Gooch, Creem-Regehr, Loomis, and Beall (2004)[24] showed that the poor quality of computer graphics cannot account for the strong distance underestimation in VR. In their study, no difference was found between a simple wire-frame representation, a low-quality image, and a high-end, photorealistic model of a real environment in a similar blind-walking task. In contrast, participants were very accurate when they were asked to perform the same task under comparable viewing conditions in the real environment. Even though several parameters have been excluded, it is nevertheless still not fully understood where the distorted perception associated with HMDs stems from. Hence, we conclude that care should be taken when using HMDs for applications or to investigate basic perceptual processes at the current stage of knowledge. Merely using a projection setup does not completely get rid of any misperception either, as Experiment 2 demonstrated for a curved projection screen of $84° \times 63°$ FOV. The half-cylindrical 180° projection screen used in Experiment 1, however, did essentially eliminate most systematic errors both in terms of relative distance perception and turn perception. So what are the critical differences between the projection setups used in Experiment 1 and 2?

First, the larger FOV of the half-cylindrical screen might have improved turn performance, even though Experiment 2 showed no clear effect of FOV between $84° \times 63°$ and $40° \times 30°$. Second, the curvature radius of the half-cylindrical screen used in Experiment 1 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 Experiment 2, however, the screen curvature of 2m was larger than the distance of the observer to the screen (1.06m) due to technical constraints. That is, the stimulus did not rotate at a constant physical distance around the observer but had also some lamellar component that might have led participants to underestimate the turned angle. Third, and in line with the second argument, the physical reference frame provided by the half-cylindrical screen might have facilitated veridical perception of both egocentric angles and angles turned, as we argued above. From the current state of knowledge, we cannot pinpoint or disambiguate the critical underlying parameters for accurate perception of distances traveled and angles turned in VR. We are currently planning experiments to tackle this challenge and disentangle the influence of display device, FOV, peripheral vision, and reference frame provided by the display geometry.

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