Enhancing the Visually Induced Self-Motion Illusion (Vection) under Natural Viewing Conditions in Virtual Reality

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Abstract

The visually induced illusion of ego-motion (vection) is known to be facilitated by both static fixation points [1] and foreground stimuli that are perceived to be stationary in front of a moving background stimulus [2]. In this study, we found that hardly noticeable marks in the periphery of a projection screen can have similar vection-enhancing effects, even without fixating or suppressing the optokinetic reflex (OKR). Furthermore, vection was facilitated even though the marks had no physical depth separation from the screen. Presence ratings correlated positively with vection, and seemed to be mediated by the ego-motion illusion. Interestingly, the involvement/attention aspect of overall presence was more closely related to vection onset times, whereas spatial presence-related aspects were more tightly related to convincingness ratings. This study yields important implications for both presence theory and motion simulator design and applications, where one often wants to achieve convincing ego-motion simulation without restricting eye movements artificially.

Keywords--- **Vection, psychophysics, spatial presence, virtual reality, illusions, motion simulation**.

1 Introduction

The topic of this paper is the visually induced ego-motion illusion ("vection") and how the illusion can be enhanced in a virtual reality setup using subtle, unobtrusive modifications. Most of us have probably experienced such an illusion when riding a train: Imagine you are sitting in a train that is standing still at a train station. You look outside the window and see another stationary train. If that train starts to move forwards, there is a good chance that you have the illusion that *your own train* is moving backwards instead. This ego-motion illusion typically breaks down as soon as additional cues (e.g., from looking outside a window on the other side or missing vibrations from the train motion) tell you that it is actually the other train that is moving. Such visually induced ego-motion illusions have long been studied in fundamental research (e.g., [3],[4]). The typical apparatus to investigate this striking phenomenon consists of a rotating drum which is painted with simple geometrical patterns like black and white vertical stripes. Investigating vection, however, can have important implication for the emerging field of virtual reality (VR) and multi-media applications, where one would often wish to convey a convincing sensation of self-motion to the user by just presenting a visual motion, without having to physically move the observer.

To bridge the gap between fundamental research and recent computer-based applications, a high-end virtual reality setup was used to present the moving visual stimuli. This had the additional advantage of enabling us to easily present not only simple and abstract geometrical patterns, but also photorealistic renderings of a natural scene. Using such stimuli for vection research has, to the best of our knowledge, hardly been investigated so far, except for recent studies by Steen & Brockhoff [5] and Riecke et al. [6][7].

So, how can we link vection research to computer-mediated applications? One of the unsolved challenges of many VR applications is to prevent users from getting lost in virtual environments; this happens much more often in virtual reality than in comparable real world situations. It seems reasonable to assume that good spatial orientation in VR critically depends on convincing ego-motion perception, which in turn requires effective ego-motion simulation. That is, any measure that increases the convincingness and intensity of visually induced ego-motion illusions without restricting the user unnecessarily would be beneficial. Furthermore, reducing the time needed until users begin experiencing ego-motion ("vection onset time") when presented with a moving visual stimulus would be advantageous.

We know from the literature that fixating on a stationary object increases the ego-motion illusion [1], especially if the fixation point is perceived as being stationary and in the foreground of a moving (background) stimulus [2][8]. Conversely, stationary objects behind the moving stimulus decrease vection [9]. In those studies, however, observers were explicitly instructed to focus and fixate on those targets. This would be comparable to fixating on some stains on a train window or the windshield of a car. From an ecological perspective, such fixation seems rather unnatural. This is especially true when one is the driver, where it might even be dangerous to pay attention to, for example, some dirt on the windshield instead of the road you want to follow.

1.1 Vection facilitation without fixation point

In this paper, we investigated whether a vection-facilitating effect might also occur under more natural conditions, i.e., under free viewing conditions and without any need to fixate on any nearby object. Furthermore, we attempted to facilitate vection in an unobtrusive manner, such that most participants would not even notice the manipulation.

To study this, the surface and reflection properties of the video projection screen that was used to present the vection stimulus were modified for one experimental group to include some subtle scratches and marks (see Figure 2). Even if participants did notice these marks, we believe that they would most likely oversee it as being an accident instead of an experimental manipulation. Furthermore, participants in our study were asked to view the stimulus in a normal and relaxed manner. They were further instructed to neither stare through the screen nor to fixate on any position on the screen (i.e., not to suppress the optokinetic reflex (OKR)).

1.2 Relation between vection and spatial presence

A recent study in VR demonstrated that vection can be closely related to spatial presence (i.e., the feeling of “being there”) and involvement in the simulated scene [6]. In that study, spatial presence was manipulated by gradually scrambling a photorealistic image of a natural scene. In the present study, however, there seems to be no obvious reason to expect that the additional marks on the projection screen should improve spatial presence and involvement. Intuitively, one might even expect a degradation of presence due to the decreased simulation fidelity. We believe, however, that it is possible that having the marks on the screen will be accompanied by higher spatial presence: As illustrated in Figure 7, the marks on the screen may enhance the sensation of ego-motion (just as a fixation point would), which in turn might lead to an increase of spatial presence and involvement.

1.3 Benefits

Any success in increasing vection and spatial presence through subtle modifications would be of considerable interest both for fundamental research and ego-motion simulation applications: To the best of our knowledge, facilitating vection and spatial presence in an unobtrusive manner and without restricting eye movements has never been shown in the literature. From an applied perspective, subtle vection-facilitating measures that allow for unrestricted eye movements could have important implications for the design of lean and elegant ego-motion simulators both for industry and consumer market.

2 Methods

2.1 Experimental design

Twenty-two naive participants were paid to participate in the study. All participants had stereo vision and normal or corrected-to-normal visual acuity. These 22 participants were randomly assigned to two groups: Twelve participants were presented with the unmarked screen, and ten participants were presented with the marked screen. For the latter condition, a different projection screen of identical size was used that contained hardly noticeable marks in the periphery of the projection screen (see Figure 2). Marks were located at the upper left part of the screen. Apart from the marks, the screens were identical in terms of material (Forex), size, and reflection properties. That is, any potential difference in results between the two screens should be attributed to the minor scratches on the screen. Each participant performed 16 trials, consisting of 4 repetitions of two different rotation velocities (20°/s vs. 40°/s, randomized) x 2 turning directions (left vs. right, alternating). This experimental design is summarized in Table 1.

	Varied between participant	Varied within participant		
Parameter	Screen homogeneity	Velocity [°/sec]	Turning direction	Repetitions
Values	Unmarked vs. marked	20, 40	Left/right	N.a.
# Values	2	2	2	4

Table 1: Experimental design

2.2 Stimuli and Apparatus

Participants were comfortably seated at a distance of 1.7m from a curved projection screen (1.68x1.42m, curvature radius: 2m) on which the rotating visual stimulus was displayed (Figure 3). The image was projected using a JVC D-ILA DLA-SX21S video projector with 1:1 optics. The projected image had a resolution of 1400x1050 pixels and was corrected for the curved screen geometry. Due to the D-ILA projector, the pixel rasterization was practically invisible. The visual stimulus consisted of a photorealistic view of the Tübingen market place that was generated by wrapping a 360° roundshot around a virtual cylinder (Figure 1). Circular vection was induced by rotating the stimulus around the vertical axis of the subject. Visibility of the surrounding room was prevented using black curtains. Furthermore, spatial auditory cues were masked by the sound of several layers of flowing water that was played through active noise-canceling headphones (Sennheiser HMEC 300) that participants wore throughout the experiment. Responses were collected using a force-feedback joystick that was mounted in front of the participants at a comfortable distance.

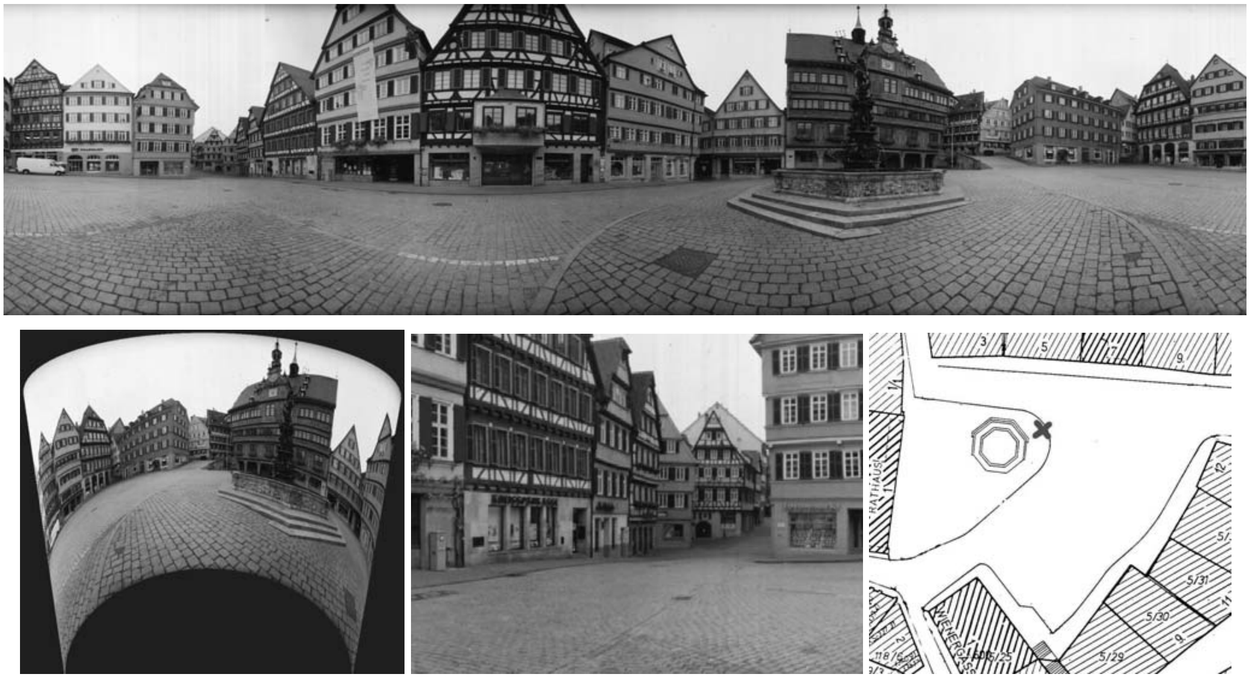

Figure 1: *Top:* 360° roundshot of the Tübingen Market Place. *Left:* Roundshot model of the Tübingen market place, wrapped around a virtual cylinder. *Middle:* For the experiments, the simulated viewpoint was centered in the cylinder, yielding an undistorted 54°x40.5° view of the Tübingen market place. *Right:* Bird's eye view of market place. The viewpoint is indicated by the cross.

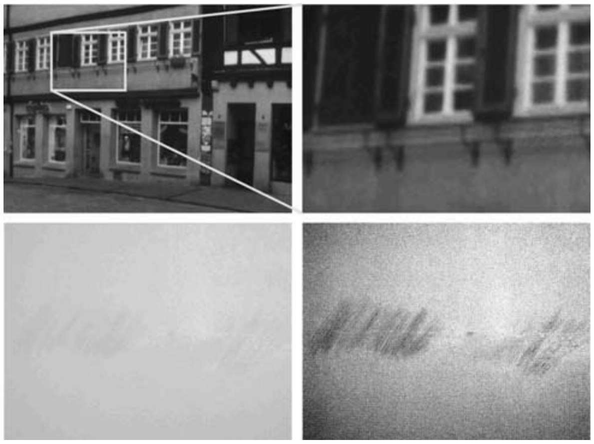

Figure 2: Top left: View of the projection screen displaying the market scene. The marks are located at the upper-left part of the screen, as illustrated by the close-ups (top right and bottom). Bottom: Close-up of the same region as above (right), but illuminated with plain white light to illustrate the marks. Left: The original photograph demonstrating the unobtrusive nature of the marks (diagonal scratches). Right: Contrast-enhanced version of the same image to illustrate the marks.

Figure 3: Participant seated in front of curved projection screen displaying a view of the Tübingen market place. The simulated FOV matched the physical FOV of 54°x40.5°.

2.3 Procedure

Experimental trials were initiated by participants' pressing a button on the joystick, upon which the static image started rotating clockwise or counterclockwise around the vertical axis with constant acceleration for 3s. Maximum rotational velocities were 20°/s and 40°/s. The maximum duration of constant velocity rotation was 60s after which the stimulus decelerated at a constant rate for 6s. Participants were instructed to pull the joystick in the direction of their perceived self-motion as soon as it was sensed.

Vection was quantified in terms of five dependent variables: The time interval between the onset of stimulus rotation and the first deflection of the joystick indicated the **vection onset time** and was the primary dependent measure. Participants were also asked to pull the joystick more the stronger the perceived self-motion was; this allowed us to record the time course of **vection intensity** (joystick deflection). This continuous recording allowed us to collect two more dependent measures: The time when 50% of the maximum joystick deflection (vection intensity) was reached (named **50% vection onset time**), and the **time between vection onset and maximum vection** reported by the participant in each trial.

The rotation of the stimulus stopped automatically if maximum joystick deflection was sustained for 10s (otherwise it continued for 60s) to reduce the potential occurrence of motion sickness. Finally, at the end of each trial participants were asked to provide a **"convincingness" rating** of perceived self-motion by moving a lever next to the joystick to select one of the 11 possible values of a 0-100% rating scale. The value of 0 corresponded to "no perceived motion at all" (i.e., perception of a rotating stimulus and a stationary self) and that of 100 to "very convincing sense of vection" (i.e., perception of a stationary stimulus and a rotating self).

Between trials, there was a pause of 20 seconds to reduce potential motion aftereffects. In order to familiarize participants with the setup, a practice block containing 4 trials preceded the experimental blocks. Furthermore, because none of the participants had experienced vection in the laboratory before, they were exposed, prior to beginning the practice block, to a vection stimulus for about 2 minutes or until they reported a strong sense of ego-motion.

Participants were instructed to watch the stimuli "as relaxed and naturally" as possible. They were also told to neither stare through the screen nor to fixate on any position on the screen (in order not to suppress the optokinetic reflex (OKR)). Instead, they were instructed to concentrate on the image in the central part of the projection screen. The marks on the screen were not mentioned to them until after the experiment. In fact, only one of the participants reported having noticed the marks in a post-experiment interview.

We did not use any fixation point, even though it is known that a fixation point reduces vection onset times [1]. The main reason was that from an applied perspective for ego-motion simulation, we were interested in investigating how one can induce convincing ego-motion sensation under natural viewing conditions. Moreover, not fixating also reduced the perceived flicker and ghost images due to the 60 Hz projection: Fast motions like rotations above 60°/s produce strong flicker and ghost images if the eyes fixate one point and do not follow the image motion. For example, a single vertical line translating sideways is seen as multiple flickering lines as it moves across a fixation point.

3 Results

3.1 Vection measures

The behavioral data for the five dependent variables are summarized in Figure 4. A first glance at Figure 4 reveals a considerable influence of the marks on the screen for all dependent measures: Vection onset times and 50% vection onset times were both about 2-3 times smaller with the marked screen. The time between vection onset and maximum vection reached was also considerably decreased due to the additional marks on the screen. Furthermore, both convincingness ratings and vection intensity were clearly increased.

To quantify these effects, a set of repeated-measures ANOVAs was computed for the five dependent variables using a 2 (rotation velocity: 20° vs. 40°/s, within-subject) x 2 (screen type: unmarked vs. marked, between-subject) factorial design. The results of the ANOVAs are summarized in Table 2. The vection-facilitating effect of the additional marks on the screen proved highly significant for all dependent measures. Likewise, increasing the stimulus velocity from 20°/s to 40°/s resulted in a highly significant increase in vection (reduced onset times and increased intensity and convincingness ratings). The effects of the marks on the screen were more pronounced for the slower rotations, as indicated by significant interactions (see Table 2).

3.2 Presence Questionnaires

At the end of the experiment, each participant rated the presence in the simulated scene using the 14-item Igroup presence questionnaire (IPQ) by Schubert, Friedmann, & Regenbrecht [10]. The questionnaire results are summarized in Figure 5. In our sample, the IPQ showed high reliability (Cronbach's $\alpha = .939$).

Furthermore, participants completed a simulator sickness questionnaire (SSQ) before and after each session [11]. As expected, the simulator sickness ratings were somewhat higher after the experiment, but all participants felt comfortable finishing the experiment.

An additional presence susceptibility questionnaire (unpublished), which is supposed to measure a person's general susceptibility to presence, did not show any clear results or correlations with any of the vection measures. In the following, only the results form the IPQ presence questionnaire will be discussed.

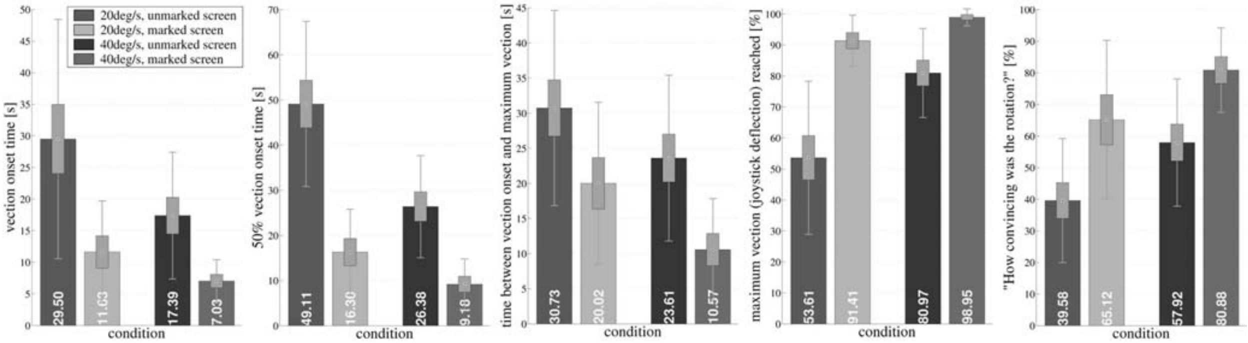

Figure 4: Plotted are the means of the five dependent variables for the four experimental conditions. The left and right pair of bars in each plot represent the low and high velocity conditions (20°/s and 40°/s, respectively). Data for the unmarked and marked screen are represented by the darker left and lighter right bar of each pair of bars, respectively. Boxes and whiskers depict one standard error of the mean and one standard deviation, respectively. Note the considerable vection-facilitating effect of the additional marks on the screen.

Dependent variable	Independent variable					
	Marked vs. Unmarked screen		Stimulus velocity		Interaction	
	F(1,20)	p	F(1,20)	p	F(1,20)	p
Vection onset time	14.45	0.001**	38.07	0.000***	6.01	0.024*
50% vection onset time	22.05	0.000***	60.12	0.000***	4.62	0.044*
Time between vection onset and maximum vection	5.15	0.034*	14.40	0.001**	0.001	0.972
Vection intensity	20.41	0.000***	51.19	0.000***	5.75	0.026*
Convincingness	9.95	0.005**	44.24	0.000***	0.007	0.933

Table 2: ANOVA results for the two factors rotation velocity (20°/s vs. 40°/s, within-subject) and screen type (unmarked vs. marked, between-subject). Both factors showed significant main effects for all dependent measures.

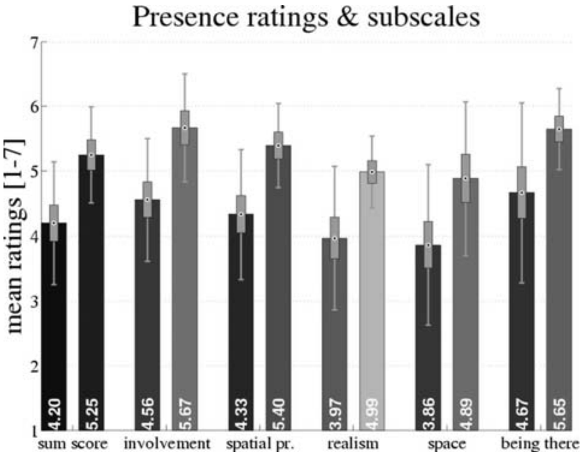

Figure 5: Presence ratings and subscales for the unmarked screen (darker bars) and marked screen (lighter bars). The mean sum score over all 14 items (left pair of bars) was split up into four subscales: involvement/attention, realism, space, and "being there". The latter three subscales were merged into the compound scale spatial presence. Note the higher presence ratings for the marked screen as compared to the unmarked screen for all presence measures.

Individual aspects of presence were investigated by analyzing the sum score (mean over all 14 items) as well as the individual subscales. Those consisted of an involvement/attention subscale (4 items), and the subscales "being there" (1 item), space (5 items), and realness (4 items). Motivated by the results of a factor analysis by Riecke et al. [6], the latter three subscales were combined to form a spatial presence compound scale (10 items) (see Figure 5).

3.3 Correlations between presence ratings and vection measures

To investigate the relation between the subjective presence ratings and the vection measures, a set of paired-samples correlation analyses were performed between the three main vection measures (vection onset time, convincingness, and vection intensity) and the presence scores. Table 3 summarizes the paired-samples correlations (r) and the corresponding p-values. The convincingness ratings showed significant positive correlations with the overall presence score as well as all subscales. Vection onset time, however, correlated significantly only with the involvement/attention subscale, and marginally with the presence sum score (p=.078). The negative sign of the correlation means that higher attention and involvement in the simulated scene was associated with shorter vection onset times.

		behavioral measures		
		onset time	convincingness	vection intensity
questionnaire measures				
presence rating	r	-.383	.724**	.423*
(14 items)	p	.078	.000	.050
subscale involvement	r	-.502*	.601**	.411
(4 items)	p	.017	.003	.057
spatial presence	r	-.275	.699*	.377
(10 items)	p	.215	.000	.083
subscale presence	r	-.147	.649**	.354
(1 item)	p	.515	.001	.106
subscale space	r	-.247	.700*	.360
(5 items)	p	.217	.000	.100
subscale realness	r	-.280	.627**	.360
(4 items)	p	.515	.002	.099

Table 3: Correlations between the three main vection measures and the IPQ presence questionnaire.

Neither spatial presence nor any of its subscales showed any clear correlation to the vection onset time. Vection intensity was only marginally positively correlated to the presence ratings ($.05 \leq p \leq .1$), with a tendency towards higher correlations for the intensity/attention subscale than for the spatial presence-related items.

4 Discussion & Conclusions

4.1 Vection-facilitating effect of marks on the screen

The comparison between the marked and unmarked screen showed a clear vection-facilitating effect for the marks in the periphery of the projection screen. The magnitude of the effect is rather striking and comparable to results obtained by a fixation point [1]. How can the effect found in this study be explained?

It has been known that both static fixation points and static foreground stimuli can facilitate vection [1][2]. This has been explained by an increased relative motion on the retina. The novel finding from our study is that this effect occurs even if the stationary objects (or marks) are hardly noticeable - only one participant reported having noticed the marks when participants were asked whether they noticed anything special about the experimental setup. In addition, observers in our study were instructed to view the stimulus in a normal and relaxed manner, without staring through the screen or fixating on any static point. Even though we did not record eye movements, we can infer that participants did in fact not fixate on the screen or stare through it; if they would have done so, they would have perceived multiple images due to the digital projection, which they did not. Hence, our result cannot be simply explained by an increase in the relative motion on the retina.

Nakamura and Shimojo [2] showed that vection can be facilitated if the moving visual stimulus is being perceived as background motion, that is, as being behind a static foreground object that participants fixated on. In the present study, however, there was no physical foreground-background or depth-separation between the static marks on the screen and the moving scene presented on the same screen. Furthermore, participants did not focus on any static object. Instead, they typically followed the moving stimulus via smooth pursuit. Hence, the foreground-background explanation cannot account for the vection-facilitating effect of subtle marks on the screen as it does not apply to this study.

So far, we can only speculate about the underlying processes. We propose that the hardly noticeable marks might provide some kind of subtle stable reference frame with respect to which the moving stimulus is being perceived. Even though there was no physical depth separation whatsoever between the marks on the screen and the visual motion stimulus presented on the same screen, participants might somehow have attributed the marks to the foreground, much like stains on a cockpit window, and the projected stimuli as moving with respect to that cockpit.

A study by Lowther and Ware [12] reported similar vection facilitation due to a stable foreground stimulus. In a vection study in VR, they overlaid a 5x5 grid on a large flat projection screen which was used to present the moving stimuli. The additional grid reduced vection onset times by almost 50%. Note that Lowther and Ware's grid extended over the whole screen and was clearly visible, which is a major difference to the marks used in the current study: They were barely noticeable (only one participant was able to report them) and covered only a small portion of the peripheral FOV. Nevertheless, these subtle marks facilitated vection consistently in all dependent variables, and the effect size was even stronger than for the clearly visible grid by Lowther and Ware [12].

Further studies are needed to corroborate the proposed explanation that the marks on the screen might provide some kind of subtle foreground reference frame that influences self-motion perception. If that was true, it would have important implications for the design of convincing ego-motion simulators, especially if participants would not have to be aware of the manipulation. However, further studies are needed to better understand this phenomenon and corroborate the main findings.

4.2 Velocity effect on vection

The vection literature reports typically no systematic influence of stimulus velocity on vection onset time. For example, Brandt and colleagues [13] reported no systematic effect of stimulus velocity on vection onset time. Kennedy et al. [11] reported no overall velocity effect, only a small increase in vection onset time for the slowest velocities used (20°/s). Those studies used optokinetic drums with full-field stimulation.

The present study, however, demonstrates a clear vection-facilitating effect of increasing the velocity. This is interesting, as doubling the velocity also doubled the acceleration, yielding a larger visuo-vestibular conflict, which is typically assumed to decrease vection. Many factors might have contributed to the different findings, including the photorealistic scene used, the relatively small field of view, and the usage of VR technology. One could for example argue that for the higher stimulus velocities, attention was drawn more towards the edges of the display. As a stable foreground stimulus as well as occluding foreground edges are known to enhance vection [2][3][9][12][14], this might explain the observed velocity effect. This would also explain why typically no velocity effect was found for full-field stimulation in optokinetic drums that do not have any screen boundaries.

4.3 Relation between vection and presence

The observed pattern of correlations between presence and vection measures points towards an interesting asymmetry: While the online measures of vection onset time (and to some degree also vection intensity) were more closely related to the involvement/attention aspect of overall presence, the subjective convincingness ratings which followed each trial were more tightly related to the spatial presence-related aspects of overall presence. This differential interrelation suggests a two-dimensional structure of presence with respect to ego-motion perception: Attentional aspects or involvement (e.g. awareness of real surroundings of the simulator vs. the simulated environment) on the one hand and spatial presence on the other hand.

In a recent vection study in a comparable VR setup, we attempted to modulate presence in the simulated scene directly by reducing the scene consistency gradually through scene scrambling [6]. This manipulation also decreased vection considerably, and a clear correlation between the degradation of presence and vection was found. One could hypothesize that presence (or other top-down factors) in that study actually mediated vection, in the sense of high presence improving vection (see Figure 6).

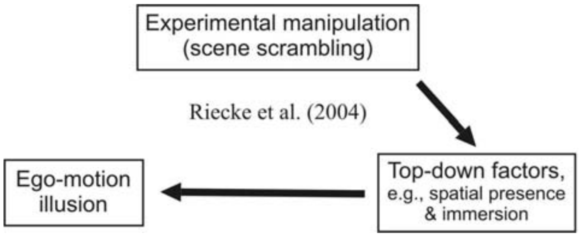

Figure 6: The study by Riecke et al. [6] suggests that top-down factors like spatial presence and involvement can mediate the visually-induced ego-motion illusion.

This might be understood in the context of the “presence rest frame hypothesis” proposed by Prothero and colleagues [15]. According to this hypothsis, “the sense of presence in an environment reflects the degree to which that environment influences the selected rest frame”. The selected rest frame is defined as the chosen subjective coordinate system with respect to which positions, orientation, and hence also motions are judged. Thus, motion of what is considered to be the selected rest frame may result in illusory self-motions (vection). According to this hypothesis, the consistent scene in [6], which induced higher presence ratings than any of the scrambled (inconsistent) stimuli, might have been more readily accepted as the selected rest frame. Consequently, the effect on the self-motion illusion should be stronger, which was confirmed by the experiment by Riecke et al. [6].

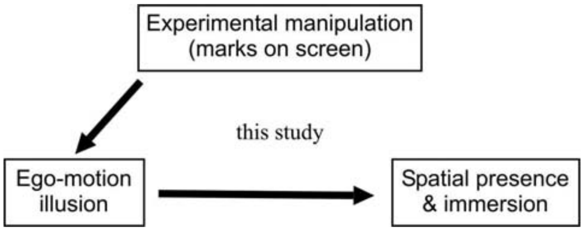

Figure 7: The current study suggests that the visually induced ego-motion illusion (vection) might have mediated spatial presence and involvement.

In the present study, there seems to be no theoretical reason to expect that spatial presence and involvement should be *directly* enhanced by the additional marks on the projection screen. Rather, one might expect a degradation due to the decreased simulation fidelity. Nevertheless, the additional marks on the screen did considerably increase spatial presence and involvement. It seems possible that the increase in spatial presence was mediated or caused by the increase in the ego-motion illusion (see Figure 7).

This sheds a novel light onto the nature of spatial presence and involvement and its relation to ego-motion perception: The study by Riecke et al. [6] suggests that spatial presence and involvement can mediate the visually-induced ego-motion illusion (see Figure 6), whereas the current results suggest that the opposite might also occur: That spatial presence and involvement can themselves be mediated by the visually-induced ego-motion illusion, as is sketched in Figure 7.

4.4 Outlook and applications

Compared to the traditional approach in circular vection studies that uses rotating optokinetic drums, the present study demonstrates that vection can indeed be reliably induced and studied using a virtual reality setup. The relatively large vection onset times without the additional marks on the screen can probably be explained by the rather small field of view used in this study, compared to full-field stimulation in optokinetic drums. Using digital display technology for presenting moving stimuli has the drawback of presenting individual images with a limited update rate (here with 60Hz) instead of a truly continuous motion like with optokinetic drums. This might impose problems and artifacts like flicker and ghost images if participants would focus on any stationary fixation point. As this study demonstrates, however, convincing ego-motion illusions with quick vection onset can indeed be reliably induced in a VR simulator in a non-obtrusive way, without any explicit fixation and under natural, relaxed viewing conditions.

This finding yields important implications for motion simulator design, because from an applied perspective, one wants to achieve realistic ego-motion simulation without restricting eye movements. Further research will investigate how such subtle, unobtrusive vection-facilitating measures can best be included in a consistent and ecologically valid motion metaphor. One application could be to design a motion simulator with stains and dirt on the (physical or simulated) windshield. As this study strongly suggests, such a simple and subtle modification would increase the strength and convincingness of the self-motion illusion as well as presence and involvement in the simulation without imposing unnatural constraints on users' behavior.

Prothero [15] proposed in the context of his presence rest frame hypothesis that vection and presence in the simulation should be tightly intertwined, if not causally linked. This was supported by the current study and other recent vection experiments by Riecke et al. [6][7]. This suggests that the joint measurement of vection and presence is a promising approach towards a deeper understanding of the underlying factors for both vection and presence. Further studies, however, are required to provide a conclusive answer about the exact relation between the two phenomena.

5 Acknowledgements

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