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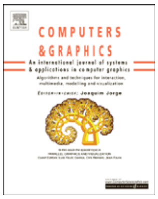

Technical Section

Circular, linear, and curvilinear vection in a large-screen virtual environment with floor projection

Laura C. Trutoiu [a,b,*], Betty J. Mohler [a,**,1], Jörg Schulte-Pelkum [a], Heinrich H. Bülthoff [a]

[a] Max Planck Institute for Biological Cybernetics, Germany
[b] Carnegie Mellon University, USA

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ABSTRACT

Vection is defined as the compelling sensation of illusory self-motion elicited by a moving sensory, usually visual, stimulus. This paper presents collected introspective data, user discomfort and perceived speed data for the experience of linear, circular, and curvilinear vection in a large-screen, immersive, virtual environment. As a first step we evaluated the effectiveness of a floor projection on the perception of vection for four trajectories: linear forward, linear backward, circular left, and circular right. The floor projection, which considerably extended the field of view, was found to significantly improve the introspective measures of linear, but not circular, vection experienced in a photo-realistic three-dimensional town. In a second study we investigated the differences between 12 different motion trajectories on the illusion of self-motion. In this study we found that linear translations to the left and right are perceived as the least convincing, while linear down is perceived as the most convincing of the linear trajectories. Second, we found that while linear forward vection is not perceived to be very convincing, curvilinear forward vection is reported to be as convincing as circular vection. In a third and final experiment we investigated the perceived speed for all different trajectories and acquired data based on simulator sickness questionnaires to compute a discomfort factor associated with each type of trajectory. Considering our experimental results, we offer suggestions for increasing the sense of self-motion in simulators and VE applications, specifically to increase the number of curvilinear trajectories (as opposed to linear ones) and, if possible, add floor projection in order to improve the illusory sense of self-motion.

1. Introduction

Vection refers to the compelling sensation of illusory self-motion elicited by a moving visual stimulus [1]. In daily life, vection may be experienced when waiting in a car at a stop light and observing another car in close proximity starting to move. Another example of naturally occurring vection is experienced while seated in a train and watching another train moving on an adjacent track. The stationary observer in these cases experiences a very compelling sensation of self-motion based solely on visual information.

According to the perceived motion, self-rotation or self-translation, researchers usually differentiate between two types of vection: circular and linear, respectively. While, for most observers, circular vection (around the vertical axis) is easily achieved in a laboratory setting, forward and backward linear vection is often much less convincing. When moving through the world different optical flow patterns are experienced according to the different directions of travel. Most studies on vection have focused on circular vection around the yaw axis, and fewer studies have addressed linear vection. To our knowledge, there is only one study that has so far investigated curvilinear vection [2]. Therefore, one of the aims of the current research is to present a systematic comparison of linear, circular, and curvilinear vection in a single experimental setting.

From a practical perspective, motion simulators would benefit from understanding how to improve the experience of vection. Linear motion, in particular, is predominant in human navigation and therefore inducing linear vection would benefit numerous applications. Especially, if within the same environment vection for a particular trajectory proves more compelling, then applying the visual information from the more compelling trajectory to a weaker one may help enhance a weaker self-motion experience. From a psychological perspective, vection has been investigated as

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[*] Also to be corresponded.

[**] Corresponding author at: Max Planck Institute for Biological Cybernetics, Germany. Tel./fax: +49 7071 601.

E-mail addresses: laura.trutoiu@tuebingen.mpg.de (L.C. Trutoiu), betty.mohler@tuebingen.mpg.de (B.J. Mohler).

URL: http://www.kyb.mpg.de/~mohler (B.J. Mohler).

[1] Human Perception, Cognition and Action Department, Spemannstr. 38, D-72076 Tübingen, Germany.

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a means to understand how the brain processes both visual and vestibular information [3,4]. Mainly circular yaw vection has been used for this purpose so far.

The focus of this research is twofold: first to evaluate our semi-spherical projection setup and determine the influence of floor projection and to provide a systematic comparison between linear (forward-backward, up-down, left-right), circular around the yaw axis (left/right rotations), and both a slow and fast curvilinear vection experience. We consider factors such as the structure of the optic flow, where the relevant visual information for a particular type of vection is presented, the perceived speed of the trajectories and the reported discomfort level of the trajectories. Using a large-screen VE setup (220° horizontal and 165° vertical field of view—see Fig. 2) we simulated 12 different trajectories in a random star field environment as well as four trajectories (circular and linear vection with and without floor) in a realistic model of a virtual town.

Initially we evaluate our experimental setup, a large field of view, immersive, projection screen that was recently upgraded to semi-spherical projection environment by adding a floor projection. In Experiment 1 we studied the influence of the floor projection on perceived linear and circular vection using the realistic virtual town model (see Fig. 3, for setup and Figs. 1 and 5 for stimulus). This experiment provided a baseline from which we could then investigate more complex factors (i.e. different motion trajectories which result in different optic flow). In order to allow the user navigation in different directions (including up and down) we used an abstract star field environment. Experiment 2 presents these results. Finally, in order to draw more insightful conclusions from these results we conducted a third experiment. For a subset of the twelve different trajectories evaluated in Experiment 2 we measured perceived speed and quantified a relative discomfort factor from simulator sickness questionnaires. We conclude by providing suggestions for improving the illusion of self-motion in simulators and virtual environment applications. The next section provides a brief overview of the relevant aspects of vection that have been investigated so far.

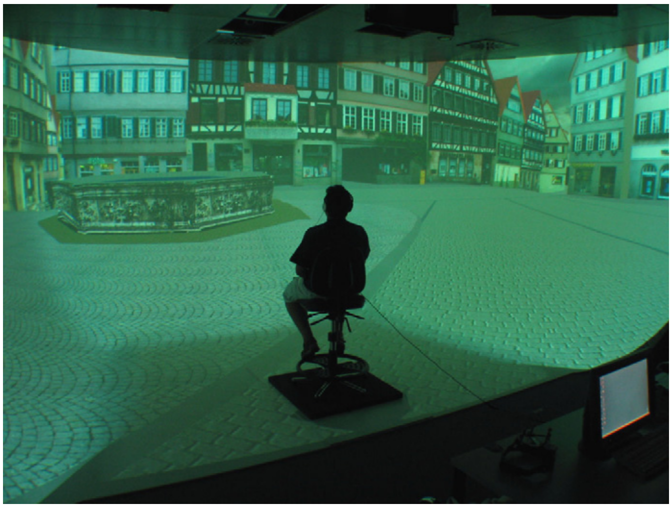

Fig. 1. The Pano Lab: semi-spherical projection screen with 220 horizontal by 165 vertical field of view (FOV).

2. Background

Vection studies have been performed in a variety of conditions and setups. The first experiments on vection in a laboratory setting were performed by Mach in 1875 using an optokinetic drum consisting of a rotating cylinder with black and white stripes [5]. In an optokinetic drum participants either sit or stand at the center of the surrounding rotating apparatus and they usually experience a very compelling illusion of rotation. The experimental setups have since diversified and extended to include television screens, projectors, and fully immersive virtual environments. The stimuli used to induce vection also ranges from the classical black and white stripes of the optokinetic drum to random dot fields, bar gratings and realistic computer graphics [6–12].

Several visual display factors have been found to affect the vection experience. Initially it was believed that self-motion perception was predominantly processed in the periphery of the retina [3,13,14], but later studies demonstrated that both kinds of vection could also be induced in central vision [4,6]. A study by Palmisano [15] further claimed that both high-spatial-frequency and low-spatial-frequency mechanisms are involved in the visual perception of self-motion—with their activities depending on the nature and eccentricity of the motion stimulation. Display time, display speed, field of view, and presence or lack of edges around the display have also been found to be contributing factors in the perception of vection [16–18]. An investigation on circular vection [18] found that circular vection is stronger when you use a photo-realistic scene which contains pictorial depth cues, compared to an incoherent version of the same image that was

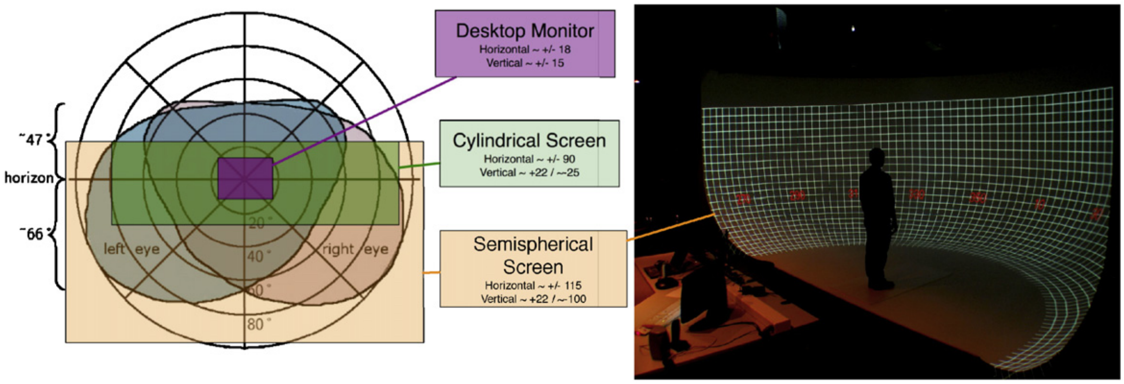

Fig. 2. User field of view in the Pano Lab. (Left) This diagram shows a comparative field of view (FOV) size for three setups (desktop monitor, semi-cylindrical projection screen and semi-spherical projection screen) relative to human field of view (elliptical shapes indicated field of view for each eye). This diagram was modified from a graphic from CHI Data Visualization (see http://www.users.cs.umn.edu/~echi/tutorial/perception2000) (Right): The right image presents the Pano Lab with a projected grid showing azimuth degrees for the horizontal FOV. The unique feature of this environment is the seamless nature of the floor projection.

scrambled so that it was not possible to recognize it as a scene anymore [19].

The structure of the optic flow, in particular, may have an influence on the perception of vection. During forward linear motion, a radially expanding optical flow field is visible. Here, the focus of expansion specifies the direction of locomotion. In one of the first linear vection studies, however, Johansson induced apparent vertical self-motion by presenting observers with random dot patterns at different eccentricities [14]. He used two parallel peripheral displays presenting lamellar optic flow patterns that we perceive during vertical linear motion. Lamellar flow is defined as uniform, homogeneous flow field without any radial component, which would be experienced if traveling up/down or left/right. For peripheral stimulation vection was reported with fields of view of as small as one degree while frontal stimulation resulted in perceived pattern motion, not self-motion. Giannopulu and Lepecq, for example, using lamellar stimulation and random grating patterns in a peripheral stimulation, compared upward/downward with forward/backward vection and found faster onset times and higher ratings for upward/downward vection [7]. In another study, Kano [20] investigated whether the advantage for upward/downward over forward/backward vection interacts with the gravitation field by having participants rate vection in upright or supine position, respectively. Results were not fully conclusive, but they indicate that both retinal and gravitational reference frames have an influence on perceived vection.

Experiments by Wolpert have shown that lamellar flow structure was more informative than radially expanding structure for the detection of changes in the speed of self-motion. In one of his experiments participants were presented with peripheral and central stimulation either perpendicular to the direction of travel (lamellar flow) or parallel to the direction of travel (radial flow). Lamellar flow structure in the side view was more informative than radial structure in the front view for specifying descent [21].

Although the phenomenon of vection has been studied in some depth for some time, there is still no conclusive understanding of how different motion trajectories (circular, linear, curvilinear), direction of motion (up/down, forward/backward, left-right), and other factors, such as display size, interact to influence the occurrence of vection.

While the different research results mentioned above all contribute interesting findings to the overall understanding of vection, it is a difficult or impossible task to make direct comparisons between the different studies due to the different display setups and different optic flow presented. Making use of our unique setup, we aimed to systematically investigate the effectiveness of adding a floor projection to a panoramic screen, and to address the issue of how different motion trajectories influence the vection response. First, we investigate the influence of the floor projection on both linear and circular vection using a photo-realistic virtual model of a town. We have reasons to believe that adding optic flow to the ground should increase vection: A study by Flückiger and Baumberger [11] showed that optic flow projected only onto the ground induced body sway reactions in observers. Furthermore, the ecological approach to perception according to Gibson argues that we are most sensitive to optical flow on the ground, since we evolved moving on a stable ground where most of the critical optical information is located for moving animals [22]. Second, we conduct an experiment which allows us to make a direct comparison between vection trajectories using a unique VE setup than allows for the control of visual stimuli on a large field of view. Specifically, we investigate curvilinear trajectories with the hope that the combination of linear and circular optic flow will result in a better experience of self-motion than linear alone. In a final study, we investigate the perceived speed and user discomfort with a subset of these trajectories.

3. General experiment setup and procedure

The VE setup used for all three experiments presented in this paper consisted of an immersive large-screen display and a joystick (Saitek ST200). Four JVC D-ILA DLA-SX21S video projectors with a resolution of 1400 × 1050 pixels were used to display visual stimuli on the front, sides, and floor of a custom made curved display (see Fig. 1). A river sound played through noise canceling head phones for all of the experimental blocks (see Fig. 5). For all experiments participants were seated in a chair that was adjusted so that each participants' seated eye-height was 1.7 m. Participants sat at a distance of 3.5 m from the curved projection screen which has a field of view of 220° horizontal by 165° vertical), as illustrated in Fig. 2).

For all three experiments an initial training phase consisted of the participant learning how to use the joystick to rate their vection experience and seeing all possible trajectories (and visual stimuli for Experiment 1 and 2, this training was combined). After the training phase, each participant completed twelve five minute sessions in either virtual Tübingen or the random star field stimulus depending on the experiment. Experiments 1 and 2 were run on the same group of participants and it took approximately 90 min to complete both. Experiment 3 took approximately 45 min to complete.

3.1. Vection measures

The most commonly used measures for vection are introspective measures, such as the moment when vection first occurs (vection onset time) or saturates, the perceived self-motion velocity, the intensity (perceived magnitude), and the convincingness of the illusion. For excellent overviews see [3,13,23,24]. More recently, pointing tasks were also used to investigate if perceived self-motion also results in a shift in the egocentric location of previously seen targets [25].

In each experiment, we measure section onset (initial feeling of self-motion), peak time (saturated self-motion), intensity (magnitude of the experience of self-motion), and the convincingness of the illusion. During each movement participants were asked to rate the intensity of their experience of self-motion through space by adjusting a sliding scale via the joystick. For this experiment, we chose to use a slider due to its uni-dimensional properties. We did not want people to confuse the direction with their intensity of perceived self-motion. Maximum intensity of vection was also recorded as the percentage that the slider was displaced compared to the maximum possible displacement. After each trial, when the experience of vection had faded, the participants were asked to rate how convincing their own self-movement was. They used the joy-stick to rate their perceived vection on a scale from 0 to 100, where 0 is no vection experienced and 100 is the most convincing experience of vection. At the end of each trial participants had to return the slider to its starting position. When they had done this and were ready they started the next trial by pressing a joystick button. At the end of the experiment participants were debriefed for additional observations.

3.2. Participants

Twenty individuals participated in these experiments. Twelve volunteers (six males and six females) between the ages of 22 and

31 (mean 25.75) participated in both Experiments 1 and 2. In Experiment 3 there were an additional eight participants (four males and four females). All had normal or corrected-to-normal vision and fully completed the experiment. Participants were paid at standard rates.

4. Experiment 1: influence of the floor projection

4.1. *Experiment 1: three-dimensional visual stimulus—photo-realistic virtual tübingen*

The Virtual Tübingen project (see http://virtual.tuebingen.mpg.de) was motivated by the emerging need for a naturalistic, controllable environment for investigating human spatial cognition. The projects' goal was to build a highly realistic virtual model of Tübingen through which one could move in real time. This project builds on experience with Virtual Reality and Navigation gathered at the Max Planck Institute for Biological Cybernetics since the 1990s. The decision to model Tübingen as a virtual city had several motivations: The first major reason relates to the observation that the center of Tübingen has a rather complex structure: there are considerable height differences, the streets often tend to be curved and have varying width, and the houses are rather different with varying facades. This high degree of complexity provides a much more interesting environment for conducting research experiments than highly regular cities like e.g. Berlin offer. The second major reason was that we would like to achieve a high degree of visual realism, which in our case is done by combining photographs and high-quality texture mapping with three-dimensional geometry. The process of making photographs of houses and streets as well as gaining access to architectural data was of course easiest for students to do in the local town where Max Planck for Biological Cybernetics is located.

The creation of Virtual Tübingen consisted of two processes: processing of geometry (the three-dimensional structure of the architecture) and processing of textures (the images, that is, photographs of the buildings and structures providing information about their visual appearance). For a house this means that creating the walls was separated from creating the textures that was put onto those walls. This division was motivated by the fact that by combining lower-resolution geometric data (which we had for most of the houses from architectural models of Tübingen) and high-resolution textures (which were collected by simply taking photographs) we were able to create a very realistic model of Tübingen's houses and streets.

The resulting three-dimensional model for Virtual Tübingen (200 houses and 500 × 150 m) which can now be downloaded at Google Earth was further modified for our experiments. A street that was long and straight enough had to be constructed from a long curved/crooked street to allow for a linear translation forward condition which could last for 45 s. The original marketplace in Virtual Tübingen (see Fig. 3) was used for the circular vection trials.

4.2. *Experiment 1: procedure and method*

As a first step we evaluated the effectiveness of adding a floor projection on our experimental setup by analyzing the differences in onset time and vection intensity for linear and circular trajectories with or without a floor projection. As we have pointed out in the introduction, there is empirical evidence that optic flow on the ground can have a strong influence on body sway [11]. Even though body sway and vection are somewhat different phenomena, it is reasonable to assume that they might be related. There is also theoretical reason to believe that floor projection might be very important for self-motion simulation. According to Gibson, we have evolved moving on a stable ground surface and are tuned to pick up relevant information about orientation and self-motion from the ground [22].

This experiment consisted of a random ordering of circular and linear motion in virtual Tübingen that was presented with and without the floor projection, resulting in four experimental blocks each consisting of 8 trials. To decrease sensory conflict a small acceleration phase preceded every trial during this session. The acceleration phase of each movement took 0.5 s to reach full velocity. The maximum linear velocity was 8 m/s and the maximum angular velocity was $30^\circ/\mathrm{s}$. These acceleration and velocity rates were chosen prior to conducting the experiment based on subjective experience of vection and previous results [17] (Fig. 4).

The visual stimuli consisted of a three-dimensional virtual model of the town of Tübingen (see Figs. 1 and 5). Translation movements in virtual Tübingen were presented by motion down a 280 m long straight street (see Fig. 5) and for circular motions the scene was consistent with rotation in place at a location near the center of the marketplace square (see Fig. 1). The main experimental program was run using veLib, an in-house VE software library, and Virtools 3.5 (Dassault Systémes, France).

4.3. *Experiment 1: results*

The results from this experiment provide us with a benchmark with which we can compare all future results. Since the experimental settings, i.e. speed, visual stimuli, field-of-view, acceleration, were all chosen to maximize vection ratings, we can expect that the ratings for this experiment are as good as experimentally possible given the current knowledge in this field. Also, we can compare our results with previous results to evaluate the validity of our methodology. A repeated measures ANOVA was performed on the virtual Tübingen data and we found that the floor had a significant influence on all the measures for linear vection, but not for circular vection (*Linear*: convincingness, $F = 23.499$, $p<0.01$; onset time, $F = 19.699$, $p<0.01$; maximum intensity, $F = 66.136$, $p<0.01$). All further statistical results refer to multiple planned comparisons (Tukey-HSD). Using the model of virtual Tübingen as our visual stimulus, all linear vection conditions were less convincing, had lower maximum intensity, and had higher vection onset times, compared to the circular vection conditions. Forward vection where floor projection was not used was less convincing, had lower maximum intensity and had a higher vection onset time than the forward vection with the floor projection. Also, the backward vection condition without floor projection was less convincing, had a lower maximum intensity, and a higher vection onset time than the backward vection ratings with the floor. When floor projection was not used backward vection was significantly more convincing, the maximum intensity was significantly higher, and the vection onset time was significantly lower than for forward vection also without floor projection. This was not the case for forward and backward vection with the floor projection. All circular vection conditions had similar introspective ratings. The floor did not impact the vection onset time, the maximum intensity, or the convincingness rating for circular vection ratings.

We find results for vection in virtual Tübingen which are comparable to previous results which used the same visual stimulus [17]. We also find that the lack of projection on the floor influences only linear vection. Specifically, we find that the floor projection improves perceived linear vection induced by forward

Fig. 3. A screen capture of the market in Virtual Tübingen. A low resolution version of this model is now available for download from Google Earth (see details at http://virtual.tuebingen.mpg.de).

Fig. 4. An image from a webcam of the same vantage point of actual Tübingen (see http://www.tuebingen.de/1559_webcam.html for an updated image.)

and backward movement but does not significantly alter the circular vection experience in virtual Tübingen (see Figs. 6–8). This argues that having the projection on the floor benefits the experience of linear vection and is an important part of rotational self-motion (see Fig. 5) (Table 1).

5. Experiment 2: multiple motion trajectories

One of our main goals of the current research is to be able to make comparisons for different motion trajectories. As was explained in the background it is often difficult or impossible to make such comparisons on previous literature due to the large differences between experimental setups. Therefore, in this within subject design experiment we use 12 different trajectories where participants were asked to provide three different measures. Investigating these trajectories in one experimental setup is now possible in our Pano Lab due to the addition of the floor projection. For this experiment, the visual stimulus was a randomly generated star field that did not contain any absolute orientation or distance cues (see Fig. 9). This stimulus was chosen because it could be carefully controlled and, unlike in virtual Tübingen all trajectories were possible (i.e. up/down). The star field stimulus was projected onto all four projection screens, including the floor projection. The visual stimuli consisted of random white dots generated as point sprites randomly located within a large virtual cube (with dimensions of 3200 units). The number of stars within this cube was approximately 300,000. The cube was large enough that the far clipping plane of the viewing frustum never exceeded its limits during the different motion trajectories. Considering these parameters and the viewing frustum the projection of the point sprites ranged from 1 × 1 to 6 × 6 pixels and the density of the points on each projection screen was approximately 1000–1500 dots at any given point in time (variance based primarily on occlusion).

Twelve different trajectories were presented in six blocks (where both directions of the trajectories seen in Fig. 10 were also randomly ordered and repeated four times, resulting in eight trials per block). Each trajectory was shown for 30 s. Participants were also asked to look at the entire screen and not to fixate at any given point on the screen. The participants took short breaks between each block of the random star field stimulus and after completing the first session of the experiment they were asked to take a 5–10 min break.

5.1. Experiment 2: results

A repeated measures ANOVA was performed on the star field data and we found that left/right and forward vection were significantly less convincing than all other trajectories. They also had later onset times and lower maximum intensity (*Left*: convincing, $F = 33.903$, $p<0.01$; onset times, $F = 53.624$, $p<0.01$; maximum intensity, $F = 41.355$, $p<0.01$. *Right*: convincing, $F = 32.105$, $p<0.01$; onset times, $F = 76.20$, $p<0.01$; maximum intensity, $F = 46.729$, $p<0.01$. *Forward*: convincing, $F = 32.025$, $p<0.01$; onset times, $F = 10.975$, $p<0.01$; maximum intensity, $F = 25.146$, $p<0.01$).

5.1.1. Experiment 2 results: convincingness ratings

All further statistical results refer to the outcome of multiple planned comparisons (Tukey-HSD) which were done to compare each of the experimental conditions of interest. Convincingness ratings provide us with some interesting insights into the differences between the different trajectories. Linear left and right are significantly less convincing than all other trajectories except linear forward. Linear forward also shows a trend to be less convincing than all other trajectories, including linear backward vection. Curvilinear is significantly less convincing than fast curvilinear for all but one of the cases. Curvilinear, backward, and circular vection is as convincing as circular vection using this visual stimulus (see Table 2 and Fig. 11).

Fig. 5. Pano Lab with three-dimensional virtual town used for linear vection. The participant is always sitting in the same way and the only difference between the floor and no floor condition is that the floor projector is turned off in the latter case.

5.1.2. Experiment 2 results: vection onset time

The vection onset time appears to be consistent with the convincingness ratings and reveals several additional insights. Consistent with the convincingness ratings, linear left and right have a significantly later vection onset time than all other trajectories. Linear down has a significantly earlier vection onset time than all other linear trajectories. As expected, due to the lower speed, curvilinear has a later vection onset time than the faster curvilinear trajectory condition. In addition, linear forward has a significantly slower onset time than curvilinear faster (see Fig. 12).

5.1.3. Experiment 2 results: maximum intensity

Finally, maximum intensity is also consistent with vection onset time, and convincingness ratings. Linear left and right have a significantly lower maximum intensity than all other trajectories except for linear forward, which also has very low maximum intensity ratings. Linear down has a higher maximum intensity than linear up and linear forward. Curvilinear has a significantly lower maximum intensity than the faster version of curvilinear. Finally, linear forward has a significantly lower maximum intensity than curvilinear faster (see Fig. 13).

6. Experiments 1 and 2: a comparison

Finally, we ran multiple planned comparisons (Tukey-HSD) to compare the virtual Tübingen results to the comparable random star field results. It is important to remember that a direct perceptual comparison is not possible, since absolute distance, therefore absolute speed, is able to be retrieved from the three-dimensional town, but not from the random star field. Therefore, though we subjectively attempted to match the perceived speeds of the stimuli a more careful analysis of the optic flow and the perceived speed would need to be done before the following results could be conclusive. That being said, we find results that are consistent with previous research [18]. The overall ratings for circular vection within virtual Tübingen were greater than for the random star field. Linear vection using virtual Tübingen with the

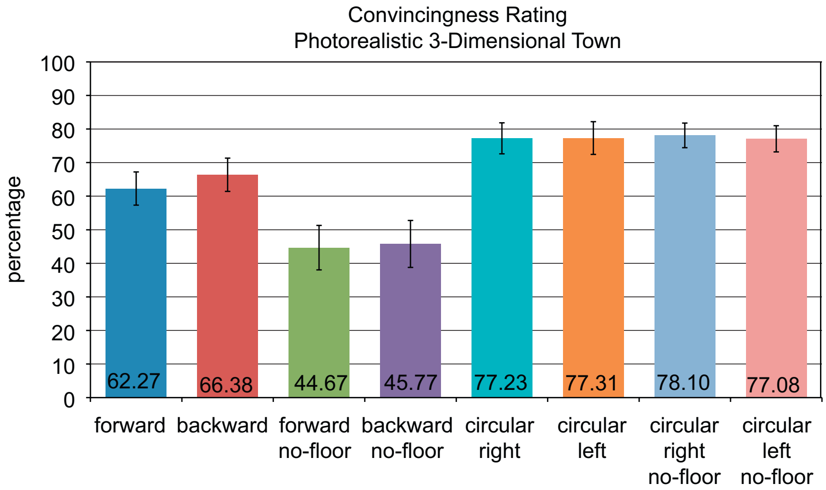

Fig. 6. Vection convincingness rating for three-dimensional town stimulus. Error bars represent ± one standard error.

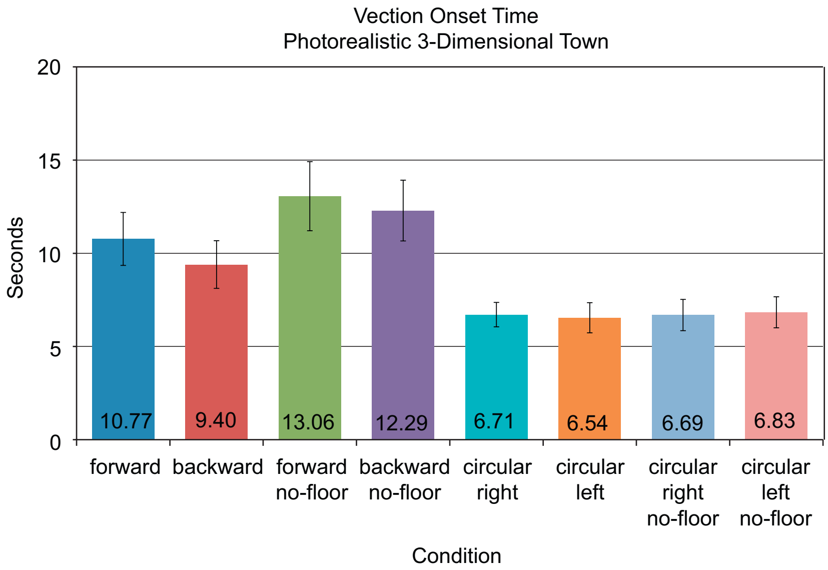

Fig. 7. Vection onset time results for three-dimensional town stimulus. Error bars represent ± one standard error.

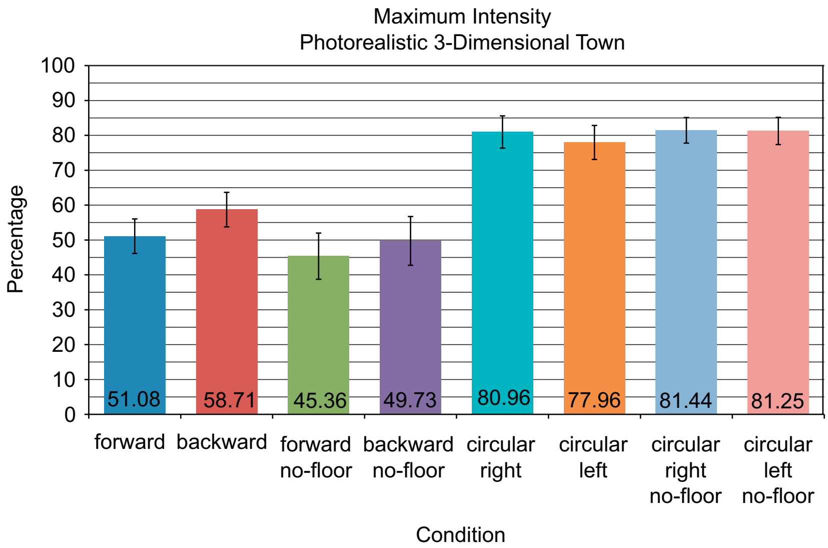

Fig. 8. Vection maximum intensity results for three-dimensional town stimulus. Error bars represent ± one standard error.

Table 1

Experiment 1 conditions listed in or order from least to most convincing (see Fig. 6).

Forward NF	Virtual town	8 m/s	z
Backward NF	Virtual town	8 m/s	z
Forward	Virtual town	8 m/s	z
Backward	Virtual town	8 m/s	z
Circ. right NF	Virtual town	30°/s	y
Circ. left NF	Virtual town	−30°/s	y
Circ. right	Virtual town	30°/s	y
Circ. left	Virtual town	−30°/s	y

For the axis of translation or rotation y is up, and z is in depth (see Fig. 10).

floor projection was significantly more convincing than linear vection in the random star field, although when compared to the same trajectory but with no floor projection these convincingness ratings did not significantly differ. However, the onset times and maximum intensity was sooner and higher, respectively, for all comparisons except when moving backwards in the random star

Fig. 9. Pano Lab with random star field used for the second experiments.

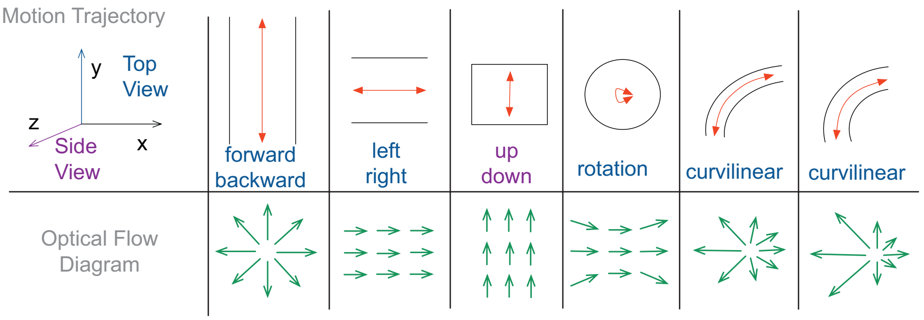

Fig. 10. Optical flow structure according to trajectory.

Table 2
Experiment 2 conditions listed in or order from least to most convincing (see Fig. 11).

Trajectory	Visuals	Self-speed	Axis
Left	Random stars	−80 units/s	*x*
Right	Random stars	80 units/s	*x*
Forward	Random stars	80 units/s	*z*
Backward	Random stars	−80 units/s	*z*
Circ. right	Random stars	30°/s	*y*
Circ. left	Random stars	−30°/s	*y*
Curv-left	Random stars	60 units/s, −15°/s	*z* *y*
Curv-right	Random stars	60 units/s, 15°/s	*z* *y*
Fast curv-right	Random stars	80 units/s, 20°/s	*z* *y*
Fast curv-left	Random stars	80 units/s, −20°/s	*z* *y*
Up	Random stars	80 units/s	*y*
Down	Random stars	−80 units/s	*y*

For the axis of translation or rotation *y* is up, *x* is horizontal, and *z* is in depth (see Fig. 10).

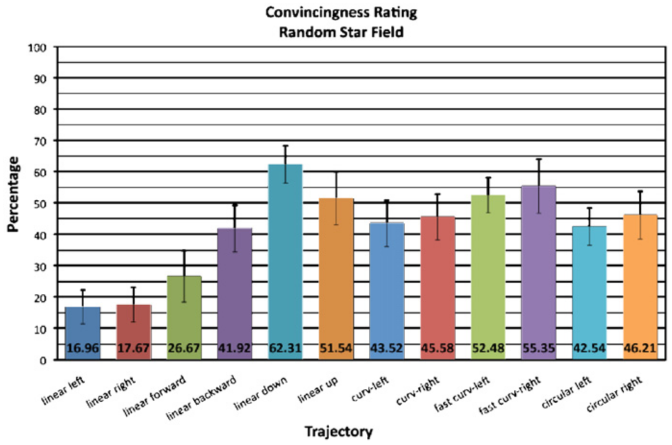

Fig. 11. Vection convincingness rating for random star field stimulus. Error bars represent ± one standard error.

field compared to moving backwards in virtual Tübingen, where the ratings were quite high even within the random star field.

Though in Experiment 2 the translational component was kept constant for each type of stimuli (8 m/s and 80 units/s), the perceived speed of the stimulus may have been different for the different trajectories. Therefore, in the next experiment we conducted an experiment which investigated whether the perceived speed was different across these conditions.

7. Experiment 3: perceived speed and discomfort factor

The goal of the third experiment was to both determine the perceived speed of a subset of the twelve trajectories and to evaluate each trajectory according to how comfortable the users were during each trial. Eight participants were paid at standard rates and asked to answer questions regarding the discomfort factor and perceived speed for most trajectories (10 out of 12, we excluded the curvilinear faster trajectory). The visual stimulus was the random star field and was projected onto all four projectors, including the floor projector.

For the visual stimuli used in Experiment 3 there was a constant linear speed component (absolute speed). However, the perceived speed may actually have been different according to trajectory since the optic flow varies across trajectories. In Experiment 3 we conducted the same design as in Experiment 2 with the addition that at the end of each block we asked participants to describe the speed and fill out a simulator sickness questionnaire. In order for participants to provide a verbal report of their perceived speed several examples of natural occurring speeds were described: walking speed as 5 km/h, running speed of 20 km/h, a car in a city as 30–40 km/h, a car on the auto bahn at 130 km/h. Though participants were encouraged to describe the speed within the limits of driving a car, some surprising observations were collected. First of all, some participants reported that due to the lack of scale in the environment and the abstract stimuli they imagined themselves as flying through space and as such they reported the speed as being considerably higher than was expected. Therefore, in our analysis we normalized the perceived speed values by dividing each of the reported speeds from one user by the maximum speed reported by that user. We then averaged across users and obtained the results presented in Fig. 14.

Since simulator sickness may significantly limit the training effectiveness of flight simulators and VE applications [23,26], we also evaluated the discomfort level generated by each of the five trajectories (forward-backward, up-down, left-right, curvilinear, and circular). A discomfort factor was associated with each condition based on a classical simulator sickness questionnaire [26] (Fig. 15).

In a previous study conducted in the same setup Riecke et al. [19] showed that, as expected, simulator sickness ratings were higher after the experiment compared to the pre-experiment data therefore we used the simulator sickness ratings only to compute the discomfort factor post experiment according to condition. This discomfort factor was calculated by adding the ratings of 16 physical symptoms associated with motion sickness for which participants could give a rating ranging from 0 (no symptom) to 3 (severe). The symptoms used were: general discomfort, fatigue, headache, eye strain, difficulty focusing, increased salivation, sweating, nausea, difficulty concentrating, fullness of head, blurred vision, dizzy, dizzy (eyes closed), vertigo, stomach awareness and burping.

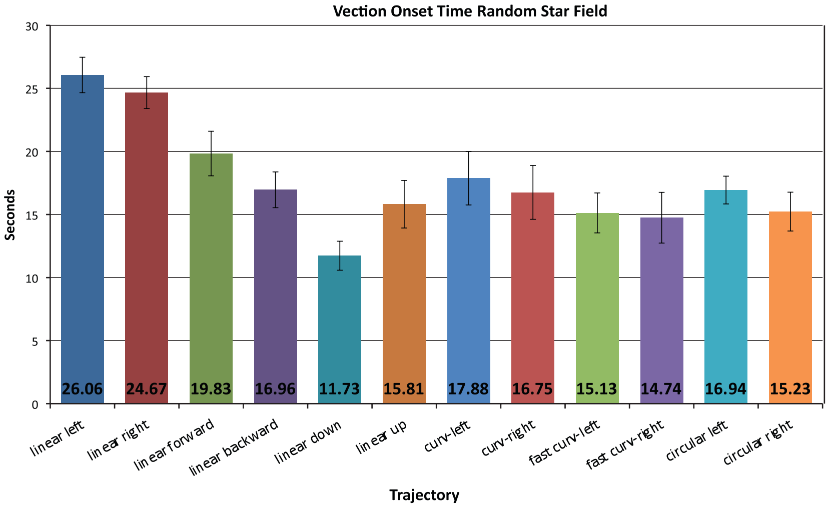

Fig. 12. Vection onset time results for random star field stimulus. Error bars represent ± one standard error.

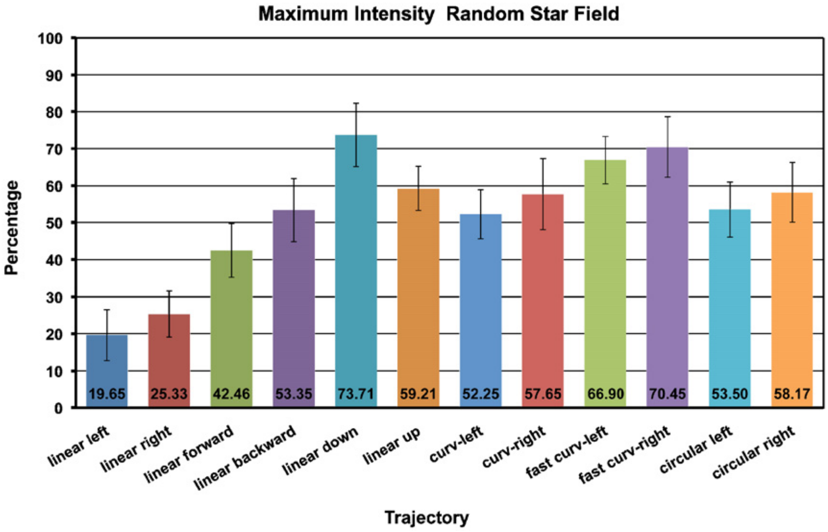

Fig. 13. Vection maximum intensity results for random star field stimulus. Error bars represent ± one standard error.

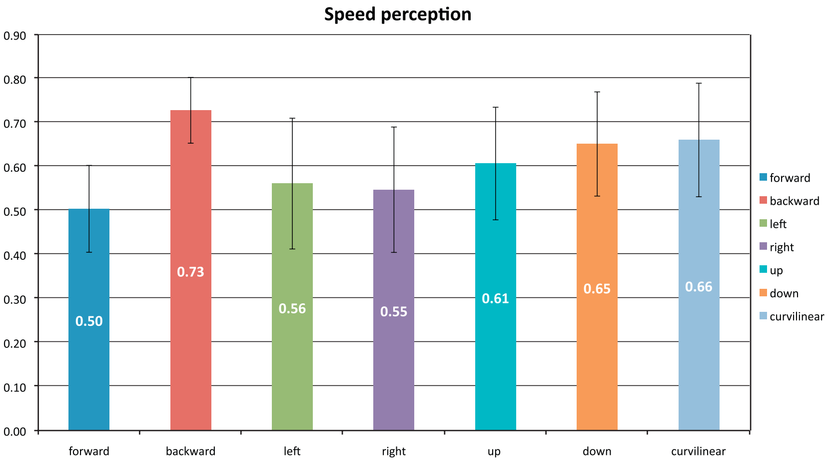

Fig. 14. Normalized speed perception results. Error bars represent ± one standard error.

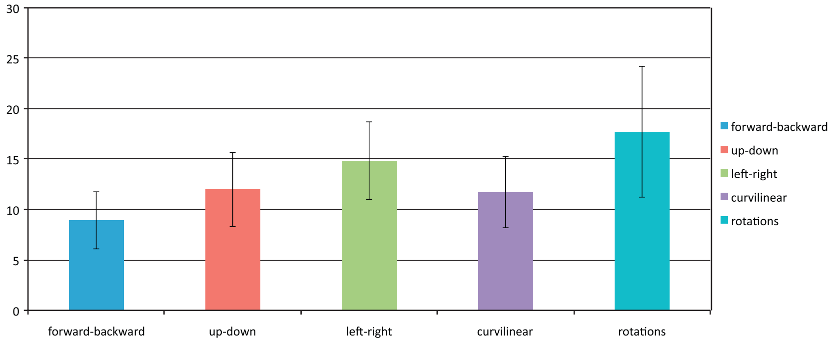

Fig. 15. Simulator sickness questionnaire results.

7.1. *Experiment 3: results*

With this particular method of evaluating perceived speed (verbal reports) we can state that the perceived speed was different between linear backward and linear forward. However linear left and right were not reported to be different than linear forward. This result does not corroborate our initial hypothesis that the difference between the high onset time for left and right trajectories compared to the other linear trajectories is due to perceived speed. We recognize the need for equating perceived speed in a continuous rather than discrete fashion by either conducting a psychophysical study or letting users adjust the speed of one trajectory until it matches a baseline condition. However, through this initial study we do not find evidence that the left and right trajectories were perceived as being slower than the other trajectories.

Furthermore, though the level of discomfort was overall relatively low (13 on a 100 scale) the discomfort factor results indicate that left–right (14.84) trajectories and circular trajectories (17.70) induce the highest discomfort level. However, this is simply a trend since no significant difference among all conditions exists. These results and several user observations have led to the development of the idea that the continuity of the illusion might be more important than how fast it is induced. Participants noticed that even though some trajectories are considerably stronger than linear vection vection for example, the illusion is not as smooth but rather suddenly switches on and off resulting in a feeling of uneasiness.

8. Discussion

The first result to discuss is the finding that of all the 12 trajectories investigated in the star field, downwards linear vection showed trends to be the most compelling stimulus. Giannopulu and Lepecq found a similar effect and explained their results by the sensitivity of the utricular vs. semi-circular canals which introduces less of a visual–vestibular conflict compared to the forward and backward self-motion [7]. In the debriefing questionnaires at the end of each block of experiments a recurring comment indicated that up/down vection intensified after participants were able to find a plausible explanation for the movement on the screens. Many of the participants reported that after thinking of being in an elevator like situation, the up/down experience of self-motion became extremely compelling. This cognitive factor however cannot be properly quantified based on the existing data. Forward and backward vection was less compelling, and leftward and rightward linear vection was the least convincing. Furthermore, curvilinear vection was found to be comparable to circular vection in all measures. Curvilinear optic flow preserves structure of the optical flow similar to rotation but still has a focus of expansion corresponding to the translation which may help orient as to the direction of movement (extra information). If circular vection is easy to achieve and linear vection does not completely disrupt the experience of self-motion, adding a rotational component to a linear path might have an additive effect. Therefore, if vection is important to a VE application then curvilinear paths, instead of only linear paths, should be used when possible.

Second, it is interesting that we found an influence of the floor projection only on linear vection. Adding the floor projection significantly increased the measures of linear vection, but not for circular vection. One possible explanation is that the floor increases immersion and the feeling of presence within the photo-realistic three-dimensional town. However, if the maximum introspective measures, for this particular stimulus, has not yet been reached for circular vection we would expect this increase in presence to also improve the circular vection experience. Another explanation is that the floor presents participants with a lamellar flow, parallel to the direction of movement. This might increase the feeling of self-motion and increase the participants' perceived speed [27]. In addition, the optic flow for linear and circular self-motion on the floor is giving very different information. Third, we found that the realistic three-dimensional model of a town induced stronger and more convincing vection than the random star field stimulus. As stated before, these comparisons need to be interpreted with caution, since low-level characteristics such as the number of contrasts, etc. largely varied, and no absolute velocity information was available in the star field. Still, this result is consistent with earlier work that found photo-realistic stimuli induce stronger vection than abstract stimuli [18]. Another possible explanation refers to presence. As previous studies have suggested [18], the realism of the scene could make people feel more present in the town environment and thus improved vection.

9. Future work

A yet not investigated avenue for vection studies refers to the continuity of the illusion. In a natural environment it is well known that vection is a transient feeling, lasting at most several seconds while the user investigates other possible explanations. In a virtual environment we can imagine that either the other non-visual sensory information needs to match to the induced motion or that the vection illusion itself needs to be strong enough to fool the user into not questioning the overall setup. How to maintain the continuity of the vection illusion remains an open question.

The changes in the direction of motion result in sharp changes in the experienced illusion. Often, participants report feeling alternate states of being in motion and being stationary and perceiving the environment move. By reporting only onset time or vection maximum intensity these sudden shifts in perception are not accounted for. In future studies, we propose to analyze the time sequence of induced vection.

Ideally, in a driving simulator, the illusion of vection would be long lasting and rapidly induced. However if a priority needs to be assigned, it may the case that having a smooth and stable experience of self-motion is more important than a fast onset time. One way to preserve the continuity of the illusion is to allow for at least partial interactions with the environment. We suspect that factors such as head motion parallax may be crucial for maintaining the sensation of self-motion. Motion parallax refers to the inverse relation between angular change and viewing distance: when an observer is in motion on a linear trajectory distant objects seem to move much slower than nearby objects. Motion parallax provides a monocular depth cue, as closer objects appear to be moving faster and further across the field of view compared to more distant objects (i.e. when driving a car the trees seem to pass by you faster than the houses in the background). Motion parallax is one of the visual cues that has received little attention with respect to vection, and in a set of future studies we hope to investigate the effect of motion parallax on the perception of the vection experienced in the various trajectories presented in this study.

During rotations all objects appear to move with approximately (due to eye disparity) the same angular velocity therefore even when presented with a three-dimensional scene no motion parallax is present during rotation. While translating through a three-dimensional environment motion parallax provides users with relative depth information. The idea that motion parallax may in part be responsible for the weaker linear as compared to circular yaw vection experience has already been proposed in a study [28] where perspective projections of a cartoon like environment (which contain motion parallax) induced faster vection than orthographic projections of the same model (equivalent with flat, two-dimensional images, with no motion parallax). In many previous studies due to the nature of the stimulus (two-dimensional displays such as black and white stripes) motion parallax is not present. This lack of an important relative depth cue for linear vection may partially explain some of reported differences between linear vection and circular vection onset times (higher, as compared to lower, respectively).

Though our research compares many different trajectories, which provides a baseline for an additional study which can vary the properties of the optic flow. In future work we hope to vary the motion parallax available within the scene, vary the density of the optic flow, and vary the perceived speed of the visual information. We also plan to investigate which complex vection trajectories are more compelling by allowing participants to navigate freely in a three-dimensional environment such that they can directly indicate a trajectory that appears to be both comfortable (no motion sickness) and convincing.

10. Conclusions

In this paper we presented three experiments which investigated introspective measures of the illusion of self-motion as well as speed judgments and a discomfort factor for various visual trajectories. In a photo-realistic visual stimulus, we found that a floor projection improved ratings for linear vection, but had no impact on circular vection. Using a random star field we were able to compare the ratings for vection for many different motion trajectories. We found that left and right linear vection was reported to be the least convincing, while backwards vection was rated quite highly. In addition, we found that while forward vection was not rated as highly as circular vection, that curvilinear vection (forward motion with a rotational component) was rated to be as convincing as circular vection. A final study investigated the perceived speeds and discomfort level of our many trajectories used in the previous study. We found no difference in the discomfort level or the perceived speeds of the different trajectories. Further research will need to be conducted to make direct comparisons between these different stimuli while varying specific aspects of the visual information. We believe that having such an experimental setup which can project so many different motion trajectories is a valuable research tool for studying self-motion perception.

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References

[1] Fischer MH, Kornmüller AE. Optokinetisch ausgelöste Bewegungswahrnehmung und optokinetischer Nystagmus. Journal für Psychologie und Neurologie 1930;273–308.

[2] Sauvan XM, Bonnet C. Properties of curvilinear vection. Perception & Psychophysics 1993;53(4):429–35.

[3] Dichgans J, Brandt T. Visual-vestibular interaction: effects on self-motion perception and postural control. In: Held R, Leibowitz HW, Teuber H-L, editors. Perception, handbook of sensory physiology, vol. VIII. Berlin: Springer; 1978. p. 756–804.

[4] Howard IP, Heckmann T. Circular vection as a function of the relative sizes, distances, and positions of 2 competing visual displays. Perception 1989;18(5):657–65.

[5] Mach E. Grundlinien der Lehre von den Bewegungsempfindungen. Leipzig, Germany: Engelmann; 1875.

[6] Andersen GJ, Braunstein ML. Induced self-motion perception in central vision. Journal of Experimental Psychology: Human Perception and Performance 1985;11:122–32.

[7] Giannopulu I, Lepecq J. Linear-vection chronometry along spinal and sagittal axes in erect man. Perception 1998;27(3):363–72.

[8] Ohmi M, Howard IP. Effect of stationary objects on illusory forward self-motion induced by a looming display. Perception 1988;17(1):5–11.

[9] Palmisano S. Perceiving self-motion in depth: the role of stereoscopic motion and changing-size cues. Perception & Psychophysics 1996;58(8):1168–76.

[10] Telford L, Frost BJ. Factors affecting the onset and magnitude of linear vection. Perception & Psychophysics 1993;53(6):682–92.

[11] Flückiger M, Baumberger B. The perception of an optical flow projected onto the ground surface. Perception 1988;17(5):633–46.

[12] Riecke BE, Schulte-Pelkum J, Avraamides MN, von der Heyde M, Bülthoff HH. Scene consistency and spatial presence increase the sensation of self-motion in virtual reality. In: APGV '05: Proceedings of the second symposium on applied perception in graphics and visualization. New York, NY, USA: ACM Press; 2005.

[13] Brandt T, Dichgans J, Koenig E. Differential effects of central versus peripheral vision on egocentric and exocentric motion perception. EBR 1973;16:476–91.

[14] Johannsson G. Studies on the visual perception of locomotion. Perception 1977;6:365–76.

[15] Palmisano S, Gillam B. Stimulus eccentricity and spatial frequency interact to determine circular vection. Perception 1998;27:1067–77.

[16] Schulte-Pelkum J. Perception of self-motion: vection experiments in multi-sensory virtual environments. Unpublished Doctoral Dissertation, Max Planck Institute for Biological Cybernetics.

[17] Mohler BJ, Thompson WB, Riecke B, Bülthoff HH. Measuring vection in a large screen virtual environment. In: Proceedings of the symposium on applied perception in graphics and visualization; 2005. p. 103–9.

[18] Riecke BE, Schulte-Pelkum J, Caniard F, Bülthoff HH. Towards lean and elegant self-motion simulation in virtual reality. In: IEEE VR2005, Bonn, Germany; 2005. p. 131–8 ⟨www.vr2005.org⟩.

[19] Riecke BE, Schulte-Pelkum J, Avraamides MN, von der Heyde M, Bülthoff HH. Cognitive factors can influence self-motion perception (vection) in virtual reality. ACM Transactions on Applied Perception 2006;3(3):194–216.

[20] Kano C. The perception of self-motion induced by peripheral visual information in sitting and supine postures. Ecological Psychology 1991;3(3):241–52.

[21] Wolpert L. Field of view versus retinal region in the perception of self motion. Unpublished Dissertation, Ohio State University, Columbus; 1987.

[22] Gibson JJ. The ecological approach to visual perception. Boston: Houghton Mifflin; 1979.

[23] Hettinger LJ. Illusory self-motion in virtual environments. In: Stanney KM, editor. Handbook of virtual environments. Lawrence Erlbaum; 2002. p. 471–92 [chapter 23].

[24] Warren R, Wertheim AH, editors. Perception & control of self-motion. New Jersey, London: Erlbaum; 1990.

[25] Lepecq JC, Jouen F, Dubon D. The effect of linear vection on manual aiming at memorized directions of stationary targets. Perception 1993;22(1):49–60.

[26] Kennedy RS, Lane NE, Lilienthal MG, Berbaum KS. Lawrance, Profile analysis of simulator sickness symptoms: application to virtual environment systems. Presence—Teleoperators and Virtual Environment 1992;1(3):295–301.

[27] Banton T, Stefanucci J, Durgin FH, Fass A, Proffitt D. Perception of walking speed in a virtual environments. Presence 2005;14(4):394–406.

[28] Trutoiu LC, Marin S-D, Mohler BJ, Fennema C. Orthographic and perspective projection influences linear vection in large screen virtual environments. In: Wallraven C, Sundstedt V, editors. APGV, ACM international conference proceeding series, vol. 253. ACM; 2007. p. 145.