Simple User-Generated Motion Cueing can Enhance Self-Motion Perception (Vection) in Virtual Reality

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ABSTRACT

Despite amazing advances in the visual quality of virtual environments, affordable-yet-effective self-motion simulation still poses a major challenge. Using a standard psychophysical paradigm, the effectiveness of different self-motion simulations was quantified in terms of the onset latency, intensity, and convincingness of the perceived illusory self motion (vection). Participants were asked to actively follow different pre-defined trajectories through a naturalistic virtual scene presented on a panoramic projection screen using three different input devices: a computer mouse, a joystick, or a modified manual wheelchair. For the wheelchair, participants exerted their own minimal motion cueing using a simple force-feedback and a velocity control paradigm: small translational or rotational motions of the wheelchair (limited to 8cm and 10°, respectively) initiated a corresponding visual motion with the visual velocity being proportional to the wheelchair deflection (similar to a joystick). All dependent measures showed a clear enhancement of the perceived self-motion when the wheelchair was used instead of the mouse or joystick. Compared to more traditional approaches of enhancing self-motion perception (e.g., motion platforms, free walking areas, or treadmills) the current approach of using a simple user-generated motion cueing has only minimal requirements in terms of overall costs, required space, safety features, and technical effort and expertise. Thus, the current approach might be promising for a wide range of low-cost applications.

Categories and Subject Descriptors

H.5.2 [**Information Interfaces and Presentation**]: User InterfacesInput devices and strategies, Interaction styles; H.1.2 [**Models and Principles**]: User/Machine SystemsHuman factors, Human information processing; H.5.1 [**Information Interfaces and Presentation**]: Multimedia Information SystemsArtificial, augmented, and virtual realities; J.4 [**Social and Behavioral Sciences**]: Psychology

General Terms

Experimentation, Human Factors, Measurement

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Keywords

Human factors, motion cueing, psychophysics, self-motion perception, self-motion simulation, vection, virtual reality, wheelchair

1. INTRODUCTION

Over the last decades, the visual quality of virtual environments has advanced at an amazing pace, and state-of-the art 3D renderings can appear almost indistinguishable from real-world stimuli. Despite this technological progress, however, visually-based self-motion simulations are still largely incapable of conveying a compelling sensation/illusion of self-motion comparable to real-world motions. This might critically contribute to the frequently observed disorientation in virtual environments when only visual cues indicate self-motion [1, 6, 9]. Thus, effective yet affordable solutions for improving self-motion perception in virtual reality (VR) would be highly beneficial for a wide range of applications.

Visually induced self-motions illusions have been described and subject to extensive research for more than a century (see [2, 4, 11] for excellent reviews). The most commonly known example for such visually-induced self-motion illusions ("vection") is the train illusion, where an observer seated in a stationary train might experience a compelling illusion of self-motion if (s)he watches a train on the adjacent track pull out of the station. In laboratory settings, vection has typically been studied using a so-called optokinetic drum: A large rotating drum painted with black-and-white striped or dotted patterns. There is one major drawback for employing vection in terms of VR applications, though: While vection seems to occur almost immediately for the train illusion, observers in the lab initially perceive themselves as stationary and the stimulus as moving when first exposed to a moving visual stimulus. Vection only occurs after an onset latency of 2-30s and gradually builds up until eventually only self-motion is experienced and the visual array appears earth-stationary ("saturated vection"). Vection onset time is often considered a measure of the potency of the presented stimuli to induce compelling self-motion perception. Reducing the onset latency of vection can thus be seen as one of the most critical aspects in devising effective ego-motion simulations when motion platforms, free-space walking areas, or treadmills are unfeasible or simply too costly.

The current study was designed to investigate whether adding small physical motions (jerks) to visual accelerations might be able to enhance vection. Even though motion cueing is heavily used in many applications, including driving and flight simulations, there is surprisingly little research directly addressing the influence of such small physical motions on vection. About 25 years ago, Wong and Frost demonstrated that the onset time for visually induced self-rotation illusions (circular vection) can be reduced by concomitant physical rotations (30° maximum deflection, about 1.1s motion du-

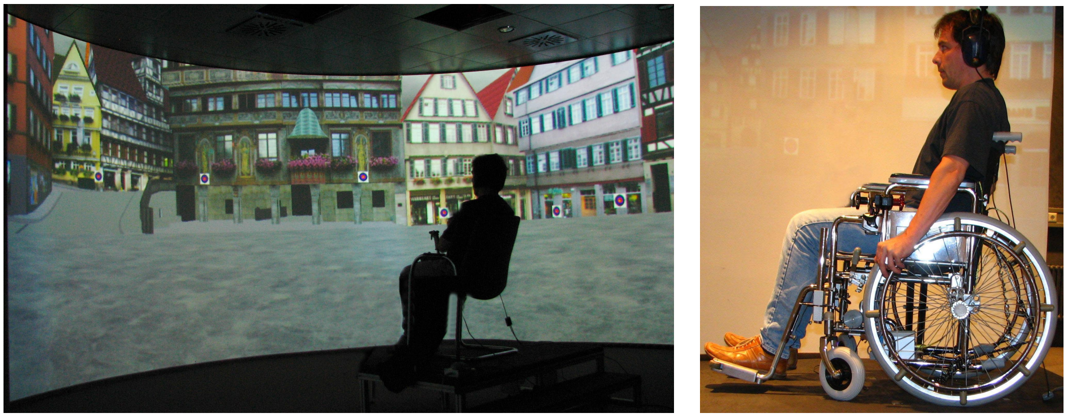

Figure 1: Left: Experimental setup displaying a participant seated in front of the 220° × 50° cylindrical projection screen showing a view of the 3D model of a market place. Right: Modified wheelchair used as a joystick-like (velocity-control) motion model where participants essentially provide themselves with a minimal motion cueing.

ration with peak accelerations of about $240°/s^2$ [12]). More recently, this finding was extended to translational vection induced in a high-fidelity virtual environment [9]: If the visual motion onset was accompanied by small physical motions (jerks of 1cm (about $0.8m/s^2$) or 3cm ($1.6m/s^2$) applied using a Stewart motion platform) vection was enhanced not only in terms of reduced vection onset latency, but also in terms of increased overall intensity and convincingness of the perceived self-motion.

Here, we tested whether vection could be enhanced without the need for costly, computer-controlled motion platforms. That is, we propose an extremely simple yet elegant approach to providing a minimal motion cueing: by having users exert their own motion cueing using a modified wheelchair as a joystick-like force-feedback input device. That is, a small translational or rotational motion of the wheelchair by a few centimeters or degrees, respectively, starts a corresponding visual motion with the visual velocity being proportional to the relative displacement/rotation of the wheelchair from it's original position/orientation.

Apart from investigating a novel input paradigm, the current study further extends classic vection research in several respects: (1) Participants actively controlled the simulated motions, which is an important issue in terms of many VR applications, but has so far been largely neglected in vection research; (2) Instead of using the classic black and white geometric patterns as visual stimuli, a naturalistic 3D computer model of a town square presented on a high-fidelity VR projection setup was used to induce vection (Previous research showed that high-quality virtual environments can be reliably employed to induce and study vection [8, 10]); (3) Instead of studying rotations and translations in isolation as is common practice in vection research, we also investigated combined rotations and translations. Such motions are quite common in real life, especially when controlling a vehicle (ground vehicles as well as most air-borne vehicles).

2. METHODS

Six participants (all male) completed the experiment. All participants had normal or corrected-to-normal vision and no signs of vestibular dysfunction.

2.1 Stimuli and apparatus

Participants were seated in the center of a cylindrical projection screen (3.5m diameter × 3.15m height, corresponding to a field of view of about 220° × 50°), as illustrated in Figure 1. Visual stimuli were projected non-stereoscopically using three JVC D-ILA DLA-SX21S video projectors with a resolution of 1024 × 768 pixel each, and purpose-built geometry correction devices and soft edge blending. The simulated scene consisted of a highly detailed, photorealistic 3D mockup a market place (see Fig. 1). To eliminate spatial auditory cues from the lab, participants wore active noise canceling headphones (Sennheiser HMEC 300), which presented broad-band noise throughout the experiment.

2.2 Motion paradigms

The main purpose of the current study was to investigate the influence of input device/motion paradigm on ego-motion perception in VR. We compared two standard motion paradigms (button-based and joystick-based) and a novel motion paradigm based on a modified wheelchair. For the sake of comparability, maximum motion velocities were kept identical among the three motion models.

Button-based motion model. Forward motion was initiated by pressing the middle button on a computer mouse, left- and rightward rotations were initiated by pressing the left and right buttons, respectively. Button presses initiated a linear acceleration phase (1.67s duration), followed by a constant velocity phase ($4m/s$ and $40°/s$) that lasted as long as the button was being pressed. The motion decelerated as soon as the button was released (1.67s deceleration time). The button-based motion model was included as it provides only a minimum amount of proprioceptive feedback and is frequently used in VR applications.

Joystick-based motion model. Forward and backward deflection of the joystick resulted in forward and backward motion in the simulated scene, respectively, with a motion velocity proportional to the amount of joystick deflection. Similarly, sideways defections controlled rotations. Joysticks and game pads are frequently used in VR simulations and games, and were included here as a baseline that provides some proprioceptive feedback about the motion, but no physical motion of the observer and only little physical effort. For the button-based and joystick-based motion models, participants were seated in a stationary chair (see Fig. 1, left).

Wheelchair-based motion model. A wheelchair-based motion model was developed to provide simple – but at least qualitatively correct – proprioceptive and vestibular feedback about the

	Vection onset time		Convincingness of motion onset		Convincingness of whole motion		Average vection intensity		Maximum vection intensity	
	F(2, 10)	p	F(2, 10)	p	F(2, 10)	p	F(2, 10)	p	F(2, 10)	p
Turning angle	*3.68*	*.063m*	2.65	.12	**6.27**	**.017***	**5.36**	**.026***	*3.79*	*.059m*
Input device	**5.49**	**.025***	**7.74**	**.009****	**8.20**	**.008****	**10.6**	**.003****	**6.32**	**.017***
Interaction	.766	.56	1.10	.39	1.04	.41	1.17	.36	1.30	.31

Table 1: ANOVA results for the the five dependent measures. The asterisks '*' indicate the significance level (5%, 0.5%, or 0.05%). Marginal significance (10% level) is indicated by an *'m'*.

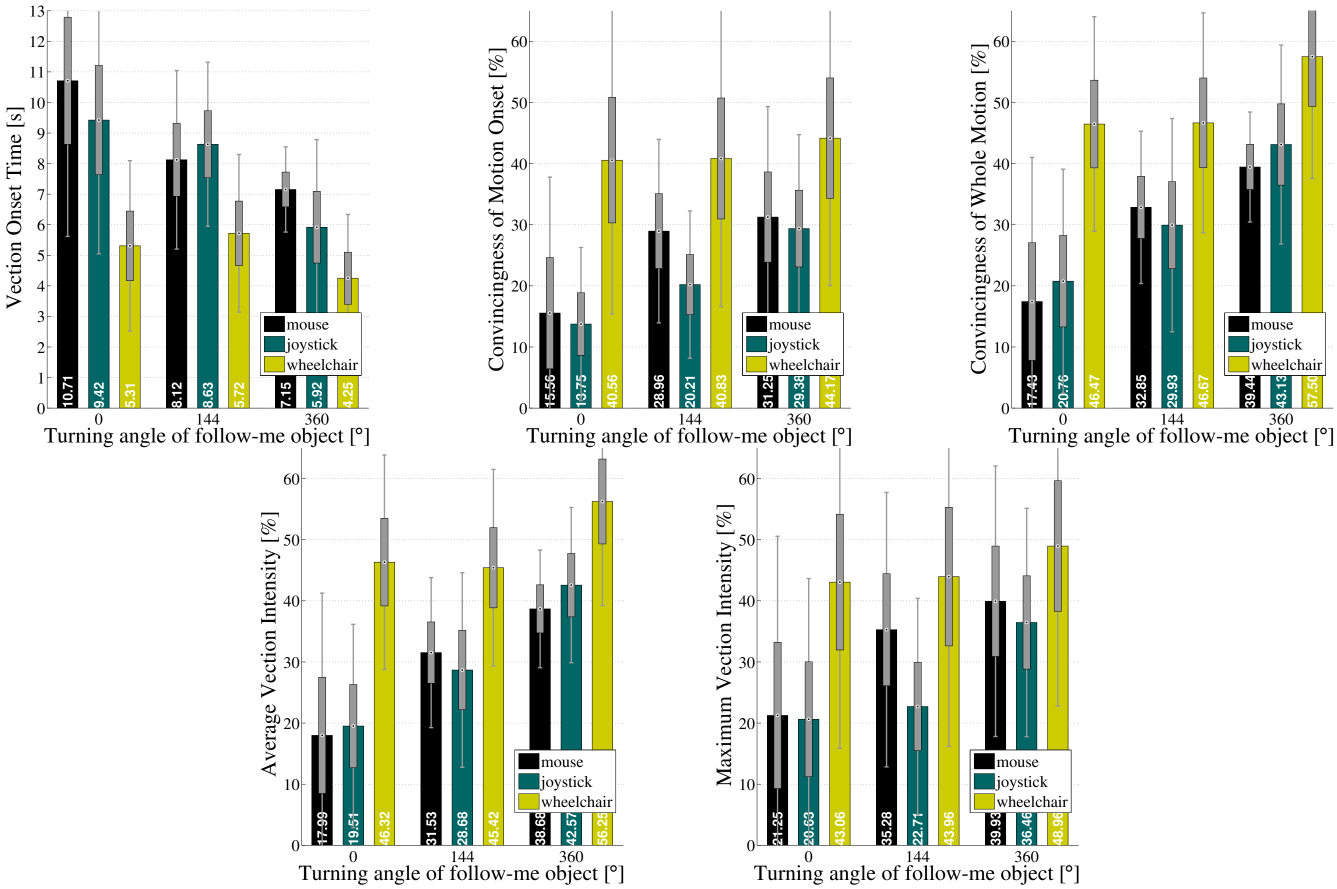

Figure 2: Mean vection data as a function of turning angle and input device. Boxes and whiskers denote one standard error of the mean and one standard deviation, respectively. The results of pairwise t-tests are displayed at the top of each plot. Note the consistent vection-enhancing effect of the wheelchair interface.

visually simulated motion. Furthermore, the wheelchair serves as an ecologically plausible motion paradigm for both indoor and outdoor locomotion, which makes it quite versatile – similar to walking interfaces, but with much less technical challenges involved. Elastic bands were attached to the wheels of a standard manual wheelchair to provide a simple (though crude) automatic re-centering mechanism, similar to the automatic re-centering used for joysticks. This restricted the wheelchair's physical motion envelope to about ± 8 cm for translations and $\pm 10°$ for rotations. Potentiometers were used to measure wheel motions, and the wheelchair was interfaced via USB. Instead of using the normal, position based motion mapping of a wheelchair, a velocity-based motion mapping was used for this study. That is, the translational/rotational velocity in the simulated scene was proportional to the amount of translational/rotational deflection of the wheelchair from it's default (initial) position.

2.3 Procedure

The experiment had three sessions, one for each of the three input devices, run in balanced order. Crossing 3 turning angles (360°, 144°, and 0° (no turn); randomized) $\times$ 2 turning directions (left/right; alternating) $\times$ 3 repetitions yielded 18 trials. At the beginning of each trial, participants were randomly positioned in the simulated scene and a "follow-me" object (a 1m radius, red-black striped ball) appeared in front of the participants and immediately started to move away from the observer at a fixed velocity of 2.8m/s along different predefined paths of 28m length. The participants' task was to use the current input device to follow the ball as closely as possible. Vection onset time was recorded as the time between the onset of the participants' motion and the participants verbally indicating the onset of vection. After each trial, participants were asked to verbally rate the convincingness/believability of the motion onset, the convincingness/believability of the whole motion, the maximum intensity of the self-motion sensation, and the mean intensity of the self-motion sensation, each on a 0-100% scale. The idea behind using a follow-me object was to ensure that (a) participants had to actively use the current input device and (b) that they traveled similar trajectories for the different input devices and trials. The follow-me trajectories were either straight paths or curved paths with constant curvatures and overall turning angles of $\pm 144°$ or $\pm 360°$. At the beginning of each session, participants were given time to familiarize themselves with the given input devices while navigating freely through the simulated scene. Once feeling comfortable with it, participants were trained on the follow-me pursuit task until they performed three consecutive trials where the maximum distance to the follow-me object did not exceed 3m.

3. RESULTS AND DISCUSSION

The vection data are displayed in Figure 2 and were analyzed using repeated-measures ANOVAs for the factors turning angle and input device (see Table 1). The factor input device showed a significant influence for all five dependent measures, with the wheelchair yielding the lowest vection onset latencies and the highest ratings of convincingness and intensity of perceived self-motion. Some participants even reported immediate vection onset for some of the wheelchair trials. The effect of using the wheelchair was strongest for linear translations, where vection onset latency was halved and ratings for the convincingness and intensity of vection were more than doubled.

Interestingly, there was virtually no difference between the vection ratings for the button-based and and joystick-based motion model, despite the joystick being arguably easier to use. The turning angle showed a tendency toward lower vection onset times and higher convincingness and intensity ratings for increasing turning angles. This tendency reached significance for the convincingness of the whole motion and the average vection intensity, and marginal significance for the vection onset time §(p=.063)§ and the maximum vection intensity §(p=.059)§.

Note that the wheelchair acted as a velocity control device, much like a joystick, and thus differed from the position control of classic wheelchairs or wheelchairs put on a motion platform [3]. Nonetheless, participants reported the wheelchair interface as being easy and intuitive to use, and were indeed able to navigate smoothly and accurately after only a few seconds of using the wheelchair.

Compared to free-space walking and motion platform setups, which are also known to improve self-motion perception in VR [7, 5, 9], using a simple locomotion paradigm like a wheelchair with self-generated minimal motion cueing has a number of practical advantages: The wheelchair interface is compact, easy-to-use, light-weight, transportable, and fits into even the smallest lab spaces. Thus, it reduces the requirements in terms of safety precautions, technical personnel/expertise, programming effort, and maintenance to an absolute minimum, and might thus help to reduce the overall costs and effort in constructing a generic ego-motion simulation setup. Furthermore, the wheelchair serves as an ecologically plausible locomotion metaphor for navigating both indoor and outdoor scenes, and could thus be used for a large variety of VR applications including architecture walk-throughs, virtual travel, and tests for wheelchair accessibility.

Further studies with more participants are, of course, needed to corroborate the current data and disambiguate the influence of inertial cues due to physical accelerations (mainly vestibular and somatosensory cues) and proprioceptive/kinesthetic cues from actively moving the wheelchair (body motion and muscle effort needed to control the wheelchair). Nevertheless, the current data are promising and suggest that adding a simple, self-generated motion cueing to an existing setup might be a promising approach to devising a simple, lean-and-elegant – yet effective – ego-motion simulation paradigm for a wide range of applications.

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