

Self-Motion Illusions (Vection) in VR – Are They Good For Anything?

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ABSTRACT

When we locomote through real or virtual environments, self-to-object relationships constantly change. Nevertheless, in real environments we effortlessly maintain an ongoing awareness of roughly where we are with respect to our immediate surrounds, even in the absence of any direct perceptual support (e.g., in darkness or with eyes closed). In virtual environments, however, we tend to get lost far more easily. Why is that? Research suggests that physical motion cues are critical in facilitating this “automatic spatial updating” of the self-to-surround relationships during perspective changes. However, allowing for full physical motion in VR is costly and often unfeasible. Here, we demonstrated for the first time that the mere illusion of self-motion (“circular vection”) can provide a similar benefit as actual self-motion: While blindfolded, participants were asked to imagine facing new perspectives in a well-learned room, and point to previously-learned objects. As expected, this task was difficult when participants could not physically rotate to the instructed perspective. Performance was significantly improved, however, when they perceived illusory self-rotation to the novel perspective (even though they did not physically move). This circular vection was induced by a combination of rotating sound fields (“auditory vection”) and biomechanical vection from stepping along a carousel-like rotating floor platter. In summary, illusory self-motion was shown to indeed facilitate perspective switches and thus spatial orientation. These findings have important implications for both our understanding of human spatial cognition and the design of more effective yet affordable VR simulators. In fact, it might ultimately enable us to relax the need for physical motion in VR by intelligently utilizing self-motion illusions.

KEYWORDS: Spatial Updating, Self-Motion Illusion, Vection, VR.

INDEX TERMS: H.1.2 [Models and Principles]: Human Factors and Information Processing; H.5.1 [Information Interfaces and Presentation, HCI]: Multimedia Information Systems – Artificial, augmented, and virtual realities; J.4 [Social and Behavioral Sciences]: Psychology.

1 INTRODUCTION

Why do we often have problems staying oriented in VR? This is often attributed to the lack of actual motion to accompany the visual simulation [1]. One way to quantify this is by asking users to adopt a new perspective (either by verbal instruction or via a VR simulation) and then quantifying the difficulty or ease of this

perspective switch using an ecologically valid behavioral task like pointing to previously-learned objects. Using this approach, researchers have convincingly demonstrated that pointing to previously learned objects after imagined or purely visually simulated perspective switches is typically rather difficult and requires considerable cognitive effort [2–5]. However, this task becomes surprisingly easy and seemingly effortless if participants are allowed to physically move to the to-be-imagined or visually simulated perspective, even with eyes closed [2,3,6,7]. This facilitation of perspective switches is typically attributed to physical self-motion cues enabling a mostly automated “spatial updating” of our egocentric mental representation of the immediate surroundings [2,3]. Here, we tested if illusory self-motion (as compared to actual self-motion) similarly benefits perspective switches (for reviews on vection in the context of VR, see [8] and [9]). That is, can illusory self-motion facilitate perceived perspective changes, just as actual self-motion would? Or, in different words, can illusory self-motions elicit or at least facilitate (automatic) spatial updating? If so, this would be of considerable relevance for VR simulations, as we might not need to allow for full physical motion, reducing the need for free-space walking areas or motion simulators and thus the overall effort, cost, and complexity.

The main idea of this study is to test the hypothesis put forth by Riecke and von der Heyde [10,11] that the sensation of self-motion (be it from actual motion or from illusory self-motion) might be a necessary prerequisite for the occurrence of automatic and continuous spatial updating. Specifically, we investigated whether the illusion of self-motion is beneficial for imagined perspective switches if participants perceived (illusory) turns from their actual to the to-be-imagined orientation. Circular vection can be elicited through various modalities, yet we focus here on bimodal vection based on auditory motion cues (sound fields rotating around the observer [12,13]) and biomechanical motion cues (from stepping along a rotating floor, similar to sitting stationary above a rotating carousel [14]). Previous studies using the same setup demonstrated that biomechanical vection can be significantly enhanced by adding matching rotating sound fields. We have intentionally excluded visual stimuli from our study because extensive pre-tests have shown that visuals seem to interfere with imagination and perspective-taking tasks [15].

To estimate the difficulty of the instructed mental perspective switch, we compared a 120° perspective switch to the supposed-to-be-easy baseline condition of no perspective switch (0°). Note that the increased difficulty of 120° condition likely originates from a combination of mental transformation costs and interference costs (due to the conflict between the orientation of the to-be-imagined and actual or sensorimotor perspective [2,3,5,16]).

We hypothesized that instructed perspective switches should be facilitated if participants experienced vection and had the illusion of rotating to the to-be-imagined orientation. This was expected to reduce both the mental transformation costs (due to spatial updating) and the interference costs (as there is no longer a conflict between ones perceived (sensorimotor) and imagined headings).

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2 METHODS

2.1 Participants

A total of 17 naive participants (11 female) completed the experiment for standard payment. Two additional participants had to be excluded, as they did not follow the experimental procedures. Two more participants were excluded in a pre-screening as they did not reliably perceive vection. Ages ranged between 18 and 47 years (25.3 years average). All participants had normal or corrected-to-normal vision, normal binaural hearing, and no signs of vestibular dysfunction, as determined by a standard Romberg test before the experiment [17]. The experiment was IRB-approved.

2.2 Stimuli, Task and Apparatus

2.2.1 Circular Treadmill and Setup

Throughout the main experiment, participants wore noise-cancelling headphones and blindfolds and were seated on a hammock chair suspended above a motorized, circular treadmill as depicted in Fig. 2a (a detailed description of the setup can be found in [18]). Although fixed, the hammock chair allowed for a slight swaying motion in all directions; a feature that provided a cognitive-perceptual framework of movability which potentially facilitated vection [9,18].

2.2.2 Pointing and Target Learning

Pointing was performed using a modified wireless Logitech Freedom 2.4 joystick that was positioned on participants' laps (see Fig. 2a). The experiment was performed in a cluttered rectangular room of 7.14m \times 5.98m, in which nine irregularly spaced objects with one-syllable names were selected as pointing target objects (see Fig. 1). A learning phase was used prior to the main experiment to ensure that participants could point without vision to all targets within 10° accuracy.

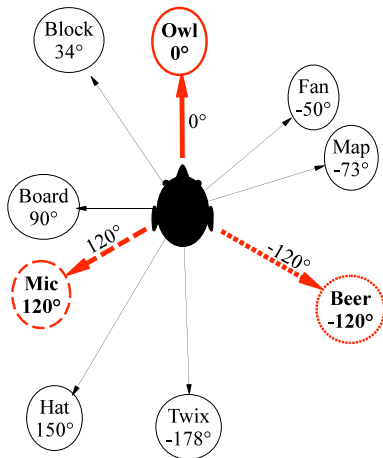


Figure 1. Pointing target layout.

2.2.3 Biomechanical Stimuli

For the VECTION condition, circular biomechanical vection was induced by rotating the circular treadmill and asking participants to comfortably step along sideways [14,15,18] (Fig. 2a). Treadmill rotation speed was controlled by the experimenter, who was trained to produce a consistent velocity profile starting with a 3s

linear acceleration phase and a subsequent 60°/s constant velocity phase.

2.2.4 Auditory Stimuli

For generating compelling vection-inducing auditory stimuli that can accompany the biomechanical vection-inducing stimuli, we positioned one speaker directly in front of the observer seated in the hammock chair (0°, 2.3m away) and a second speaker to their right (270°, 3.3m away), see Fig. 2b. For the recordings, the 0° speaker displayed a purpose-made mix of 14 bird songs, whereas the 270° speaker displayed a mix of several waterfall and river sounds. These stimuli were chosen in pre-experiments because they could be well localized, easily disambiguated, and were much less disturbing than the white or pink noise stimuli used in many studies. The vection-inducing auditory cues consisted of binaural recordings of one of the experimenters rotating on the circular treadmill with 60°/s while both speakers provided easily localizable sound cues. A more detailed description of the binaural recordings can be found in [18]. For the IMAGINE condition, a non-spatialized (mono) recording of the same sounds was used to mask all sounds from the actual lab.

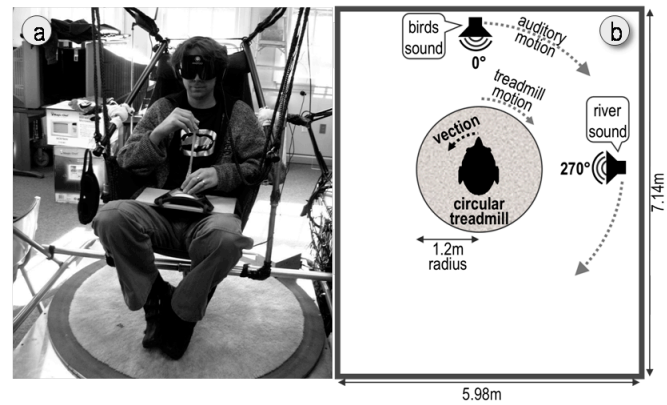


Figure 2. Experimental Setup. (a) Circular treadmill with hammock chair suspended above. Blindfolded participant wearing noise cancellation headphones points using the joystick. (b) Top-down schematic view of the setup.

2.3 Procedure and Experimental Design

After signing informed consent and prior to the main experiment, participants underwent a training phase to familiarize themselves with the pointing procedure and target layout (see Fig. 1). After learning the target layout, participants were asked to point to targets announced in random order via headphones order until having pointed to each target three times with less than 10° absolute error. They were asked to close their eyes during target announcement and pointing to ensure that they would be able to point to the targets while blindfolded during the main test. During training, they were free to open their eyes in between trials, though.

As customary in vection research, a within-participants design was used for the main study to reduce the typically large between-subject variability. Each participant completed 16 trials, a factorial combination of

- 2 motion conditions (IMAGINE, VECTION)
- 2 turning angles (0°, 120°)
- 2 turning directions (clockwise/counter-clockwise)
- 2 repetitions per condition

Turning direction was alternated to balance conditions and to reduce the occurrence of motion sickness and motion after-effects, but was not analyzed separately.

To assess if vection would facilitate imagined perspective switches, participants had to imagine a perspective switch of 120° away from the learned, default orientation of 0°. In the IMAGINE condition, perspective switches had to be performed purely mentally, without any real or illusory self-motion. In the VECTION condition, however, biomechanical and auditory vection-inducing cues were carefully controlled such that participants first perceived one full 360° illusory self-rotation (to make sure that vection was reliable and stable) and then continued to perceive illusory self-rotation until facing the to-be-imagined perspective.

For the VECTION condition, participants were asked to step along with the platform disk which was slowly ramped up to 60°/s (with a 3s linear acceleration phase), while headphones displayed a sound field that rotated with the same velocity. To be able to track participants' perceived orientation in the lab, they were asked to use the joystick to continuously point toward the 0° object ("owl") during the illusory self-rotation. In addition, participants were asked to indicate when they approached the "owl" and the to-be-imagined object. Participants' joystick responses confirmed that they perceived vection in all trials, with vection onset times of around 3s on average, and values ranging from immediate vection onset to more than 20s (standard deviation: 3.1s).

Just before the end of one full illusory self-rotation (indicated by almost a 360° joystick rotation), the to-be-imagined facing target was announced (i.e., "imagine facing owl" for to-be-imagined headings $H_{TBI} = 0^\circ$, or "imagine turning counterclockwise until facing mic" for $H_{TBI} = 120^\circ$), and the experimenter smoothly decelerated the treadmill such that it came to a complete stop when participants' perceived orientation (as indicate by the joystick) matched the to-be-imagined facing direction ($H_{TBI} = 0^\circ, 120^\circ$). That is, treadmill speed was manually controlled to yield a perceived self-rotation of either 360° (baseline condition) or 360°+120°. The rotating sound field was cross-faded to the non-spatialized (mono) recording as the platform was slowed down.

A similar procedure was used for the IMAGINE condition, but without providing any vection-inducing auditory or biomechanical stimuli. Instead, participants were presented with mono recordings and asked to step in place for comparability.

Immediately after the previous perspective switch phase, participants used the joystick to point, in randomly determined order, to six of the nine target objects (cf. Fig. 1) announced consecutively via headphones.

2.4 Dependent Measures

Spatial updating and the facilitation of perspective switches were quantified using pointing response time, absolute pointing error and configuration error as performance measures. The **response time** was defined as the time between the beginning of the target pronunciation (which was adjusted to 500ms for all targets) and the subsequent pointing, and is typically assumed to indicate the ease of access of our mental representation from the to-be-imagined orientation and the potential degree of interference between the actual/perceived and to-be-imagined orientation. The **absolute pointing error** was used to assess how accurately participants knew where they were with respect to specific objects of interest. To quantify the consistency of participants' spatial knowledge of the target configuration, the **configuration error** was computed as the mean angular deviation (which is the circular statistics analogue to the linear standard deviation) of the signed pointing error, taken over the 6 pointings. This configuration error

is a measure of the inconsistency when pointing to multiple targets and is independent of the overall heading error.

3 RESULTS AND DISCUSSION

IMAGINE and VECTION performance for the 120° condition were plotted in Figure 3 and analyzed using paired 2-tailed t-tests (see insets in Figure 3). While response times showed no significant effect of the motion condition, both absolute pointing errors and configuration errors were significantly reduced for the VECTION condition: Absolute pointing errors were 23% higher in the IMAGINE condition as compared to the VECTION condition. The effect size η^2 of .469 is considerable and indicates that 46.9% of the variability in the data can explained by the factor motion condition. Similarly, the configuration error was 18% higher in the IMAGINE condition, with $\eta^2=22.8\%$ [expressed as % here but prop. previously] of the variability in the data being explained by the factor motion condition. That is, participants were both more accurate and consistent in pointing to novel perspectives when they experienced illusory self-motion to the to-be-imagined perspective.

Performance in the baseline 0° condition showed as expected no significant differences between the IMAGINE and VECTION condition for any of the dependent measures (all p's > .32). Together, this suggests that the observed performance advantage of the VECTION condition over the IMAGINE condition for instructed 120° perspective switches is indeed due to the instructed perspective switch and not caused by baseline differences or other potential confounds. That is, illusory self-motion indeed seems to have facilitated to-be-imagined perspective switches, confirming our initial hypothesis.

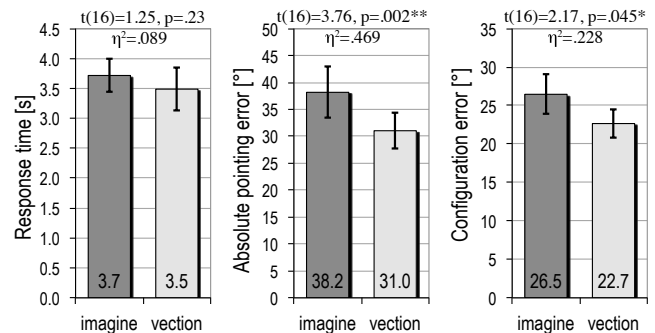


Figure 3. Means, standard error bars, significance values and effect size estimates for the 120° perspective switch condition.

4 CONCLUSIONS

When moving through real environments, automatic spatial updating ensures that our mental spatial representation remains aligned with the outside world [2–4]. In VR that does not allow for full physical locomotion, however, users often become disoriented more easily, possibly due to an impairment or lack of automatic spatial updating. This difficulty in updating to novel perspectives in VR is typically attributed to the lack of physical motion cues: Prior research demonstrated that perspective switches are greatly facilitated if participants are allowed to physically move to the new perspective [1–4]. In this study, we investigated if the mere illusion of moving to a new perspective might yield a similar benefit as actual motion. Using a combination of auditory and biomechanical vection, we found that perspective switches were indeed facilitated if participants had the illusion of being rotated to the to-be-imagined heading.

This facilitation effect could, on the one hand, be related to a **reduction of the interference costs** due to vection [5,16]). As participants had the illusion of rotating to the instructed perspective, there was no longer a conflict between the cognitive (to-be-imagined) perspective and the sensorimotor (perceived) perspective, as participants' perceived heading (sensorimotor perspective) was presumably rotated by the self-motion illusion. Indeed, when participants took off the blindfold at the end of each trial, they were surprised to still be in the original orientation, suggesting that they experienced embodied self-rotation illusions [9].

On the other hand, the facilitation of perspective switches in the VECTION condition might also stem from a **reduction of the transformation costs** [2,3,5,16]. Similar to physical motion cues, the sensation of illusory motion could have facilitated the required mental transformation. That is, vection might have elicited some kind of (potentially automatic) spatial updating to the to-be-imagined perspective, as proposed by [10,11].

The current study was not designed to disambiguate between the potential contributions of interference versus transformation cost. Although it seems feasible that compelling vection might reduce both interference and transformation costs, further research would be needed and is planned to address this issue. No matter what the underlying processes turn out to be, the current findings are promising for the design of VR simulators, as they suggest that illusory self-motions might, at least in part, be able to compensate for the lack of actual physical motion.

There are, however, several limitations of the current study and experimental paradigm that we are well aware of. Most critically, we had to ensure that the vection-inducing stimuli did not interfere with the instructed perspective switch. This was addressed by removing all visual stimuli in the test phase and using biomechanical and auditory vection instead of visually-induced vection. Although participants perceived self-rotation in all VECTION trials and had overall low vection onset latencies of around 3s, it is possible that using visually-induced vection (which can also provide compelling embodied self-motion illusions [8,9]) or combined visual and biomechanical vection would have resulted in different or more pronounced effects. We are currently designing experiments to investigate this possibility.

Moreover, it was challenging to manually control the vection-inducing stimuli such that participants' perceived motion indeed ended at the required orientation. At the same time, we had to provide consistent stimuli across participants and conditions. It is possible that participants' perceived final heading was slightly different than the instructed orientation. Participants' post-experimental verbal reports suggest, however, that this difference was typically rather small and generally below 30°, which is well below the instructed perspective switch of 120°, such that this should not critically affect the results. If anything, it should have decreased performance in the VECTION condition. Despite all these limitations, the behavioral results were clear, and two of the three response measures showed a clear and noteworthy improvement in the VECTION condition. We are currently designing studies to further investigate this phenomenon and directly compare it with a physical motion condition, and hope to be able to incorporate visual cues eventually.

In conclusion, this study produced the first evidence that self-motion illusions can facilitate perspective switches in stationary observers. That is, when confronted with a to-be-imagined perspective switch, participants responded more accurately and consistently when they perceived illusory self-rotation to the novel perspective (even though they never actually rotated). This suggests that actual motion might not always be needed to overcome the frequently observed disorientation and reduced task perfor-

mance in VR – the mere illusion of self-motion might, at least under certain conditions, be sufficient. By pursuing this research agenda further, we hope to gradually be able to reduce the need for physical motions of the observer in VR. Ultimately, intelligently utilizing multi-modal self-motion illusions might enable us to design more affordable yet effective VR simulators.

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