VR: Getting the Reality Part Straight

Does Jitter and Suspension of the Human Body Increase Auditory Circular Vection?

Thesis

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Abstract

Current developments in creating the illusion of being in a virtual world (VR simulations) aim to increase detail and technical complexity to further realism and immersion for the observer. Consistent, multimedia sensor manipulation using audio, video and self motion is the key approach to increase immersion and thus, the feeling of "being there". Despite those technical efforts, achieving a high level of immersion and reducing the appearance of simulator sickness and disorientation in VR simulations still poses quite a challenge. Physical motion brings a certain amount of financial and implementational effort along (Platforms, Treadmills, etc.) and does not yield satisfactory results when taking the ratio of effort and results into account. Previous research show, that convincing self motion can be achieved using vection, the illusion of self motion (e.g., Riecke, Schulte-Pelkum, Caniard, & Bülthoff, 2005a). Not having to use physical motion devices would bring us closer to our main goal of building a lean and elegant motion simulator. In pursuit of evoking convincing self motion illusion, we manipulated auditory and vibrotactile sensor channels to determine the effect of jitter and body suspension on auditory circular vection. We quantified experiences using intensity ratings, vection onset time, direction of perceived rotation and perceived rotational speed. We found, that purely auditory vection can be achieved with the setup we used. Participants were more likely to experience vection in either combination with jitter or the body suspended. Vection ratings were higher in either condition compared to pure auditory vection, where the participant's feet are on the ground and jitter is off. Furthermore, jitter in combination with a suspended body was more likely to produce auditory vection and yielded higher intensity ratings than all conditions mentioned in above. Suspending the participant's body and adding jitter using a simple excenter motor enhances the self motion experience and thus brings us one step closer to designing a lean and elegant self motion simulator.

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1 Introduction

Vection is the illusion of self movement, without actually moving. When presented with a moving stimulus covering a large part of the field of view, the observer can experience a compelling sensation of self motion. As examples of visually induced vection, most people already experienced this phenomenon in the field of transportation. When sitting in the train waiting at the train station, we usually observe the surroundings and what happens outside the train through the window. In some situations, another train pulls out of the station on the adjacent track, which can give a convincing sensation of self-motion even though one's own train does not move. The same effect can also be observed in traffic, when a car and a trailer both wait in front of a traffic light. The view from the car's windows shows a trailer, which covers most of the observer's field of view. When the truck gets the green signal and pulls into the intersection, one can also get a strong impression of self movement.

There have been extensive studies in the field of visually induced vection for several years now (Dichgans & Brandt, 1978; Fischer & Kornmüller, 1930; Howard, 1986; Mach, 1875; Warren & Wertheim, 1990). The research on acoustically induced vection has come surprisingly short, however. This gets even more striking considering that auditory vection has been reported since 1923 (Dodge, 1923) and been replicated several times since then (Gekhman, 1991; Hennebert, 1960; Lackner, 1977; Marmekarelse & Bles, 1977). In 1977, Lackner induced auditory vection for blindfolded participants using a rotating sound field presented trough an array of speakers (Lackner, 1977). Only recently, a few self-motion studies showed interest in that field and researched the phenomena of auditory induced vection for both rotational and translational motion. A few studies successfully induced auditory vection for a fraction of participants tested (Kapralos, Zikovitz, Jenkin, & Harris, 2004; Larsson, Västfjäll, & Kleiner, 2004; Riecke, Västfjäll, Larsson, & Schulte-Pelkum, 2005b; Sakamoto, Osada, Suzuki, & Gyoba, 2004; Väljamäe, Larsson, Västfjäll, & Kleiner, 2004, 2005, 2008a, 2008c).

More recently, several studies have been conducted using virtual reality (VR) to induce vection (Hettinger, 2002; Riecke et al., 2005a; Riecke, Schulte-Pelkum, Avraamides, von der Heyde, & Bülthoff, 2006; Schulte-Pelkum & Riecke, 2007). In the light that VR has the capability to successfully induce vection, researchers now have a tool set to manipulate multimodal sensory cues as they please. This opens up new research possibilities where stimuli are independent from real-world events, creating more flexibility, stimulus control, and reproducibility while offering a high degree of naturalism.

In the current experiment, we address the question if vection induced by auditory cues might be enhanced through vibro-tactile cues and higher-level, top-down mechanisms. If this were the case, the results in this experiment might give us valuable information about the multimodal self-motion perception. Furthermore, they will help us improve the design of virtual reality and self motion simulators.

1.1 Auditory and vibro-tactile self motion perception cues

Human and most animals move about and change their viewpoint constantly. We rely on multimodal sensory input to determine the properties of our motion relative to the space we occupy and the objects in it. Visual and vestibular cues are seen as the predominant modes for inducing the illusion of self-motion (Howard, 1982), which can be indistinguishable from real motion (Brandt, Dichgans, & Held, 1973). While auditory cues *can* induce vection, previous experiments show that auditory induced self motion perception is weaker, less compelling and occurs only in 25-60% of participants (Kapralos et al., 2004; Larsson et al., 2004; Riecke et al., 2005b; Sakamoto et al., 2004; Väljamäe et al., 2004, 2005; Väljamäe, Larsson, Västfjäll, & Kleiner, 2008b; Väljamäe et al., 2008c).

Auditory cues can be indistinguishable from real-world cues when presented through artificial means like headphones. Compared to visual stimuli presented through visual display solutions, the auditory presentation quality is higher. In fact, up to date there is probably not a single visual display that would be confused with "the real thing", whereas affordable, off-the-shelf audio equipment like the one used in the current experiment provide just that in the auditory realm.

Acoustic stimuli alone are not sufficient to reliably evoke vection in everybody. In purely acoustical vection situations, participants need to be blindfolded. When the blindfold is removed, the visual stimulus of stationary surroundings let the experience of self motion disappear. The question whether or not the effectiveness of auditory cues is dependent on how the perceptual system weights them still remains to be answered. Just recently, some research has been done that shows that the interpretation of sound sources have an effect on vection. It shows that "acoustic landmarks", i.e., sounds that are associated with stationary objects (e.g. church bells), are more efficient in triggering vection than artificial noises or cues that are associated with moving objects (e.g. footsteps) (Larsson et al., 2004; Riecke et al., 2005b). The effect of interpretation on vection might indicate an involvement of higher cognitive functions, so-called "top-down" processes (Riecke et al., 2005b; Schulte-Pelkum & Riecke, 2008) . The results presented in those studies stays in opposition to the common opinion that vection is a bottom-up driven process.

The Author is only aware of a few studies involving multimodal sensor stimulation in concert with auditory cues: Schinauer, Hellmann, & Höger (1993) experimented with auditory-vestibular sensor integration. Their studies showed that a binaurally recorded acoustic cues rotating in the opposite direction of the actual physical rotation increased vection ratings. They were, however, reduced in the condition when the acoustic cue rotated in the same direction the participant did. Another study showed that both self-motion perception and presence can benefit from adding spatialized, auditory cues to visual vection (Riecke, Schulte-Pelkum, Caniard, & Bülthoff, 2005; Riecke, Väljamäe, & Schulte-Pelkum, 2008). Vibrations have recently been shown to facilitate both visually induced vection (Riecke et al., 2005a; Schulte-Pelkum, Riecke, & Bülthoff, 2004) and auditorily induced vection (Riecke et al., 2005b; Väljamäe, Larsson, Västfjäll, & Kleiner, 2006; Väljamäe et al., 2008b). Auditory vection was also facilitated by subsonic cues that could not be consciously perceived (Riecke et al., 2005b; Väljamäe et al., 2008b).

In this study, we take a closer look on sensor integration between auditory and vibro-tactile cues. We took first steps to investigate higher cognitive processes on vection. Our goal is to find out, whether or not vibro-tactile cues aid auditory vection (bottom-up) and if the body placement, setup and types of auditory cues have a positive effect on vection ratings (top-down).

1.2 Problems with evoking self motion sensation in VR

Due to the fact that VR components have become more evolved and affordable, self-motion simulators based on VR become more and more popular in professional training facilities and research institutions. Since the aim of virtual reality is to present an experience close to reality, self motion illusion is a necessity for innovative, modern and elegant VR simulators. The question still remains, however, how to optimally implement self motion methods in those simulators. A number of methods have been introduced in the past like presenting a visual stimulus of movement on a head mounted display, physical movement on treadmills, motion platforms, or in free-space walking rooms, or the combination of those methods. Conventional methods like these require a considerable technical and financial effort to acquire and maintain. In addition, they have drawbacks inherent to their design. Head-mounted displays usually have a rather limited field of view, making it impossible to create a convincing visual environment. Treadmills and motion platforms need a considerable amount of space and do not come close to the performance of real-world tasks, which poses a considerable problem when used in training situations (Boer, Girshik, Yamamura, & Kuge, 2000; Burki-Cohen, Go, Chung, Schroeder, Jacobs, & Longridge, 2003; Mulder, van Paassen, & Boer, 2004). The option for participants to walk freely in free-space walking rooms require tracking mechanisms and a large walking area, that is either infeasible or too costly especially for simulations encompassing large virtual spaces. Even though it is often believed that locomotion interfaces like treadmills are the ideal solution for physical movement in simulations, critical design questions for an optimal and affordable simulator still need to be carefully considered (Hollerbach, 2002). There have only been few studies of vection using locomotion interfaces. In one study though, an informal observation stated, that “during treadmill locomotion, there is rarely any illusion that one is actually moving forward” (Durgin, Pelah, Fox, Lewis, Kane, & Walley, 2005, p. 401).

Despite the fact that VR technology has improved considerably, self motion simulation does not come close to real-world motion in terms of effectiveness and convincingess resulting in the conflict of different sensor modes and stimuli. The results of those shortcomings can include poor task performance, motion sickness, or discomfort (Chance, Gaunet, Beall, & Loomis, 1998; Riecke & Wiener, 2007; Riecke, 2008; Schulte-Pelkum & Riecke, 2008).

Even though 3D audio hardware is available and affordable, and might thus pose a potential to increase the effect of VR at a relatively low cost, there have not been many investigations about the integration of auditory cues in multi-sensory VR-systems. In addition, the fact that previous studies successfully used auditory self motion cues was reason enough for us to study how acoustically induced self motion perception can be made more convincing through lean and elegant means.

The distinction of our approach is therefore to achieve cross modal contribution of vibrations to auditory vection cues considering top-down factors. Instead of using artificial noise, we utilized naturalistic acoustic landmarks as auditory cues, which are ecological more valid (Riecke et al., 2006; Larsson et al., 2004). Furthermore, we think that the way participants are seated has an impact on how they perceive motion. Participants are usually seated in office chairs or stools that can be rotated. To give participants the impression or expectation that they might be moving, we suspended them in a sling-chair that is capable of rotating. To test this, we examined if there is a benefit of being free to move and thus disconnected from the room and any stationary objects in it. The naturalisation of the auditory cues as well as the feeling of suspense is in line with the idea of presence being the perceptual illusion of non-mediation, creating higher immersion by reducing the perception of methods providing it (Lombard & Ditton, 1999).

1.3 Applications

Without the need for physical motion platforms, treadmills, or walking rooms, which require extensive tracking, future motion simulators can be lean and elegant opening new possibilities. With increased immersion, affordable design and less motion sickness and disorientation, simulators will hopefully be more effective in training and virtual learning environments. Affordable motion simulators might become popular for being used as human interface devices for entertainment purposes or other mainstream applications. With vection, many interesting questions arise in the field of spatial updating and orientation. Key findings about top-down processes can influence the design of future experiments and give clues on how perceptual processes behave and work (Riecke et al., 2005b; Schulte-Pelkum & Riecke, 2008).

1.4 Definitions

The following abbreviations, expressions and terms will be used and referred to in this document.

1.4.1 Vection

Vection, as mentioned above, is a phenomena where observers feel like they are moving even though being stationary. The only truth is the sensation, not the motion itself.

Circular Vection (CV) Circular Vection, or CV, is a phenomenon where observers feel like rotating, even though they are not. It is part of the vection repository of self motion illusions.

1.4.2 Binaural recording, iHRTF and gHRTF

Binaural recording Binaural recording is technically similar to a stereo recording, except the fact that the two microphones are very small and positioned very close to the ear canal, one in each ear. Depending on the extend of the setup, microphones are either placed in the ear canal, or in the center of the pinna, outside the ear canal. Sound traveling to the microphones will go through a transformation caused by the form and position of the head and pinna, giving it specific and individual properties. Since sound waves travel different distances from ear to ear (delay) and frequency responses vary from ear to ear and person to person, a spatial component is embedded in the recording, that would not be there using just two mics positioned next to each other with a head's width apart. Taking the properties of an individual head and ears into account is referred to as Head Related Transfer Function or short, HRTF. In application, there are two types of HRTFs, generalized (gHRTF) and individualized (iHRTF).

Generalized Head Related Transfer Function (gHRTF) Generalized Head Related Transfer Function, or gHRTF, describes a method where a recording is used based on the microphones positioned at one person's ears and then used on different other people. That is, people essentially listen "through somebody else's ears" in the sense that they hear the sound that somebody else (who's ears were used for the recording or HRTF generation) would hear. Since it involves a high effort to create a recording or auditory simulation considering for each individual, the usage of generalized recordings help to save time and effort. Usually, there are several generalized recordings to choose from when selecting the one that comes closest to the properties of one's head and ears.

Individualized Head Related Transfer Function (iHRTF) Individualized Head Related Transfer Function, or iHRTF, is a method where an individualized recording or auditory simulation is used for each individual. That is, participants essentially listen "through their own ears", as their own ears were used for the recordings. This can result in improved auditory localization ability and reduced front-back confusions (Begault, 1994; Gilkey & Anderson, 1997). Furthermore, using individualized HRTFs has been shown to increase externalization and auditory presence as compared to gHRTFs (Larsson, Väljamäe, Västfjäll, & Kleiner, 2008; Väljamäe et al., 2004; Väljamäe, Västfjäll, Larsson, & Kleiner, 2008d). Recording individualized HRTFs for each participant takes much time and effort to achieve, though.

The only study that I am aware of that explicitly compared vection for iHRTFs versus gHRTFs did not show any systematic benefit of using individualized HRTFs with respect to vection

(Väljamäe et al., 2004). Note that the study used real-time HRTF convolution, where as we used pre-recorded individualized HRTFs in the current study.

1.4.3 Session

In this document, a session is referred to as a collection of trials with a specific participant. When a participant comes to several experiments and has to leave but comes back another time to finish the experiments, all experiments would have taken two sessions.

1.4.4 Bottom-up processes

The process of physical events perceived through sensory systems is refferred to as bottom-up processes. That is, when a physical event like a sound wave approaching the ear is sensed, it will be transformed and then processed by our brain.

1.4.5 Top-down processes

A top-down process does not start with a sensory input, which is then analyzed by the perceptual system. Instead, it is knowledge, anticipation, guesswork and interpretation about something, that might influence perception. For example, one might not recognize what a bad picture shows, but when the knowledge about the content of that particular picture is known, it can help the process of seeing, what is there (which did not present itself beforehand).

1.5 Motivation and preview of the main experiment

While modern virtual reality simulations can have stunning photorealism, they are typically unable to provide a life-like, compelling experience of actually moving through the simulated world, which might limit usability, user acceptance, and thus commercial success. Hence, we propose that investigating and exploiting self-motion illusions might be a lean and elegant way to overcome such shortcomings and provide a truly “moving experience” in computer-mediated environments.

Here, we investigated circular vection induced by rotating auditory cues in blindfolded observers. On one hand, we tested the contribution of adding low-level vibrations, which were expected to reduce the perception and assumption of stationarity. On the other hand, we investigated higher-level, top-down contributions on vection by testing if the knowledge whether one is stationary (participants were seated in a hammock chair, but put their feet on solid ground and their right hand was touching a stationary object) or might potentially move (participants’ feet were suspended in a footrest attached to the hammock chair and their hands were on their lap).

Self-motion illusions have recently been shown to be influenced not only by bottom-up processes, as was traditionally believed, but also by higher-level and top-down processes like the interpretation/meaning of the vection-inducing stimulus. Larsson et al. (2004), Riecke et al. (2005b) demonstrated, for example, that sound sources that are normally expected to be stationary are more effective in inducing vection than sounds that are normally attributed to moving objects. Similar higher-level and top-down influences have been observed for visually induced vection (see Riecke et al., 2005b; Schulte-Pelkum & Riecke, 2008, for reviews on top-down influences on vection).

Lepecq, Giannopulu, & Baudonniere (1995) demonstrated that seven year old children perceive visually induced vection earlier when they were previously shown that the chair they were seated in could in principle be moved – even though it was never moved during the actual experiment. This top-down effect disappeared when eleven year old children were tested, though (Lepecq et al., 1995), and adults also did not show any such vection benefits when they knew that they could potentially be moved. While several studies on auditory vection seated participants on chairs that could be rotated (e.g., Larsson et al., 2004; Väljamäe, 2005, 2007), we are not aware of any study that explicitly investigated the influence of participants' knowledge or assumptions about stationarity on auditory vection.

Furthermore, we were interested in testing whether there might be any synergistic effects between participants' suspension of disbelieve ("I might, in fact, be moving, as I know it is possible") and providing subtle vibrations. Such effects would be interesting both from a theoretical perspective of cue integration and from an applied perspective of how to design affordable yet effective self-motion simulators.

1.6 Hypotheses

Only recently have studies considered the involvement of higher cognitive and top-down processes on vection. Equally new is the examination of cross modal benefits of vibration on self motion perception induced by auditory cues. Here, we studied the performance of auditory vection joint with vibrotactile cues. In this experiment, we tested two hypotheses:

Hypothesis 1: Influence of adding constant vibration to natural, auditory vection cues With the introduction of vibration according to the auditory stimuli, we added specific content to benefit vection. This hypothesis was tested by using a set of conditions with and without vibration. It is conceivable, that vibrations add realism to the presented auditory cues, supporting the motor noise and moving stimuli (Väljamäe et al., 2006).

Hypothesis 2: Influence of suspending the feet (physical disconnection) in auditory vection condition. In line with Larsson et al. (2004), Riecke et al. (2005b), Schulte-Pelkum & Riecke (2008), we believe that there are higher cognitive processes influencing vection.

Suspending the feet along with the body might thus make the stimuli more plausible and increase believability and, in turn, vection.

2 Methods

2.1 Participants

All 13 Participants used in this experiment had normal or corrected-to-normal vision, normal hearing and vestibular function. Participants involved in the experiment participated voluntarily and gave their informed consent prior to the experiment. They were paid standard rates of $10/hour. The experiment was conducted in accordance with ethical standards laid down in the 1964 declaration of Helsinki. Participants stem from different occupational backgrounds ranging from 18 to 26 years of age. All participants tested were females.

We had to reject 8 participants since they were not able to perceive auditory vection at all. This is in accordance with the literature on auditory vection, where vection only happens for 25-60% of the tested participants (Kapralos et al., 2004; Larsson et al., 2004; Riecke et al., 2005b; Sakamoto et al., 2004; Väljamäe et al., 2004, 2005, 2008b, 2008c). For our experiments, five participants out of the 13 were able to participate in the study, which equals 38.5%.

2.2 Stimuli

We used two different iHRTF audio stimuli, one for each rotational direction, clockwise (cw) and counterclockwise (ccw). Two natural auditory cues were used in the experiment. A collection of Brazilian birds coming straight from the front (0°) of the participant's initial seating position, and a mixed river noise, coming from straight right (90°, see Figure 1). The sounds mixes were specifically created to include a wide frequency spectrum and sharp onsets to improve localizability. Furthermore, the two sounds were chosen because they could easily be disambiguated. The river poses an acoustic landmark since it is associated with a stationary object. This might influence perception according to previous studies (Riecke et al., 2006; Larsson et al., 2004). The collection of Brazilian birds might also be associated as a landmark, since it is more likely for a single or a few voices of a particular species to be moving, rather than hundreds of birds across different species.

Besides the auditory cues, we used vibro-tactile stimuli, transduced from all over the chair to the body. Those cues were used for an cross-modal benefit. Shaking the chair slightly through the vection phase might suggest actual movement, making the auditory stimuli more convincing.

Using the footrest for an additional condition and asking participants to touch a stationary object with their right hand, the tactile feedback of the feet and hands on solid ground was expected to give a sensation of being stationary, thus making it perceptionally more unlikely that the body is moving. Suspended feet in a footrest along with the rest of the body doesn't produce any information on whether or not the body is moving, thus reducing conflict cues.

2.3 Apparatus

2.3.1 Overview of the setup

To study auditory circular vection, a self-motion simulator is required. The simulator we build can perform individualized spatialized audio (iHRTF) recordings, convincing playback of those recordings with noise canceling headphones, chair vibration, and two modes of chair rotation, where the chair gets either rotated by a drive rod that is attached to it, or by a platform underneath the particiant's feet, as illustrated in Figure 2. Main components of our self-motion simulator are a circular treadmill, a hammock-chair, various audio gear, and three computers (see Figure 2 and 1). To reduce overall costs and allow for reproducibility, the whole setup was held simple and most parts were available at local department stores like The Home Depot.

2.3.2 Circular treadmill

The circular treadmill has been delivered by a third party and was custom made about 15 years ago. The base and platter are made of aluminum. The base measures 120 x 20 x 120 centimeters, the diameter of the platter is 120 centimeters in diameter. The platter is covered with carpet to reduce stepping sounds on the platform during recording sessions.

The treadmill features two motors, one for rotating the platform, the other for rotating the center rod extending 21 centimeters above the middle of the platter, as illustrated in Figure 3. This way, the chair and the platter underneath could be rotated independently, to provide independent vestibular cues from physical motion and biomechanical cues from actively stepping around on the platter, respectively.

The circular treadmill is controlled by a set of two wired analog handsets, one for each motor (see Figure 3, right). Each set controls rotational direction, emergency stop, 0-100% of max. motor rpm and on/off. For our work here, the platform and chair were rotated at 60° per second, which equals 65% of max. motor rpm.

2.3.3 Hammock chair

Throughout the experiment, participants were seated on a suspended chair. This particular style is known as a hammock-chair. There are two basic components, the mount with stand and the chair itself, featuring a footrest.

Figure 1: Roundshot photograph of the lab space and the experimental setup showing the hammock chair, the experimenter setup, and the two speakers, one in front of the chair and participant's default orientation at 0° (left, Guitar amplifier), the other one to the right of of the chair at -90°.

Figure 2: Experimental setup, as seen from the experimenter's view (left) and the front with a participant seated in it with his feet suspended in the footrest (right). The left picture shows the computer interfaces. The screen to the experimenter's left displayed the data sheet in which the conditions and responses were accessible. The right screen displayed the Pro-Tools audio suite. The chair can swing slightly forwards and backwards. During trials, the participant's knees are in a 90° angle, as illustrated in Figure 4. In the top right part, a microphone (Realistic 331070B) is hanging from the mount. It can be used optionally for session recordings.

Figure 3: **Left:** Experimental setup, as seen from the back. The u-bar (70 centimeters in width and height) beneath the chair holds it in position and relays the rotation of the rod extending from the platform to the chair. As shown in the picture, the u-bar can be fixed trough a beam 140 centimeters in length attached to the support bars on the far sides for walking conditions. The black laptop-bag is hanging from the the back of the chair. Two strong wires from the left and right connect the bag to the u-bar, preventing the it from moving extensively and hitting the participant's back. **Right:** Analog control unit that could be used to rotate the chair and platform independently. The white unit next to the yellow envelope is the access point (Netgear WGT 624v3) for wireless communication between the laptop and desktop computers. The clock and metronome (mounted on the right controller) can be optionally used for timing purposes.

Hammock chair stand and mount Next to the circular treadmill on the left/right and backside reside an overall of six concrete blocks measuring 40 x 25 x 19 centimeters as base for the stand (see Figure 3). The stand itself consists of several pipes, connected to each other and fixed in place, creating a mounting point for the chairs's pivot carabiner and chains. The stand is about 2.15 meters in height, at the base 135 centimeters wide and 143 centimeters deep, the contraption has an overall height of 2.40 meters. At the far top, a hook holds a chain to which a pivot carabiner is connected which in turn holds the chair. This construction enables it to rotate around the earth-vertical axis as we please.

Chair and footrest The chair is made of polymer linen, held together by steel piping and polymer ropes. Most parts of the chair are adjustable as well as removable, which was extremely helpful during the process of creating and optimizing this device. The integral parts are a crossbar 93 centimeters in length and two pipes on the left and right side measuring 75 centimeters, holding the construction together. The crossbar not only carries the chair, it also holds the footrest beneath the participant's feet (see Figure 4). A headrest comes along for comfort and convenience, and is not fixed to the chair and can be removed when needed.

A u-bar made of plumbing pipes connects the chair trough a rod to a motor in the middle of the platform, such that the chair can be moved independently from the platter. We used flexible bands wrapped in white cloth to connect the u-bar with the side-bars of the chair. The distance between the lowest point of the chair and the platter measures 32 centimeters. The u-bar was also used to fix the chair in conditions where participants were stepping in place on top of the rotating platter. In those conditions, the chair needed to be fixed additionally using a bar that was attached to the frame of the stand as well as to the u-bar, which can be seen in Figure 3 (left).

2.3.4 Vibration mechanism and operation

The vibration function is provided by a simple excenter motor mounted in the middle of the crossbar. For this purpose, we used an USB fan, detached the propeller and mounted a wire in its place that holds a cork as an excentrically mounted weight (see Figure 5). The motor was powered using an USB extension cable, that was connected to the PC 2 USB-port when needed. This contraption mildly shakes the chair with about 7 HZ, creating a slight, but noticeable shaking sensation. Here, the vibration mechanism was only used in conditions where the chair was stationary.

The auditory recording contains a platform noise in the background when the platform starts rotating. This is the point when the stimuli suggest movement. We synchronized the start of the vibration with the start of the motor sound in the recording. The vibrations stop when the motor sound in the recording stops. The synchronization was done using a spike in the recording material, that was caused by the turn/brake-switch of the controller. The spike was visible in the audio suite and the jitter was then operated accordingly.

Figure 4: Side view of the experimental setup, showing a participant with the feet either touching the ground (left) or suspended in the footrest (right). In the recording condition, participants were asked to keep their feet on the platform without stepping. The platform movement then rotated them in the chair in sync with the patter. In conditions requiring them to suspend their feet in the footrest, participants were disconnected from the room, moving freely to a certain extent. The blindfold seen in this picture were hanged on a hook fixed on a rope, which carries the chair. The same method was used for the binaural microphones and the headphones.

Figure 5: A USB fan was modified to act as an excenter motor that provided a barely noticeable jitter of the hammock chair. The picture shows the wire, which connects the cork with the motor which in turn is connected to the crossbar. A tubing extends beneath the motor, guiding the USB cables safely to an extension cord, which was connected to the USB port of the left monitor on the desk. It was plugged/unplugged to switch on/off the motor. The battery module of the binaural microphones can be seen beneath the USB connection of the motor, mounted on the crossbar using Velcro.

2.3.5 Audio setup

Two speakers were placed in the room, as shown in Figure 1. One in front of the participant's seating position (which was defined as 0°) and one to the right side (-90°=270°). We used a Gorilla GG-20 guitar amp for the 0° speaker and a Harman Kardon PC speaker on the right side. Both speakers were connected to the built-in sound card of PC 2, which was running VLC player as playback software. The guitar amp was connected to the left channel and the Harman Kardon to the right channel.

The audio function was implemented using miniature microphones, noise cancellation headphones and an audio interface, that was connected to a computer. All components were mounted on the chair, to keep cable lengths and mechanical parts to a minimum while increasing reliability. With no cables extending to external devices and an independent system on the chair, we were able to continuously rotate participants as we please and were flexible for future additions such as a head mounted display and position tracking.

Binaural microphones and headphones Acoustic cues were recorded through the Core Sound Binaural Microphone Set (for specifications see http://www.core-sound.com/mics/3.php). Since those are condenser microphones, they need an external power source, which was mounted on the crossbar. The microphones were connected to the battery-box and from there to the two inputs of the audio interface. In order to mount the microphones on the participants heads, we used a simple bent wire holding those two microphones in place in front of

Figure 6: **Left:** Core Sound Binaural Microphone that was mounted right outside the ear canal for binaural recordings. **Middle:** Audiotechnica AT-7ANC active noise canceling headphones used for playback. **Right:** DigiDesign MBOX2 audio-interface used for high-quality recording and display. The laptop computer mounted in the bag is visible beneath.

the entrance of the ear canal and ensuring a secure position without obstructing the ear or altering the head's acoustic characteristics much (see Figure 6, left).

We used Audiotechnica AT-7ANC active noise canceling headphones for cue playback (see Figure 6, right). A spiral cable connects the headphones with the microphone output of the audio-interface.

An additional microphone was mounted on the stand in order to be able to record the experimental sessions (see Figure 2). It was connected to a Sure professional microphone mixer which in turn was connected to the line input of the PC 1 built-in sound card. We wanted to use this as an option, in case we need to record the questions and answers of participants for later review.

DigiDesign MBox2 The DigiDesign MBox2 audio-interface is a device that provides two analog inputs and two (stereo) analog outputs. As shown in Figure 6, it is connected to a laptop computer that was mounted on the back of the chair using USB 2 interconnection. It completely relies on USB power and does not require additional power adapters. The MBox2 converts analog signals from the microphones into an digital data stream, that is then recorded into a wave file onto the laptop computer's hard drive. The same process applies for the payback through the headphones but in the opposite direction. We chose the Mbox2 since it is the standard of the music industry, opening up a variety of options and providing high audio quality, especially compared to built-in sound cards. The latter was important to provide optimal binaural recording and playback.

2.3.6 Computer setup

An overall of three computers were used to power the setup, each with a specific task. All computers were connected through ethernet.

The computer mounted on the back of the chair (see Figure 6, right) provided the recording and playback function using the MBox2 audio interface. The laptop was connected to the other computers using the high-gain external wireless network adapter Planet WL-U356A, that connected with an access point on the table next to the setup. We used an IBM Thinkpad T40 computer with a high capacity battery. It was recharged when the chair was not moved.

In addition, we used two desktop computers, PC1 (Dell Optiplex GX270) and PC 2 (Dell Dimension 4500), placed next to the setup (see Figure 7). PC 1 was connected to the laptop on the chair using remote desktop. This function enabled us to remotely control the applications on the laptop in any experimental condition. The second computer, PC 2 was used to type in responses of participants as well as measured times and comments. We also used PC 2 to play back the auditory vection cues over speakers.

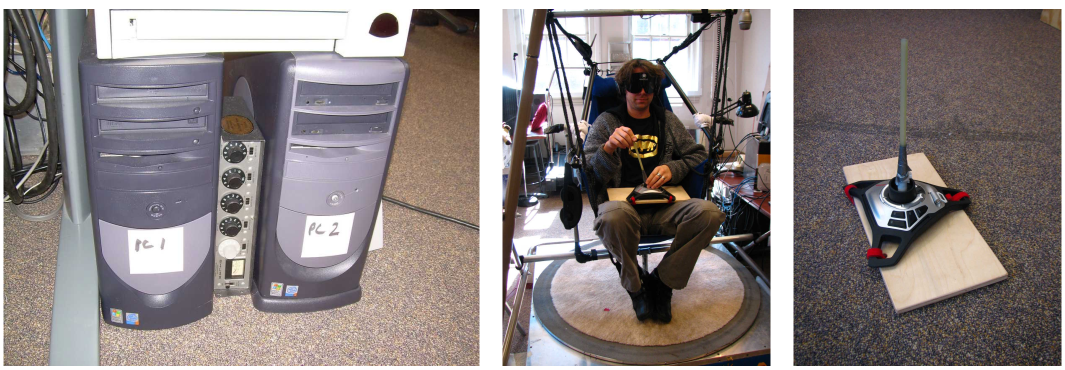

Figure 7: **Left:** Two standard PCs used in the experiment. The microphone preamp is visible in between. On top of the two computers resided a HP LaserJet 2200dn printer connected to all systems via ethernet to print out payment or consent forms. **Middle:** Participant seated on the hammock chair pointing to his front-right. **Right:** Logitech Freedom 2.4 Cordless Joystick used as a pointing device during the pre-tests.

Applications Four integral applications were used on our computers.

1. The laptop computer on the back of the chair was running DigiDesign ProTools 7.3.1, which is the audio-suite that powered the Mbox2 and gave us the recording, editing, and playback features.

2. The remote-desktop application, that comes with MS-Windows XP, was used on the laptop and on one of the desktop computers.

3. The other desktop computer was running MS-Excel for data collection.
4. A custom-programmed stop-watch tool, which recorded times in a format that made it easy to copy-and-paste the data into the excel sheets.

Furthermore, Videolan player was used on PC 2 for cue playback. Audacity can be used as additional software for the recording of the experiment sessions through the additional microphone mounted on the stand.

2.3.7 Pointing device

The pretest phase required participants to point to a specific direction. We used a modified Logitec Freedom 2.4 Cordless Joystick as a pointing device. To make the pointing process more accurate, we removed the handle and replaced it with a simple acrylic rod, approximately 20 centimeters long (see Figure 7 and 7, right). Participants used their fingers placed on top of the rod to control the position. The joystick was wirelessly connected to a receiver, which relayed the information to the calibration software, that comes along with Windows XP. The joystick was connected to PC 2, to switch easily between the Excel-sheet and calibration tool to copy the X and Y data from the calibration tool to the Excel-sheet.

Pointing training Before every session that required pointing, participants were asked to point straight forwards, zero, straight backwards, zero, straight left, zero and straight right and then back to zero again, where zero is the position in which the rod automatically moves back when released. We observed the accuracy with which they used the device. If the pointing was off by more than 1% (X and Y values ranging from 0 to 1023, where 1% equals approximately 10), participants were corrected and asked to repeat this procedure, until they handled the device within the 1% accuracy margin.

2.4 Procedure

The following section describes the procedure used in this experiment. The order in which the different parts appear is the order in which those parts occurred during the experiment. The time used for methods described in subsections 2.4.1 – 2.4.4 was about 2 hours, and the main experiment described in subsection 2.4.5 took 45 minutes, resulting in a 2:45 hour session.

2.4.1 Forms, general questions, screening for motion sickness and Romberg test

Participants were appointed through an online system contracted by the Vanderbilt University. Upon arrival, participants were asked to fill out and sign the IRB approval form and payment statement. A screening phase followed, where participants needed to complete certain tasks in order to be admitted to the experiments. We screened them for motion sickness on a scale from 0 to 100%, 0% = I have never experienced motion sickness, 100% = I get motion sick very easily.

Romberg test to assess proper vestibular function After screening for motion sickness, it was important to know whether the vestibular system of the participant is working properly. A healthy vestibular system gives cues about a person being accelerated or moved. In case of a defect or insufficiency of the vestibular system, conflict cues might be less intense for participants suffering this condition. To asses, if the vestibular system works within common parameters, participants underwent the Romberg test, which is easy to implement.

Participants were asked to remove their shoes, stand heel-to-toe such that their feet formed a straight line. Both arms were in a relaxed position next to the body and the eyes were closed. Normal young participants should be able stand like this for about 30s, and low normal performance should still exceed 6s (Khasnis & Gokula, 2003). Each participant performed three of these Romberg tests and were required to switch feet each time. We observed how long they were able to remain stable without falling or opening their eyes. All participants passed all three tests for at least 30s and thus had sufficient vestibular function to participate in the subsequent experiments.

2.4.2 Vection demonstration phase

After successful completion of the screening phase, participants got a short 2 step demo phase, where we showed them what the setup can do. In step one, we rotated the platform as well as the chair, so everybody knew that there is rotation possible with this setup. Through this demo, we created the knowledge that one can in principle move freely (top-down influence). This might help participants to get easier into vection and might also effect how they perceive it.

In step two, we showed them how circular vection feels like. This demonstration serves as comparison for the later experiment, where no vection experience was rated 0% and the most intense 100%. Since most participants have not experienced vection to that point, the demonstration phase made sure that they know what we are talking about in the experiment. For the vection demo, we used a combination of biomechanical and auditorily induced vection. This is the condition where our motion simulator produces the highest vection intensity where all other conditions in the experiment will be measured by (gold standard).

Participants sat down in the chair with their feet resting on the platform. They were required to wear a blindfold and headphones. We started the playback of spatialized, rotating acoustical gHRTF cues trough the headphones and presented a 10 second stationary acoustic signal which then started turning. At the same time, the platform kicked in and participants were required to step along the platform sideways. The chair did not move and was fixed in position.

In this condition, conflicting visual cues were blocked out by the blindfold and vestibular conflict cues were minimized by the movement of the feet, since the chair was fixed loosely and had some freedom in both directions. Vection was induced by biomechanical through stepping in place and synchronized auditory cues. In this condition, all participants experienced vection. Two vection demonstrations were used. In demonstration one, participants were asked to relax and just let the experience come. After the first demo, we asked them how and what they felt. All participants reported a sensation of rotation that started some time after the stimulus rotation. In demonstration two, we asked them to remember four specific objects in the room which were placed 90° apart from each other. The first object when turning clockwise was a toy-monkey that we named "ape". It is 45° to the participant's right from the seating position in the chair. The next objects were a bottle of beer at 135°, a mat at 225° and a door at 315°. All objects were labeled with their names on post-it-notes to identify them. Object names were all monosyllabic to make it easier for participants to call them out later on. This vection demonstration phase was conducted similar to the previous one, except, that subjects were required to indicate the onset of vection and to call out one of those four objects, when they feel like facing it.

When both demonstrations were finished, we asked participants about how this experience compares to the other and how they currently feel.

2.4.3 Recording phase

We took an overall of 11 recordings. 9 recordings were conducted for 2 pretest phases (auditory localization ability test and auditory motion direction pretest, see subsection 2.4.4) and two for the actual experiment described in subsection 2.4.5. Those recordings were taken using each participant's own ears (iHRTF). In addition to that, we had 11 recordings fashioned the same way used for a gHRTF condition, which means a set of 11 recordings was taken "trough" somebody's ears but played back for somebody else in order to compare the performance of participants during the pretest regarding individual versus generic recordings.

For the recording phase, participants were seated in the chair, facing towards the guitar amp at 0°. They were wearing the core microphones correctly placed on their ears during the whole recording phase to ensure the same microphone-placement for all recordings (see Figure 6). Each participant was asked to rest the elbows on the armrest while placing the head on the back of both fists in order to stabilize the head in an unobtrusive manner . We then played back a collection of Brazilian birds and a river noise, positioned at 0° and -90°, respectively. Several different birds were added to an audio track and individually looped for about 240 seconds, longer than any condition in the pretests or the actual experiment would take. All bird tracks were then put on the left channel. The same procedure was undertaken for the river noise, where different river and water sounds were added to individual audio tracks and then individually looped for 240 seconds. The river audio tracks were put on the right channel. For the auditory localization ability test recordings, we played back the bird sound originating from the guitar-amp in front of the participant's initial 0° seating position only.

Stationary audio localization recordings We asked participants to rotate to 9 positions using their feet. Each position is determined by an object located in the room (objects named in clockwise order): amp at 0°, post-it-note marked as "R" at 10°, ape at 45°, beer at 135°, treadmill at 180°, mat at 225°, door at 315° and a post-it-note marked "L" at 350°. They were facing it until notified by the experimenter to move on to the next object. We took 12 second recordings (2 second fade-in, 10 seconds auditory cue) for each object participants were facing, creating a collection of sound samples containing different acoustic directions of the same sound source.

Moving audio recordings Three additional recordings were taken in stationary and rotating condition. For those, we used two sound sources. The bird noise (as we did in the previous recordings) originated from the guitar amp (left channel) and additionally the river noise emitting from the Harman Kardon speaker (right channel). Participants kept sitting in the chair and rotated themselves back into the 0° position facing the guitar amp. Two recordings were taken for the rotational condition (clockwise and counterclockwise) and one for the stationary condition. Participants kept their feet on the platter of the platform which rotated, moving person and chair along with it. The two rotational conditions had the following profile: both sound sources were active and the participant was in alignment with the guitar amp (0°). The recording started and the first 10 seconds were completely motionless. At second 10, the platform started rotating with an acceleration from 0 to 60°/second in 2 seconds. In constant velocity, we rotated participants at a rate of 60°/second for 90 seconds and then slowed them down to the stationary (initial) position, facing the guitar amp at 0°.

We wanted the same acoustic sound sources to be included in the stationary recording as well to make stationary and rotational recordings comparable, so we used the same platform rotation profile for the stationary recording. Participants had their feet rested on the footrest and were stationary during the whole recording.

After the recording phase, we cut a 20 second piece out of the middle of the stationary recording and the two rotating recordings to use them later in the auditory motion direction pretest. To manage all recordings, we created a template which already contained the gHRTF recordings. Every audio track was labeled accordingly and color-coded to ensure reliable operation by the experimenter.

2.4.4 Auditory pretests

Auditory localization ability test The ability of participants to localize a stationary sound source in an acoustically presented room might have an influence on the vection experience and in turn on the experiment that follows. To test this, we conducted an auditory localization ability test that used 2 HRTF conditions (iHRTF and gHRTF) for each of the 9 locations. Participants had to point to the direction where they perceive the sound coming from (2 different HRTFs (iHRTF, gHRTF) x 9 locations (9 object positions) = 18 trials, lasting 12 seconds each). Participants were seated in the stationary chair (0° position), wearing headphones and a blindfold. Pointing was achieved with the use of the pointing device mentioned in subsection 2.3.7. We used the opportunity to compare the localization performance between conditions with iHRTF and gHRTF. All conditions were randomized to prevent effects that might occur due to the order in which trials were conducted.

see Figure 7

Auditory motion direction test We conducted the auditory localization ability test because we think, that the ability to judge auditory motion direction might also influence the results of the experiment. The auditory motion direction test had 12 trials, 20 seconds each (2 HRTF conditions (iHRTF, gHRTF) x 3 auditory cue conditions (clockwise, counter-clockwise, stationary) x 2 repetitions). In this pretest, participants were seated in the chair (0° position), wearing headphones and a blindfold. The participant indicated the perceived motion direction trough the pointing device mentioned in subsection 2.3.7. They were asked to deflect the joystick in the direction they perceived the bird noise to originate from, and change the direction of deflection when they perceived the sound to rotate around them. The latter resulted in a circular motion of the joystick rod which was used to assess the perceived auditory rotation direction. In case of the stationary condition, the pointing response was used to test for front-back confusion and whether participants correctly perceived the sound as stationary. As it was the case with the previous test, we used the opportunity to compare the performance of judging auditory motion direction between iHRTF and gHRTF conditions. Again, we randomized conditions for the reasons mentioned above.

2.4.5 Main experiment phase

The main experiment was conducted upon completion of all methods in the order listed above (subsection 2.4.1 – 2.4.4) and took about 45 minutes. It consisted of 16 trials (2 motion directions (clockwise, counter-clockwise) x 2 jitter conditions (jitter on/off) x 2 feet conditions (feet on ground/suspended) x 2 repetitions per condition). All conditions were balanced to avoid effects due to the order of trials.

Participants were seated in the chair (0° position) and were stationary for all conditions in this experiment. They were asked to remember the following objects in the room: the ape (45°), beer (135°), mat (225°) and the door (315°) and had to call out the object name whenever they felt like they were facing it during circular vection. Furthermore, we asked them to indicate vection onset, which is the first moment when they feel like they were moving. After participants familiarized themselves with those objects, we explained the questions that followed each trial.

During the trials, participants were asked to wear headphones and a blindfold. After each trial, they had to take off the headphones and blindfold to re-anchor themselves with the physical room. In conditions where their feet rested on the footrest, participants put their feet back on the platform after each trial for the same purpose. Using those measures avoids effects of being blindfolded for a long duration: Depriving a participant from conflict cues over several trials might create a situation where the vection intensity is lower at the beginning and higher towards the end. The perceptual system might weight auditory cues stronger towards the end since other (mainly visual) sensory inputs might have decreased in their priority (e.g. blindfolded eyes meaning no new input for a while). This would effect trials towards the beginning differently than trails at the end and hence might have impaired our data.

After participants were briefed regarding the procedures, we started a series of test-trials in order for them to learn the routine. When participants were sufficiently secure in performing the tasks required, we started the actual experiment.

Each trial required the playback of iHRTF recordings either clockwise our counter-clockwise (alternating). Depending on the trial, participants had their feet on the footrest or on the ground, with or without additional vibrations.

2.5 Variables

The following section describes which variables were modified ("independent variables") and which variables we got as a result of the modification (the actual measurements or "dependent variables").

2.5.1 Independent variables

Independent variables are factors or control variables that can be changed by the experimenter in order to observe effects resulting due to that change. Independent variables in this experiment were

- jitter (on/off),
- feet on/off ground
- turning direction of the audio cues (clockwise/counter-clockwise).

2.5.2 Dependent variables

Dependent variables are the measurements we took for each given set of independent variables. During each trial, participants were asked to verbally indicate when they started perceiving any kind of vection, which was defined as the vection onset time. As many participants experienced trials where they did not perceive any vection at all (this was particularly true in the no-jitter, feet-on-ground condition), we assigned a fictitious vection onset time of

102s to those trials, which was the whole duration of the motion phase. This was referred to as the “estimated vection onset time” in Figure 8. Note that this is a conservative estimate of the vection onset time in the sense that if participants would have perceived vection for longer stimulus presentation, the resulting vection onset times would all be beyond 102s. Hence, any statistical result should hold true if we would instead use a longer stimulus presentation. The percentage of trials where any vection was experienced was used as an additional measure for the vection-inducing power of the respective experimental stimuli.

In addition to vection onset, participants also reported one of the four previously memorized objects in the moment when they feel like facing it by calling out its name as described above. The experimenter used a stop watch to take times between the beginning of the playback and the verbal indications of the participant. This method resulted in a table of data for each participant containing lines with values for each trial marking the absolute time between the beginning of the recording and the event a participant reported. A line starts usually with the time between the beginning of the payback and the moment, when the participant indicated the perception of self-movement (vection onset time). The following values are the absolute times between the beginning of the recording and each object they felt like facing.

Through this table, we could determine the vection onset time (time between start of the recording and indication of movement) and the function of perceived rotational speed over time. In addition, the experimenter noted the first and the last two object names, that were called out, to verify the perceived rotational direction.

At the end of each trial, participants were verbally asked the following questions to quantify their vection experience:

- “How intense was the onset of vection?” [0,100]%
- “How intense was the sensation of self-motion towards the end?” [0,100]%
- “How intense was the sensation of self-motion overall?” [0,100]%
- “Did you really feel like rotating in the physical room?” [0,100]%

Participants responded verbally on a continuous scale from 0-100%.

2.6 Data analysis

The following section describes in short what measures we used to gather and present the data. For data collection and presentation, we used Microsoft Excel. The data analysis was done using SPSS. One data sheet was used for the collection of data in this experiment. Columns were describing the variables and the lines contained values and collected data across all variables, one line for each trial. Independent variables were color coded to make the preparation of the setup easier, reducing mistakes in and between trials. We used the same color coding for the audio tracks in ProTools so that the operator knew what track to select for the next trial. When the data was collected, complete and checked, we summarized and visualized it to show basic features through plots. In the following section are the methods we used to describe basic properties of the data we collected:

2.6.1 Standard deviation (SD)

$SD = \sqrt{\frac{\sum(X-\bar{X})^2}{(n-1)}}$

X each data point or score

$\bar{X}$ the mean over all X

n number of values or scores

The standard error is most commonly used as a measure of spread. In this case, it showed us the volatility in our data. Since two sets of measurements can have the same mean, the values around that mean can differ for each set. For example, picture a sports team that performs well in one field and poor in another field. As comparison, we look at another sports team, that performs moderately in all areas. Both have the same mean, but the prediction of performance of the second team is closer to what happens when they are playing than it is with team one. The standard Deviation takes all scores into account and is not as strongly effected by an outlier as it is the case with the mean.

2.6.2 Standard error (SE)

The benefit of calculating the standard error is to avoid running experiments several times in order to determine error rates from all experiments conducted. As one might suspect, the standard error gets less with a rising number of participants.

$SE = \frac{SD}{\sqrt{N}}$

SD Standard Deviation

N Number of participants

With the standard error, we were able to calculate a confidence interval as seen in the graphical analysis below. Error bars are means to show confidence intervals in graphical analysis. As a rule of thumb, one can conclude, that the difference between two means is statistically insignificant when two error bars overlap.

2.6.3 Analysis of variance (ANOVA)

An ANOVA helps us to determine if there is a systematic and statistical significant difference between the four sets of measures we took for the no-feet-no-vibration condition, the feet-condition, the vibration-condition and the feet-and-vibrations-condition. It basically compares variances and tests if there is an effect of the conditions. The Null hypothesis in the context of this study is that all conditions yield the same effect. If the Null Hypothesis is rejected, at least two of those conditions are different from each other and thus, have an effect.

2.6.4 Statistical power η^2

η^2 is a statistical measure that quantifies what proportion of the observed variance of a dependent measure (e.g., vection intensity) can be accounted for by the tested independent variable (e.g., adding vibrations). An η^2 value of 35% is regarded as strong.

3 Results

The data from the various dependent measures were analyzed using separate repeated measures within-subject ANOVAs for the independent variables jitter (on/off) and feet (on floor/suspended). The ANOVA results are summarized in Table 1, and the data are graphically represented in Figure 8.

3.1 Influence of adding jitter to auditory vection

Vection was significantly enhanced in all dependent measures, and even the percentage of trials where vection was reported showed a marginally significant (p=.057) increase when jitter was added. Considering the small number of participants tested, these results are, in fact, quite substantial. Furthermore, more than 60% of the variability in the data could be attributed to the jitter, as indicated by values of $\eta^2 > 60\%$ for all dependent measures.

3.2 Influence of suspending feet

When participants were asked to put their feet on the solid, non-moving ground (instead of having them suspended with the hammock chair) and held one hand onto a stationary chair that was positioned within reaching distance, there was an overall tendency towards reduced vection in all dependent measures – this trend did not reach significance though. Nevertheless, between $\eta^2 = 38.5\%$ and $\eta^2 = 53.5\%$ of the variability in the data could be ascribed to the hand and feet sensing a stationary position. This suggests that more reliable effects might be expected if more participants were to be tested, which we plan to do in the near future.

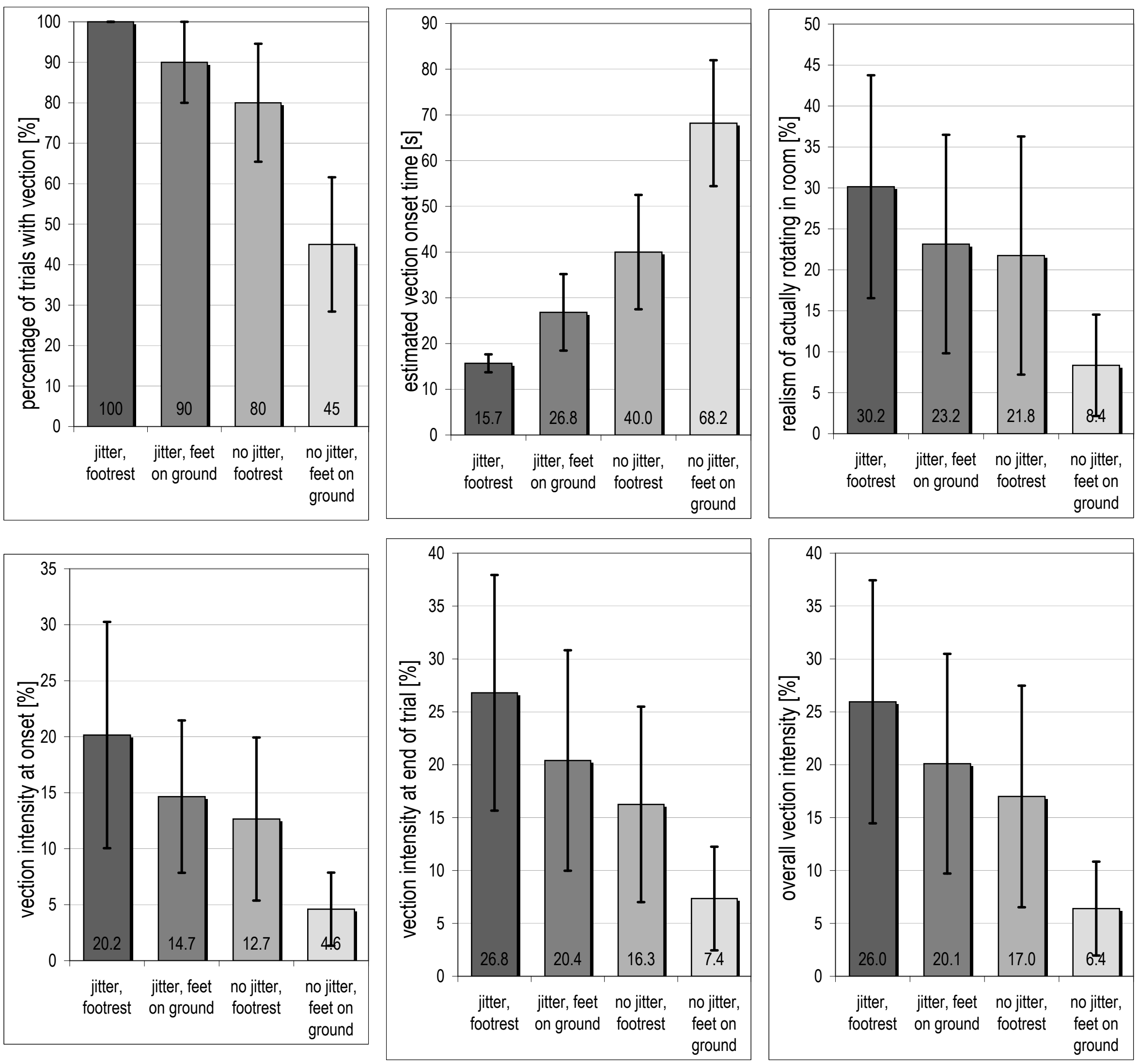

Figure 8: Vection data for experiment 1. The bars represent the arithmetic mean, the whiskers depict one standard error of the mean.

	Jitter (on/off)			Feet on floor/suspended			Interaction jitter – feet		
	F(1,4)	p	η^2	F(1,4)	p	η^2	F(1,4)	p	η^2
Percentage of trials with vection	*7.04*	*.057m*	*63.8%*	3.86	.121	49.1%	*5.00*	*.089m*	*55.6%*
Estimated vection onset time	**8.41**	**.044***	**67.8%**	3.41	.138	46.0%	*5.01*	*.088m*	*55.9%*
Realism of actually rotating in room	**10.13**	**.033***	**71.7%**	*4.61*	*.098m*	*53.5%*	.44	.54	9.9%
Vection intensity at onset	**8.00**	**.047***	**66.7%**	2.51	.189	38.5%	.64	.466	13.9%
Vection intensity at end of trial	**9.83**	**.035***	**71.1%**	4.42	.103	52.5%	.25	.645	5.8%
Overall vection intensity	**9.88**	**.035***	**71.2%**	3.66	.128	47.8%	.59	.484	12.9%

Table 1: Analysis of variance results for the different dependent variables. The asterisks indicate the significance level (α = 5%, 1%, or 0.1%). Significant and marginally significant effects are typeset in bold and italics, respectively. The effect strengths η^2 indicates the percentage of variance explained by a given factor.

4 Discussion and conclusions

As the data shows above, adding jitter to the auditory stimuli has a significant effect on vection ratings. Using vibration in concert with auditory vection yields clearly a cross-modal benefit. The fact that we synchronized onset and end of vibrations with the appearance of the motor noise in the auditory stimuli seems to support the auditory cues and make them more plausible. The strong effect of vibration in any condition becomes more striking considering the small sample we used.

A look at the effect sizes (quantified using η^2) and the data plots in Figure 8 suggests that by just suspending one's feet, one can get almost the same enhancement of vection as by adding vibrations. This is a substantial finding since recent studies showed a strong benefit of vibration for auditory as well as visually induced vection. There might be two aspects to this effect. 1) The setup we used gives participants more leeway to move in the sling-chair than it would be the case with office-chairs. Placing the feet on the floor creates a connection to a stationary object which limits its freedom to swing. Especially in conditions where the feet are suspended and vibrations are on, the slight physical swinging of the chair might provide sufficient proprioceptive noise to substantially decrease conflict cues from the vestibular system. 2) The knowledge that participants have about the chair and its capabilities might convince them that they are rotating when the feet are suspended. It is actually hard to tell if one is moving or not when the feet are suspended. Minimal factors can then lead to the assumption of movement, like swinging or vibrations. Further data from more participants is needed to corroborate this hypothesis. If true, however, this would be an intriguing finding that suggests higher-level and top-down contributions to auditory vection – especially considering that these issues have been largely neglected in studies so far.

Across all other items, the difference of those two conditions is marginal. All bars indicate a trend towards the benefit of having the feet suspended either in combination with vibration or without it. Considering the rather large effect size, studying this further is worth while pursuing. Due to time constraints and the limited number of participants who actually experienced vection, revisiting this study with more participants might most likely support this trend further and increase differences between conditions.

Looking at cross-modal benefits of adding vibrations to suspended feet one can clearly see the highest ratings across all items. In those condition it seems easier for participants to experience vection indicated by strongly decreased vection onset times. Participants indicated the highest sense of realism and the strongest feeling of rotating in this study. Realism ratings are about 3.5 times higher in cross modal conditions than in the pure auditory vection condition (see Figure 8, top right). Vection is happening more likely for participants with their feet placed in the footrest and more so when they keep their feet on the ground and experience jitter, which shows a slightly stronger effect of vibrations over feet position. Vection most likely occurred in this study, when the feet are suspended and vibrations are on, which is consistent with other ratings for this condition. Since auditory vection is only occurring in about 25-60% of all participants, the implications of “enabling” auditory vection for a broader range of participants pose quite a potential. Pursuing this finding might make it easier to study auditory vection since it could be evoked more commonly. It shows a clear benefit for the design of motion simulators, where vection is required to be reliable for certain applications.

Due to time constraints, we did not further look into the data gathered during the auditory localization ability as well as the auditory motion direction pretests. We plan on revisiting this study soon and hope to find a relationship between hearing accuracy and self motion perception. We do look forward to the results comparing the performance of gHRTF with iHRTF cues when localizing sound sources. We did not take a closer look into the data we gathered through the indication of the object names, but would like to integrate the data collected in the light, that we get a more in-depth look into the vection experiences.

We found in this study, that vibrations not only benefit visually (Riecke et al., 2005a; Schulte-Pelkum et al., 2004) but also auditory vection, which is in agreement with (Riecke et al., 2005b; Väljamäe et al., 2006, 2008b). We were the first to take a closer look into the placement of participants and successfully showed, that body suspension actually increases perceived motion. A synergistic effect seems to surface when joint modes or different sensory stimuli are specifically combined to facilitate each other(Riecke et al., 2005b, 2005a; Riecke, Schulte-Pelkum, & Caniard, 2006; Riecke et al., 2008; Schulte-Pelkum & Riecke, 2008; Väljamäe et al., 2006, 2008b; Wong & Frost, 1981).

The human perception is by far not yet fully discovered and hopefully the findings laid down in this experiment will shed some light on how we perceive and motivate further research in the field of cross-modal or auditory vection. The chance we presented here, that top-down processes might benefit vection adds a new field of interest to the studies of self motion perception. In practice, by just showing and telling participants what a simulator could in principle do might benefit vection. Imagine to increase the capabilities of a simulator by just providing participants with the right information about the setup. It would then e.g. be sufficient to use a simple, rotating platter that could never turn a subject, but produces the desired impression which then effects the assumption of turning. In theory, the implications of a perception that is bidirectional (bottom up as well as top-down) changes the way and established opinion on how to look at human perception, where top-down processes might be equally important. Examples of optical illusion where “one sees what one knows” could give a fresh view on self motion perception.

Applying this knowledge in further research and the design of motion simulators brings us closer to our goal of creating the perfect illusion.

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