Auditory self-motion illusions ("circular vection") can be facilitated by vibrations and the potential for actual motion

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Abstract

It has long been known that sound fields rotating around a stationary, blindfolded observer can elicit self-motion illusions ("circular vection") in 20-60% of participants. Here, we investigated whether auditory circular vection might depend on whether participants sense and know that actual motion is possible or impossible. Although participants in auditory vection studies are often seated on moveable seats to suspend the disbelief of self-motion, it has never been investigated whether this does, in fact, facilitate vection. To this end, participants were seated on a hammock chair with their feet either on solid ground ("movement impossible" condition) or suspended ("movement possible" condition) while listening to individualized binaural recordings of two sound sources rotating synchronously at 60°/s. In addition, hardly noticeable vibrations were applied in half of the trials. Auditory circular vection was elicited in 8/16 participants. For those, adding vibrations enhanced vection in all dependent measures. Not touching solid ground increased the intensity of self-motion and the feeling of actually rotating in the physical room. Vection onset latency and the percentage of trials where vection was elicited were only marginally significantly ($p<.10$) affected, though. Together, this suggests that auditory self-motion illusions can be stronger when one senses and knows that physical motion might, in fact, be possible (even though participants always remained stationary). Furthermore, there was a benefit both of adding vibrations and having one's feet suspended. These results have important implications both for our theoretical understanding of self-motion perception and for the applied field of self-motion simulations, where both vibrations and the cognitive/perceptual framework that actual motion is possible can typically be provided at minimal cost and effort.

CR Categories: H.1.2 [Models and Principles]: User/Machine Systems—Human factors, Human information processing H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems—Artificial, augmented, and virtual realities J.4 [Social and Behavioral Sciences]: Psychology

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1 Introduction

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. This might limit perceived realism, behavioral effectiveness, user acceptance, and thus commercial success. 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.

1.1 Self-motion illusions

Among the most compelling illusions are self-motion illusions ("vection"), where moving visual stimuli can induce a powerful sensation of self-motion, even though one never physically moves [Dichgans and Brandt 1978; von Helmholtz 1867; Mach 1875; Warren and Wertheim 1990]. Many people know this phenomenon as the "train illusion": When sitting in a stationary train waiting to depart from the train station, watching a train departing from the adjacent track can induce a strong (but erroneous) sensation that one's own train is departing in the opposite direction.

Moving auditory stimuli can elicit similar, albeit less compelling, illusions of self-motion in blindfolded listeners. Although auditory vection has been described a long time ago [Dodge 1923] and later been replicated several times [Gekhman 1991; Hennebert 1960; Lackner 1977; Marmekarelse and Bles 1977], there has only recently been an increased interest in this interesting phenomenon [Larsson et al. 2004; Riecke et al. 2005c; Sakamoto et al. 2004; Väljamäe et al. 2004]. For recent reviews on auditory vection, see [Riecke et al. 2008a; Väljamäe 2005; Väljamäe 2007]. While earlier studies typically used an array of speakers to present sound fields rotating around the stationary blindfolded listener, more recent studies demonstrated that headphone-based, real-time spatialized audio rendering can also be employed to induce both circular and linear vection. In the current study, we addressed two open questions that will be outlined in the following subsections.

1.2 Does the possibility of actual self-motion facilitate illusory self-motion?

Recently, there has been an increasing number of studies showing that vection is not only affected by low-level, bottom-up factors like the physical parameters of the vection-inducing stimuli, but also by cognitive, higher-level factors like the interpretation and meaning of the vection-inducing stimulus [Palmisano et al. 2000; Palmisano et al. 2003; Riecke et al. 2005c; Schulte-Pelkum and Riecke 2008]. Here, we were interested in investigating whether one's perception, pre-knowledge, and assumptions about whether actual motion is possible or not might affect circular auditory vection.

1.2.1 Visual vection

Lepecq and colleagues demonstrated that children of 7 or 11 years perceive visually induced linear forward vection earlier when they were seated on a chair that could potentially move [Lepecq et al.

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1995]. However, the probability of obtaining vection remained unaffected by this manipulation. Later studies showed that adult observers perceive linear up-down ("elevator") vection as more compelling when they knew that actual body displacement was possible [Wright et al. 2006]. Note that neither the vection onset latency nor the perceived distance traveled was affected. Several others linear vection studies also seated participants on movable platforms [Andersen and Braunstein 1985; Berthoz et al. 1975; Pavard and Berthoz 1977], but without quantifying whether this manipulation affected vection responses.

We are not aware of any study that demonstrated the influence of the possibility of actual self-movement on circular vection. Riecke and colleagues showed that about 2/3 of participants can be fooled into believing that they physically rotate if they know that this is, in fact, possible [Riecke et al. 2005c; Schulte-Pelkum et al. 2004]. Neither vection onset latency, intensity, or compellingness were affected by whether or not actual motion was possible.

1.2.2 Auditory vection

Here, we investigated whether auditory circular vection induced by a rotating sound field in blindfolded adult participants might be facilitated if they knew and sensed that actual rotation was possible. To this end, participants were seated in a hammock chair, and either put their feet on solid ground ("motion impossible" condition) or on a footrest attached to the hammock chair ("motion possible" condition). Even though participants are often seated on a potentially rotating chair in auditory circular vection studies [Lackner 1977; Väljamäe 2005; Väljamäe 2007], we are not aware of any study that investigated whether this does, in fact, facilitate circular vection. If this should turn out to be true, however, it would not only be of theoretical interest, but also relevant for many self-motion simulation applications, where it is often desired to provide a natural and compelling experience of the simulated environment and one's movement through that environment: Actual movements in the real world are typically accompanied by a strong sense of self-motion, suggesting that all virtual reality or multi-media simulations that do not elicit a similar feeling of self-movement might be severely limited and might not enable natural, effortless behavior and spatial orientation in particular [Riecke et al. 2005b].

1.3 Influence of vibrations on vection

Albeit vibrations being frequently used in motion simulation and multi-media applications, there has only recently been experimental evidence that providing vibro-tactile stimulation of the participants' seat can in fact increase both visually induced linear/circular vection [Riecke et al. 2005b; Schulte-Pelkum et al. 2004; Schulte-Pelkum 2008] and auditorily induced linear vection [Väljamäe et al. 2006]. Note that in the study by Väljamäe and colleagues on linear, auditorily induced vection, adding vibrations facilitated vection only when accompanied by an engine sound and/or when only one rotating sound source was used. In a recent study on auditory circular vection, however, vibrations did not facilitate the self-motion illusion [Väljamäe 2007, paper C]. This negative result might, in part, be related to the low amplitude to the vibrotactile stimulation: Only one of the 16 participants apparently noticed the vibrations when debriefed.

Here, we assessed whether vibrations that are still quite subtle, but above the perception threshold, can facilitate auditory circular vection. If so, this would extend our understanding of multi-modal cue integration for self-motion simulation. Furthermore, it would provide important evidence for self-motion simulation applications, where seat vibrations can be readily applied with affordable, off-the-shelf hardware.

1.4 Underlying mechanisms for the facilitation of vection

We propose that vibrations might facilitate vection by reducing our perception and assumption of stationarity. That is, vibrations are expected to decrease the reliability of the information indicating stationarity and/or might be conceptualized as a Bayesian prior [Ernst and Bülthoff 2004]. In a cue combination framework like a maximum likelihood estimation model, this would be expected to decrease the relative weighting of the cues indicating stationarity, such that the (auditory) cues indicating self-motion might be more likely do dominate, leading to an increase in vection. Similarly, if our feet are stationary on solid ground, this might serve as a Bayesian prior indicating stationarity and/or increase the reliability and in turn the weighting of the cues indicating stationarity, which would be expected to decrease vection.

Now why do we not use a theoretical framework like the maximum likelihood estimation model to mathematically predict the influence of the different control parameters on vection in the current experiment? As we will outline below, such a framework seems simply unfeasible for our context, unfortunately: In cue combination studies using a maximum likelihood estimation approach, the prevailing approach seems to be to compare two estimates of the *same absolute quantity* (e.g., haptic and visual estimation of absolute object size [Ernst and Banks 2002]). The weighting of the individual cues is typically based on their respective reliability, which is estimated as the inverse of their respective variances $(1/\sigma^2)$ divided by a normalization factor. For the example of visuo-haptic size estimation, visual-only and haptic-only pre-experiments would be used to assess the visual and haptic variability of the size estimates, respectively. These single-cue visibilities define the weighting factor and thus predict the combined-cue (here: visuo-haptic) size estimate.

To extend the maximum likelihood formalism to the case of vection, we would need to define an absolute quantity that can be estimated in both single-cue and combined-cue experiments. Measures like vection, perceived self-rotation velocity or perceived stimulus velocity might come to mind as potential candidates. But as vection studies by there very nature comprise a cue-conflict situation between cues indicating stationarity (here: vestibular, proprioceptive, or biomechanical cues) and vection-inducing cues indicating object- or self-motion (here: auditory cues), measures of the former will under normal circumstances always yield null-results with zero variability, in the sense that participants will experience no vection, no object motion, and no self-motion, with zero variability in there estimates. Moreover, it seems impossible to perform single-cue experiments with just the vection-inducing stimulus alone, as there is simple no (or at least no ethically acceptable) way to completely switch off potentially interfering vestibular, proprioceptive, and biomechanical sensations. A further complication is the exponential decay of vestibular signals over time, which would require a time-dependent model [Mergner and Becker 1990].

2 Methods

Participants All 16 Participants in this experiment had normal or corrected-to-normal vision, normal, binaural hearing, and no signs of vestibular dysfunction, as determined by a Romberg test [Khasnis and Gokula 2003]. Only eight of these 16 participants experienced any auditory vection[1]. The remaining eight participants thus had to be excluded from the data analysis. This ratio is in accordance with the literature, where auditory vection typically occurs

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[1] In the condition without vibrations and feet on the ground, only six of them experienced auditory vection. In the other conditions, all eight participants perceived vection in at least some of the trials.

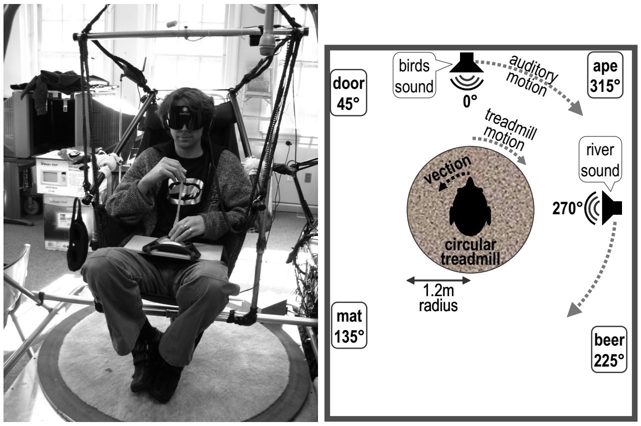

Figure 1: ***Left:*** *Experimental setup showing the circular treadmill and a participant seated on the hammock chair with blindfold, noise-canceling headphones, and a pointing device used for a sound localization pre-test. Note that throughout the test phase, the treadmill was switched off and the hammock chair was fixed to prevent actual chair rotations.* ***Right:*** *Top-down schematic view of the experimental setup (not drawn to scale). Note that treadmill motion was only used during the vection demonstration phase.*

only in about 20-60% of blindfolded observers [Lackner 1977; Väljamäe 2007]. The eight participants (five female) who perceived auditory vection were between 18 and 32 years old (mean: 22.7) and had various occupational backgrounds. Participation was voluntary and paid at standard rates. The experiment was approved by the IRB and conducted in accordance with ethical standards laid down in the 1964 declaration of Helsinki. Participants gave their written informed consent prior to the experiment.

2.1 Stimuli and apparatus

Hammock chair and circular treadmill Throughout the experiment, participants were seated on a hammock chair that was hanging from a swivel joint centered above a 1.2×1.2m circular treadmill, as illustrated in Figure 1. A detailed description of the setup can be found in [Feuereissen 2008]. The treadmill was used to rotate participants during the binaural recordings and thus provide the experience that the hammock chair can, in fact, rotate. The circular treadmill was switched off for the rest of the experiment.

Vibrations To provide barely noticeable vibrations in half of the trials, a small eccentric motor (a modified USB fan) that rotated at about 7 Hz was mounted on the horizontal cross-bar of the hammock chair, as illustrated in Figure 2 (Right). The onset and offset of the vibrations was synchronized with the onset and offset of the auditory motion, respectively, as this was expected to enhance the sensation of a consistent motion metaphor, which has been shown to be essential for auditory vection [Väljamäe 2007].

Sound sources and target objects As illustrated in Figure 1 (right), two speakers were placed directly to the front (0°, 2.3m away) and the right (270°, about 3.3m away), respectively, of the participant seated in the hammock chair. During the binaural recordings (and only then), the 270° speaker displayed a custom-made mix of several river and waterfall noises, and the 0° speaker displayed a custom-made mix of 14 different bird sounds. The stimuli were chosen because they could be well localized, easily disambiguated, and were much less disturbing than the white/pink noise stimuli used in many studies. As sketched in Figure 1, the room contained four target objects positioned at 45° (door), 135° (mat), 225° (beer), and 315° (ape) with respect to the observer seated in the default orientation.

Figure 2: ***Left:*** *Side view of the experimental setup, showing a participant with his feet suspended in the footrest attached to the hammock chair ("movement possible" condition).* ***Center:*** *Miniature microphones positioned at the entrance of the ear canals during the binaural recordings* ***Right:*** *A USB fan was modified to act as an eccentric motor that provided barely noticeable vibrations to the hammock chair.*

Binaural recordings Binaural recordings served to generate the sound files that were later used to induce auditory circular vection. To this end, participants were seated on the hammock chair facing 0°, and were passively rotated either counterclockwise or clockwise, at the velocity profile described in Figure 3 and a maximum velocity of 60°/s. To ensure that participants moved in sync with the treadmill, they were asked to keep their feet stationary on the platter of the rotating treadmill without stepping along. The speakers located at 0° and 270° displayed the bird and river sound mixes, respectively, throughout the recording. For the binaural recordings, we used miniature microphones (Core Sound Binaural Microphone Set) mounted at the entrance of the ear canal, as illustrated in Figure 2. An external high-quality analog-to-digital audio converter (DigiDesign MBox2) attached to a laptop mounted on the hammock chair was used for the binaural recordings as well as the audio playback during the experiment. Participants were instructed to rest their elbows on the armrest while placing the head on the back of their fists in order to stabilize their head in an unobtrusive manner. Note that participants always listened to their own, individualized recordings during the subsequent vection experiment in order to improve spatialization fidelity. Hence, the binaural recording sounded just like what it would sound like to rotate in the lab, and the recording naturally included all reflections, reverberations, and ambient sound of the room. Sound recording samples are available at `www.kyb.mpg.de/publication.html?publ=5097`.

Audio playback During the main experiment, participants were seated on the hammock chair, blindfolded, and equipped with active noise canceling headphones (Audiotechnica AT-7ANC) displaying the individualized binaural recordings. Note that the binaural recording acted not only as a vection-inducing stimulus, but also as a masking sound for the noise and ambient sound present in the actual lab.

2.2 Procedure

The experiment lasted a total of about 2h per person and consisted of the following parts described in chronological order.

Demonstration of possibility of movement To demonstrate that physical motion is possible, participants were seated on the hammock chair, and the chair and treadmill were rotated. We hypothesized that this experience and knowledge that actual rotation is possible might facilitate experiencing vection later ("suspension of disbelief").

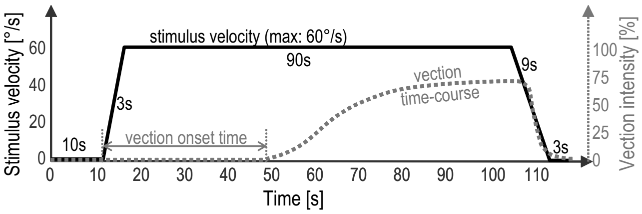

Figure 3: *Time-course of the rotating vection-inducing sound field (solid black line) and hypothetical vection intensity (dashed gray line).*

Vection demonstration phase To explain the concept of vection and demonstrate what compelling vection should feel like, participants were exposed to four trials where the auditory motion was accompanied with synchronized treadmill rotation (see Fig. 3), thus resulting in a combination of auditory and biomechanical vection [Riecke et al. 2008b]: While being blindfolded, wearing headphones, and seated on the stationary hammock chair, participants were asked to step along with the platform once it started rotating [Bles 1981]. As expected, this procedure elicited compelling circular vection in all participants.

Calling out target objects Throughout the vection demonstration phase and main experiment, participants were instructed to continuously keep track of their orientation with respect to the lab and the four targets positioned at 45°, 135°, 225°, and 315°. To quasi-continuously assess which direction participants perceived themselves facing once they perceived actual self-motion, they were asked to call out the name of the respective target object whenever they believed they were actually facing it. This allowed us to assess whether vection is decoupled of the surrounding environment or whether vection resulted in an updating of one's mental representation of the surrounding lab. Furthermore, this procedure allowed us to estimate the time course of the perceived self-rotation velocity. The mean perceived vection velocity was estimated by dividing the total angle turned (estimated by the adding the relative angles between all the passed target objects) by the total duration of the vection experience (estimated by subtracting the vection onset time from the total stimulus motion time of 102s).

Binaural recording phase Three binaural recordings of 115s were taken for each participant as described above, one for clockwise motion, one for counterclockwise motion, and one stationary recording.

Auditory motion direction perception pre-test A pre-test using 20s sound clips showed that all participants could correctly determine whether or not a presented binaural recording was stationary or moving. When asked to indicate the rotation direction (left/right) of a binaural recording, they correctly responded in 85.7% of the trials. The remaining 14.3% of erroneous responses can probably be ascribed to front-back confusions: When the presented sound is consistently perceived as front-back mirrored, the resulting motion direction should be left-right reversed as well.

Main vection experiment For the main vection experiment, participants were seated in the chair that was fixed in the 0° position. They were wearing headphones and blindfold and had their feet resting either on the floor ("motion impossible" condition) or the footrest attached to the chair ("motion possible" condition, see Fig. 2). Throughout the main experiment, a large wooden board was put across the turntable of the treadmill such that it could not be moved. This was intended to ensure that participants believed that actual motion was impossible when they had their feet resting on the wooden board in the "motion impossible" condition. During each trial, participants were asked to verbally report as soon as they sensed vection ("vection onset"). Furthermore, they were asked to keep track of their orientation in the lab and in particular their orientation with respect to the four target objects, and call out the object's name whenever they believed they were facing one. The experimenter used a custom-written stop watch program to record these events. After each trial, participants were asked to take off the headphones and blindfold and put their feet on the ground to re-anchor themselves within the physical lab and to reduce potential after-effects and motion sickness. To familiarize participants with the experimental procedure and demands, we performed four practice trials (on for each stimulus combination) prior to the main experiment.

Handling of trials where no vection was perceived As most 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 used the following procedure to avoid discarding those trials and thus biasing the results: Whenever no vection occurred, we assigned a fictitious "estimated vection onset time" of 102s to those trials, which was the whole duration of the motion phase. Note that this is a conservative estimate of the vection onset time in the following sense: If participants would have perceived vection for longer stimulus presentation (as is not unlikely), the resulting vection onset times would all be beyond 102s. Hence, any statistical result should hold true if we would have used a longer stimulus presentation. The percentage of trials where any vection was experienced was used as an additional measure of the vection-inducing power of the respective experimental stimuli.

Post-trial debriefing At the end of each trial, participants were verbally asked the following questions to quantify their vection experience: (1) "How intense was the onset of vection?" (2) "How intense was the sensation of self-motion towards the end?" (3) "How intense was the sensation of self-motion overall?", and (4) "Did you really feel like you were rotating in the physical room?" Participants responded verbally using a continuous scale from 0-100%. Although some of these measures might be highly correlated, we decided to use several different vection measures to test if the experimental manipulation would affect the various aspects of the self-motion experience differently.

2.3 Experimental design

For the main experiment, each participant completed 16 vection trials in one session of about 45 minutes. These trials consisted of a factorial combination of 2 motion directions (clockwise vs. counterclockwise; alternating) × 2 vibrations conditions (jitter on vs. off;) × 2 feet conditions (feet on ground, "motion impossible" vs. feet suspended on the footrest, "motion possible") × 2 repetitions per condition. All conditions were balanced to avoid order effects.

3 Results

The data from the various dependent measures were analyzed using repeated measures within-subject 2 × 2 ANOVAs for the different vection measures and 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 4.

Auditory vection was perceived in 53.1-96.9% of all trials, depending on the experimental condition (see Fig. 4, top left). While 3/8

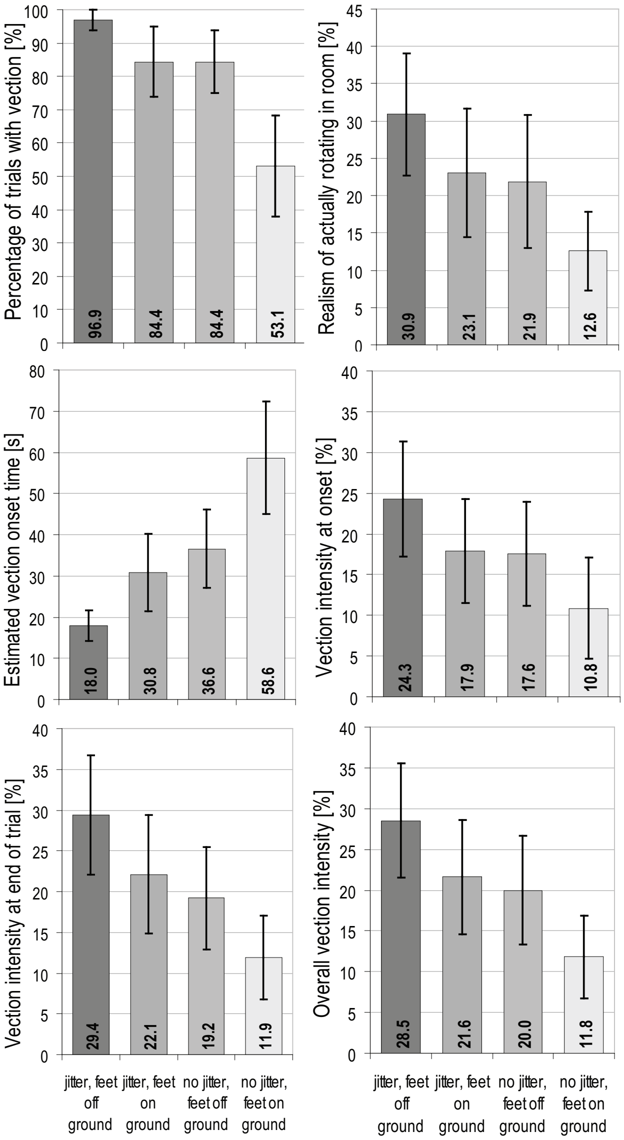

Figure 4: *Vection data for experiment 1. The bars represent the arithmetic mean, the whiskers depict one standard error of the mean.*

participants always experienced vection, others perceived only occasional vection, and 2/8 never perceived any vection in the condition without jitter and feet on ground. This implies that adding jitter or suspending one's feet did not only enhance vection for those participants who can experience vection with pure auditory stimulation, but also increased the overall percentage of participants who experienced auditory vection. Overall vection intensity ranged between 11.9-28.5% and was thus rather low. This is in agreement with the literature, where auditory vection is always found to be much less compelling than visually induced vection.

3.1 Influence of adding jitter to auditory vection

Table 1 shows that adding barely noticeable jitter to the participants' seat significantly enhanced auditory circular vection in all dependent measures. That is, the percentage of trials where vection was perceived was increased, and the intensity of the self-motion sensation was higher throughout the trial whenever vibrations accompanied the auditory motion. Furthermore, vection was perceived earlier, and participants had a more realistic sensation of actually rotating in the physical lab. The effect strength (partial η_p^2) ranged between 45 and 68%, indicating that between 45-68% of the observed variance in the data can be explained by the experimental manipulation of adding jitter[2].

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), there was an overall tendency towards reduced vection in all dependent measures. This trend reached significance ($\alpha \leq 5\%$) for the realism of actually rotating in the physical lab and the vection intensity at the end of the trial. All other dependent measures reached marginal significance ($\alpha \leq 10\%$). Between $\eta_p^2 = 35\%$ and $\eta_p^2 = 49\%$ of the variability in the data could be ascribed to the feet being suspended or not. These effect sizes can be described as quite large [Cohen 1988], even though some of the effects reached only marginal significance. 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. Considering the small number of participants tested, these results are already quite substantial, though.

3.3 Interaction jitter – feet

The percentage of trials where vection was perceived showed a significant interaction between the independent variables jitter and feet. Figure 4, top left, suggests that this interaction might be due to a ceiling effect: Adding jitter and suspending one's feet at a time increased the percentage of vection trials from 53.1% to 84.4%, which is already close to the ceiling level of 100%. Combining both measures raised the percentage of vection trials to 96.9%, indicating that vection was almost always perceived when vibrations were present and one's feet did not touch the ground. None of the other dependent measures showed any significant interactions, suggesting independent (e.g., additive) facilitation of vection: Both adding jitter and not touching solid ground facilitated vection, and combining both measures enhanced vection even further.

3.4 Perceived vection velocity

All but one participant experienced actual self-motion with respect to the lab, and thus called out the target name whenever they believed they were facing one of the four target objects. The data from these seven participants were used to estimate their perceived vection velocity (see Figure 5). Although there was a tendency towards higher perceived self-rotation velocities when jitter was added and one's feet did not touch solid ground, none of these effects reached significance (F(1,6)=2.62, p=.157, $\eta_p^2 = 30.4\%$ and F(1,6)=1.84, p=.224, $\eta_p^2 = 23.4\%$, respectively). Mean perceived vection velocities per condition varied considerably between participants, and ranged from 0°/s to 48.7°/s. Note that even the highest reported mean vection velocities were still slightly below the stimulus velocity of 60°/s, suggesting that participants were typically not "locked" to the auditory rotation velocity. This is an interesting difference to visually induced vection, where providing a naturalistic visual environment can lead participants' vection velocity to be locked to the stimulus velocity [Riecke et al. 2006a, informal observations].

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[2] The effect strength (partial η_p^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 a given independent variable (e.g., adding vibrations) [Cohen 1988].

	Jitter			Feet			Interaction		
	on/off			on ground/suspended			jitter – feet		
	F(1,7)	p	η_p^2	F(1,7)	p	η_p^2	F(1,7)	p	η_p^2
Percentage of trials with vection	**5.81**	**.047**	**45.4%**	*5.12*	*.058*	*42.2%*	**5.73**	**.048**	**45.0%**
Estimated vection onset time	**7.32**	**.030**	**51.1%**	*4.90*	*.062*	*41.2%*	2.45	.161	25.9%
Realism of actually rotating in room	**13.63**	**.008**	**66.1%**	**5.56**	**.050**	**44.3%**	.05	.824	0.8%
Vection intensity at onset	**9.72**	**.017**	**58.1%**	*3.71*	*.096*	*34.6%*	.02	.887	0.3%
Vection intensity at end of trial	**14.76**	**.006**	**67.8%**	**6.60**	**.037**	**48.5%**	.00	1.000	0.0%
Overall vection intensity	**12.64**	**.009**	**64.4%**	*4.92*	*.062*	*41.3%*	.09	.770	1.3%

Table 1: *Analysis of variance results for the different dependent variables. Significant ($\alpha \leq 5\%$) and marginally significant ($\alpha \leq 10\%$) effects are typeset in bold and italics, respectively. The effect strengths partial η_p^2 indicates the percentage of variance explained by a given factor.*

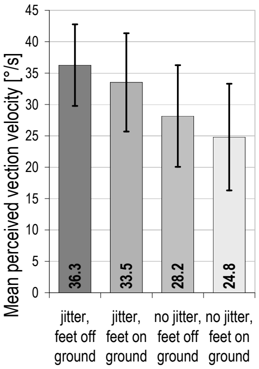

Figure 5: *Mean estimated perceived vection velocity, plotted as in Figure 4.*

Furthermore, naturalistic visual stimuli can induce obligatory spatial updating, such that one's mental spatial representation is always aligned with the orientation of the presented visual scene [Riecke et al. 2005d]. Interestingly, this did not seem to happen for the auditory stimuli used here. Nevertheless, participants clearly updated the surrounding lab while being blindfolded and perceiving vection – albeit at a lower speed than the auditory rotation velocity.

4 Discussion and conclusions

4.1 The possibility of actual self-motion can facilitate vection

One main goal of this study was to investigate whether auditory circular vection might be affected by participants either having their feet touch solid ground, such that they sensed and knew that actual motion was impossible, or by having their feet suspended while sitting on a hammock chair, such that they had no direct contact to any stationary object and actual motion might seem more plausible. Participants are often seated on movable chairs in auditory vection studies to facilitate vection [Lackner 1977; Väljamäe 2005; Väljamäe 2007], but it has never been shown that this procedure actually does facilitate auditory vection. The current study provides first evidence that such facilitation does indeed exist: Vection was enhanced when participants had no direct contact with the floor or any other obviously earth-stationary object. That is, not having one's feet touch the ground showed significant and or at least marginally significant facilitation of vection in all six vection measures used.

It is important to consider that this facilitation could have occurred both via perceptual and/or cognitive mechanisms. That is, having one's feet touch the ground provides on the one hand lower-level, perceptual information like biomechanical, inertial, and deep pressure cues that specify stationarity, in the sense that we "sense/feel" that we are stationary. On the other hand, one's feet standing on solid ground also provides us with higher-level, more cognitive information that one cannot move in the sense that we "know" that we cannot possibly be moving. In a cue combination framework, such perceptual and cognitive information about stationarity might be expressed as a Bayesian prior, as discussed in subsection 1.4 [Ernst and Bülthoff 2004]. Conversely, sitting on a hammock chair with one's feet suspended with the chair and having experienced that the chair can, in fact, be moved, might help to cognitively prime participants to anticipate vection or at least believe that actual self-motion is not absolutely impossible, similar to a suspension of disbelief often employed in arts and entertainment.

The literature has convincingly shown that both lower-level, perceptual and higher-level, more cognitive influences on vection exist [Dichgans and Brandt 1978; Hettinger 2002; Lepecq et al. 1995; Riecke et al. 2005c; Schulte-Pelkum and Riecke 2008; Wright et al. 2006]. Thus, it seems possible that both influences might have contributed in the current study, although further experiment would be needed to disambiguate between them.

4.2 Vibrations can enhance vection

Adding vibrations has been shown to facilitate visual circular and linear vection [Riecke et al. 2005b; Schulte-Pelkum 2008] as well as auditory linear vection [Väljamäe et al. 2006], but not auditory circular vection [Väljamäe 2007, paper C]. Here, we investigated whether barely noticeable jitter might enhance auditory circular vection, in particular in situations where actual motion might seem possible.

Adding jitter was found to facilitate auditory circular vection in all dependent measures, and the effect sizes were all quite high. This finding came somewhat as a surprise, as Väljamäe found no such facilitation for circular auditory vection [Väljamäe 2007, paper C]. Apart from minor differences in the experimental methodology, there are three main factors that might have contributed to these seemingly contradicting findings:
First, while Väljamäe used vibrations that were just below the perception threshold for most people, the current study used vibrations that were just above the perception threshold and thus slightly stronger. Due to differences in the seating and vibration procedure, and the difficulty of assessing how the applied vibrations are transduced through the chair and the participants' body, it is quite difficult to quantitatively compare the actual amount of vibration exerted to different parts of the human body.
Second, while Väljamäe seated participants on a solid chair mounted on a small turntable that could be rotated by a computer but was otherwise perfectly stationary, participants in our study were sitting in a hammock chair that was held in place using soft

connections, such that minimal swinging was still possible (as intended), whether or not one's feet were touching the ground. Albeit such swinging motions being possible, their amplitudes during the vection trials were sufficiently small to pass unnoticed by the experimenter's naked eye. Thus, it is conceivable that very subtle swinging motions might be sufficient to facilitate auditory vection and enhance the influence of jitter.
Third, while Väljamäe employed non-individualized HRTF rendering of the stimuli (i.e., participants were "listening through somebody else's ears"), we used individualized binaural recordings (i.e., participants were "listening through their own ears"). We are currently running experiments to test whether individualization of the binaural recordings might affect auditory circular vection, but so far found no evidence supporting this hypothesis. This is in agreement with earlier findings by Väljamäe and colleagues where individualizing HRTFs did not facilitate auditory circular vection, although it successfully reduced the occurrence of perceptual artifacts (e.g. distorted trajectories of the rotating sound objects or in-head localization) and even increased auditory spatial presence [Väljamäe et al. 2004].

It is interesting to note that jitter enhanced vection irrespective of whether or not participants' feet touched the ground. This suggests that a cognitive/perceptual framework of actual self-movement being possible is not absolutely essential for the vection-facilitating effect of adding jitter. Nevertheless, lifting one's feet off the ground such that actual self-motion might seem more likely enhanced vection, even when vibrations were present.

4.3 Conclusions

The current data suggest a clear cross-modal benefit for auditory vection, in the sense that vection was enhanced when the rotating auditory cues were combined with non-auditory cues (like vibratory cues or having one's feet off the ground), even though these non-auditory cues did not provide any explicit self-rotation cues. This contributes to the growing interest in multi-modal/multi-cue contributions and interactions, and is in agreement with recent studies showing that auditory vection can (at least under some circumstances) benefit from adding infrasound, vibrations, or engine sound [Väljamäe 2005; Väljamäe 2007] as well as apparent stepping-around on a circular treadmill [Riecke et al. 2008b]. Similarly, visual vection can be facilitated by adding vibrations [Riecke et al. 2005b; Schulte-Pelkum 2008], small jerks that coincide with the visual motion onset [Riecke et al. 2006b; Schulte-Pelkum 2008; Wong and Frost 1981], or spatialized auditory cues that rotate in sync with the visual stimulus [Riecke et al. 2005a; Riecke et al. 2008a].

In conclusion, the current study provides the first evidence that adding vibrations can enhance auditorily induced circular vection. Furthermore, providing a perceptual/cognitive framework of "movability" was found to facilitate auditory vection, irrespective of whether or not vibrations were present. These findings have potentially interesting theoretical as well as applied implications: On the one hand, understanding how different perceptual and cognitive factors influence vection fosters our theoretical understanding of human multi-modal perception and cue integration, a field that receives growing research interest. On the other hand, the current findings have several applied implications. In terms of designing auditory vection setups, care should be taken to allow participants to sense and believe that actual motion is possible. This extends previous findings that found such influences on visually induced vection [Lepecq et al. 1995; Riecke et al. 2005c; Wright et al. 2006]. Furthermore, many application that involve simulated movements of the observer might benefit from the current findings, as both vibrations and a perceptual/cognitive framework of "movability" can often be provided cost-effectively and with little effort. Such potential applications include driving/flight simulations, first-person computer/arcade games, movies, architecture walk-throughs, virtual travel, and other tele-presence applications. Finally, spatialized sound of compelling fidelity can nowadays be provided with relatively little effort and costs, and has been shown to induce self-motion illusions as well as facilitate visually or biomechanically induced vection [Riecke et al. 2008a; Riecke et al. 2008b]. The current study adds to the growing body of evidence highlighting the importance of consistent multi-modal simulation embedded in a coherent perceptual and cognitive framework.

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References

ANDERSEN, G. J., AND BRAUNSTEIN, M. L. 1985. Induced self-motion in central vision. *Journal of Experimental Psychology – Human Perception and Performance 11*, 2, 122–132.

BERTHOZ, A., PAVARD, B., AND YOUNG, L. R. 1975. Perception of linear horizontal self-motion induced by peripheral vision (linearvection) - basic characteristics and visual-vestibular interactions. *Exp. Brain Res. 23*, 5, 471–489.

BLES, W. 1981. Stepping around: circular vection and coriolis effects. *Attention and performance*, 47–61.

COHEN, J. 1988. *Statistical Power Analysis for the Behavioral Sciences*. Hillsdale, NJ: Erlbaum.

DICHGANS, J., AND BRANDT, T. 1978. Visual-vestibular interaction: Effects on self-motion perception and postural control. In *Perception*, R. Held, H. W. Leibowitz, and H.-L. Teuber, Eds., vol. VIII of *Handbook of Sensory Physiology*. Springer, 756–804.

DODGE, R. 1923. Thresholds of rotation. *J. Exp. Psychol. 6*, 107–137.

ERNST, M. O., AND BANKS, M. S. 2002. Humans integrate visual and haptic information in a statistically optimal fashion. *Nature 415* (Jan.), 429–433.

ERNST, M. O., AND BÜLTHOFF, H. H. 2004. Merging the senses into a robust percept. *Trends in Cognitive Sciences 8*, 4 (Apr.), 162–169.

FEUEREISSEN, D. 2008. *VR: Getting the Reality Part Straight – Does Jitter and Suspension of the Human Body Increase Auditory Circular Vection?* Bachelor's thesis, Department of Computer Science in Media, Furtwangen University, Germany. Available: `http://webuser.fh-furtwangen.de/~fetzner/spacestudies/uploads/uploads/vr-vection-t1.pdf`.

GEKHMAN, B. 1991. Audiokinetic nystagmus. *Sensornye Sistemy 5*, 2, 71–78. (in Russion).

HENNEBERT, P. E. 1960. Audiokinetic nystagmus. *Journal of Auditory Research 1*, 1, 84–87.

HETTINGER, L. J. 2002. Illusory self-motion in virtual environments. In *Handbook of Virtual Environments*, K. M. Stanney, Ed. Lawrence Erlbaum, ch. 23, 471–492.

KHASNIS, A., AND GOKULA, R. M. 2003. Romberg's test. *J Postgrad Med 49*, 2, 169–172. Available: http://www.jpgmonline.com/text.asp?2003/49/2/169/894.

LACKNER, J. R. 1977. Induction of illusory self-rotation and nystagmus by a rotating sound-field. *Aviation Space and Environmental Medicine 48*, 2, 129–131.

LARSSON, P., VÄSTFJÄLL, D., AND KLEINER, M. 2004. Perception of self-motion and presence in auditory virtual environments. In *Proceedings of 7th Annual Workshop of Presence*, 252–258. Available: www.kyb.mpg.de/publication.html?publ=2953.

LEPECQ, J. C., GIANNOPULU, I., AND BAUDONNIERE, P. M. 1995. Cognitive effects on visually induced body motion in children. *Perception 24*, 4, 435–449.

MACH, E. 1875. *Grundlinien der Lehre von der Bewegungsempfindung*. Engelmann, Leipzig, Germany.

MARMEKARELSE, A. M., AND BLES, W. 1977. Circular vection and human posture ii: Does the auditory-system play a role. *Agressologie 18*, 6, 329–333.

MERGNER, T., AND BECKER, W. 1990. Perception of horizontal self-rotation: Multisensory and cognitive aspects. In *Perception & Control of Self-Motion*, R. Warren and A. H. Wertheim, Eds. Erlbaum, New Jersey, London, 219–263.

PALMISANO, S., GILLAM, B. J., AND BLACKBURN, S. G. 2000. Global-perspective jitter improves vection in central vision. *Perception 29*, 1, 57–67.

PALMISANO, S., BURKE, D., AND ALLISON, R. S. 2003. Coherent perspective jitter induces visual illusions of self- motion. *Perception 32*, 1, 97–110.

PAVARD, B., AND BERTHOZ, A. 1977. Linear acceleration modifies perceived velocity of a moving visual scene. *Perception 6*, 5, 529–540.

RIECKE, B. E., SCHULTE-PELKUM, J., CANIARD, F., AND BÜLTHOFF, H. H. 2005. Influence of Auditory Cues on the visually-induced Self-Motion Illusion (Circular Vection) in Virtual Reality. In *Proceedings of 8th Annual Workshop Presence 2005*, 49–57.

RIECKE, B. E., SCHULTE-PELKUM, J., CANIARD, F., AND BÜLTHOFF, H. H. 2005. Towards lean and elegant self-motion simulation in virtual reality. In *Proceedings of IEEE Virtual Reality 2005*, 131–138.

RIECKE, B. E., VÄSTFJÄLL, D., LARSSON, P., AND SCHULTE-PELKUM, J. 2005. Top-down and multi-modal influences on self-motion perception in virtual reality. In *Proceedings of HCI international 2005*, 1–10.

RIECKE, B. E., VON DER HEYDE, M., AND BÜLTHOFF, H. H. 2005. Visual cues can be sufficient for triggering automatic, reflex-like spatial updating. *ACM Transactions on Applied Perception (TAP) 2*, 3, 183–215.

RIECKE, B. E., SCHULTE-PELKUM, J., AVRAAMIDES, M. N., VON DER HEYDE, M., AND BÜLTHOFF, H. H. 2006. Cognitive factors can influence self-motion perception (vection) in virtual reality. *ACM Transactions on Applied Perception 3*, 3, 194–216.

RIECKE, B. E., SCHULTE-PELKUM, J., AND CANIARD, F. 2006. Visually induced linear vection is enhanced by small physical accelerations. In *7th International Multisensory Research Forum (IMRF)*. Available: www.kyb.mpg.de/publication.html?publ=3901.

RIECKE, B. E., VÄLJAMÄE, A., AND SCHULTE-PELKUM, J. 2008. Moving Sounds Enhance the Visually-Induced Self-Motion Illusion (Circular Vection) in Virtual Reality. *ACM Transactions on Applied Perception*. (accepted).

RIECKE, B. E., FEUEREISSEN, D., AND RIESER, J. J. 2008. Contribution and interaction of auditory and biomechanical cues for self-motion illusions ("circular vection"). In *Proceedings of CyberWalk workshop*. Available: http://www.kyb.mpg.de/publication.html?publ=5043.

SAKAMOTO, S., OSADA, Y., SUZUKI, Y., AND GYOBA, J. 2004. The effects of linearly moving sound images on selfmotion perception. *Acoustical Science and Technology 25*, 100–102.

SCHULTE-PELKUM, J., AND RIECKE, B. E. 2008. An integrative approach to presence and self-motion perception research. In *Immersed in Media Experiences: Presence Psychology and Design (Handbook of Presence)*. Lawrence Erlbaum. in print.

SCHULTE-PELKUM, J., RIECKE, B. E., AND BÜLTHOFF, H. H. 2004. Vibrational cues enhance believability of ego-motion simulation. In *International Multisensory Research Forum (IMRF)*. Available: www.kyb.mpg.de/publication.html?publ=2766.

SCHULTE-PELKUM, J. 2008. *Perception of self-motion: Vection experiments in multi-sensory Virtual Environments*. PhD thesis, Ruhr-Universität Bochum. (submitted).

VÄLJAMÄE, A., LARSSON, P., VÄSTFJÄLL, D., AND KLEINER, M. 2004. Auditory presence, individualized head-related transfer functions, and illusory ego-motion in virtual environments. In *Proceedings of 7th Annual Workshop of Presence*, 141–147.

VÄLJAMÄE, A., LARSSON, P., VÄSTFJÄLL, D., AND KLEINER, M. 2006. Vibrotactile enhancement of auditory induced self-motion and spatial presence. *Journal of the Acoustic Engineering Society 54*, 10, 954–963.

VON HELMHOLTZ, H. 1867. *Handbuch der physiologischen Optik*. Voss, Leipzig.

VÄLJAMÄE, A. 2005. *Self-motion and presence in the perceptual optimization of a multisensory virtual reality environment*. Licentiate dissertation, Chalmers University of Technology, Göteborg, Sweden. Available: `http://lab5.ta.chalmers.se/~sasha/Aleksander_Valjamae_Licentiate.pdf`.

VÄLJAMÄE, A. 2007. *Sound for Multisensory Motion Simulators*. PhD thesis, Chalmers University of Technology, Göteborg, Sweden.

WARREN, R., AND WERTHEIM, A. H., Eds. 1990. *Perception & Control of Self-Motion*. Erlbaum, New Jersey, London.

WONG, S. C. P., AND FROST, B. J. 1981. The effect of visual-vestibular conflict on the latency of steady-state visually induced subjective rotation. *Perception & Psychophysics 30*, 3, 228–236.

WRIGHT, W. G., DIZIO, P., AND LACKNER, J. R. 2006. Perceived self-motion in two visual contexts: dissociable mechanisms underlie perception. *J Vestib Res 16*, 1-2, 23–28.