Auditory Self-Motion Simulation is Facilitated by Haptic and Vibrational Cues Suggesting the Possibility of Actual Motion

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Sound fields rotating around stationary blindfolded listeners sometimes elicit auditory circular vection, the illusion that the listener is physically rotating. Experiment 1 investigated whether auditory circular vection depends on participants' situational awareness of "movability," that is, whether they sense/know that actual motion is possible or not. While previous studies often seated participants on movable chairs to suspend the disbelief of self-motion, it has never been investigated whether this does, in fact, facilitate auditory vection. To this end, 23 blindfolded participants were seated on a hammock chair with their feet either on solid ground ("movement impossible") or suspended ("movement possible") while listening to individualized binaural recordings of two sound sources rotating synchronously at 60°/s. Although participants never physically moved, situational awareness of movability facilitated auditory vection. Moreover, adding slight vibrations like the ones resulting from actual chair rotation increased the frequency and intensity of vection. Experiment 2 extended these findings and showed that nonindividualized binaural recordings were as effective in inducing auditory circular vection as individualized recordings. These results have important implications both for our theoretical understanding of self-motion perception and for the applied field of self-motion simulations, where vibrations, nonindividualized binaural sound, and the cognitive/perceptual framework of movability can typically be provided at minimal cost and effort.

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1. INTRODUCTION

While modern virtual reality simulations can have stunning photorealism, they do not typically provide a life-like, compelling experience of actually moving through the simulated world. This might limit learning, 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. In particular, we investigated whether self-motion perception and simulation can benefit from manipulating one's situational awareness of movability, that is, by providing a cognitive/perceptual framework suggesting that actual self-motion might in fact be possible [Banbury et al. 2004; Endsley et al. 2003].

1.1 Self-Motion Illusions

Among the most compelling visual illusions are self-motion illusions ("vection"), where moving visual stimuli can induce a powerful embodied 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, although less compelling, illusions of self-motion in blindfolded listeners. Although auditory vection was described by Dodge [1923] more than 85 years ago, and although the illusions have been replicated by others [Gekhman 1991; Hennebert 1960; Lackner 1977; Marmekarelse and Bles 1977], it is not as reliable as one might hope. Only recently has there been increased interest in this phenomenon [Larsson et al. 2004; Riecke et al. 2005; Sakamoto et al. 2004; Väljamäe et al. 2004]. For recent reviews on auditory vection, see Riecke et al. [2009], Väljamäe [2005, 2007], and Väljamäe et al. [2009]. 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 first experiment of the current study,[1] we addressed two open questions that will be outlined in Sections 1.2 and 1.3. The motivation and background for Experiment 2 is detailed in Section 1.4.

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, 2003; Riecke et al. 2005; Schulte-Pelkum and Riecke 2009]. Here, we investigated whether one's perception, pre-knowledge, and assumptions about whether actual motion is possible or not might affect circular auditory vection. These factors can be subsumed under the notion of one's situational awareness of movability [Banbury et al. 2004; Endsley et al. 2003].

1.2.1 *Visual Vection.* Lepecq and colleagues demonstrated that 7-to-11-year-old children perceive visually induced linear forward vection sooner after the stimulus onset when they were seated on a chair that could potentially move [Lepecq et al. 1995]. However, the probability of obtaining vection remained unaffected by this manipulation. Later studies showed that adult observers perceive linear up-down

[1]A subset of the data of Experiment 1 (with 8 instead of 14 participants who reliably perceived vection) has previously been presented at a conference [Riecke et al. 2008a]. Experiment 2 has not been presented before.

("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 two thirds of participants can be fooled into believing that they physically rotate if they know that this is, in fact, possible [Riecke et al. 2005; Schulte-Pelkum et al. 2004]. Neither vection onset latency, intensity, or compellingness were affected by whether actual motion was possible.

1.2.2 *Auditory Vection.* In Experiment 1, 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, 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 multimedia 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 Do Vibrations Facilitate Self-Motion Illusions?

Albeit vibrations being frequently used in motion simulation and multimedia applications, there has only recently been experimental evidence that providing vibrotactile 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 failed to facilitate the self-motion illusion [Väljamäe 2007]. This negative result might, in part, be related to the low amplitude of the vibrotactile stimulation: Only one of the 16 participants apparently noticed the vibrations when debriefed.

In Experiment 1 of the current study, we assessed whether vibrations that are quite subtle but above the perception threshold, can facilitate auditory circular vection. If so, this would extend our understanding of multimodal 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 Influence of Individualized vs. Nonindividualized Binaural Recordings on Vection

The goal of Experiment 2 was to investigate whether providing participants with nonindividualized binaural recordings of a rotating soundfield (i.e, recordings using somebody else's ears and head-related transfer function) would show a similar vection-inducing effect as using individualized (own-ear)

recordings, as used in Experiment 1. From a practical standpoint, having to perform individual recordings for each participant is quite cumbersome and not feasible for most applications, hence it would be desirable if one generic recording would yield a similar facilitation of vection.

Previous research demonstrated that individualizing binaural recordings or head-related transfer function (HRTF) renderings is important for improving spatial localization ability (in particular, to reduce the occurrence of front-back confusions or up-down confusions) and sound externalization (see Begault [1994], Blauert and Allen [1997], and Shilling and Shinn-Cunningham [2002] for reviews). The first pre-experiment (see Section 3.2) showed indeed a marginally significant trend toward reduced front-back reversals for individualized recordings. Väljamäe et al. [2004] even reported an increase in auditory spatial presence for individualized as compared to nonindividualized HRTFs. There is, however, only little research on the relevance of individualizing HRTF recordings on auditory vection. In fact, we are only aware of one study that directly compared individualized with generic HRTFs for auditory vection, and this study did not find a benefit for using individualized HRTF recordings for binaural sound synthesis [Väljamäe et al. 2004].

It is, however, conceivable that using binaural recordings directly, as opposed to HRTF convolution on a sound card, as was done in Riecke et al. [2009] and Väljamäe et al. [2004], might capture subtle auditory cues (in particular, >5KHz) that are important for vection but might get lost or somewhat distorted during the HRTF interpolation and convolution [Begault 1994; Langendijk and Bronkhorst 2002]. To test this hypothesis, we directly used binaural recordings of a rotating complex sound field (as compared to dry HRTF recording and subsequent HRTF rendering using sound source interpolation, as in Riecke et al. [2009], Väljamäe et al. [2004]) and thus investigated whether using a direct own-ear (individualized) recording would provide a stronger vection facilitation than a nonindividualized recording using somebody else's ears (here: the author's).

2. GENERAL METHODS

Participants. A total of 23 participants (8 female and 15 male) voluntarily participated in all parts of this study in exchange for monetary compensation. All participants 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]. The study 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 experiments.

2.1 Stimuli and Apparatus

Hammock Chair and Circular Treadmill. Throughout the study, 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(b). 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 of Experiment 1, a small eccentric motor (a modified USB fan) that rotated at about 7Hz was mounted on the horizontal crossbar of the hammock chair, as illustrated in Figure 1(e). The onset and offset of the vibrations were 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].

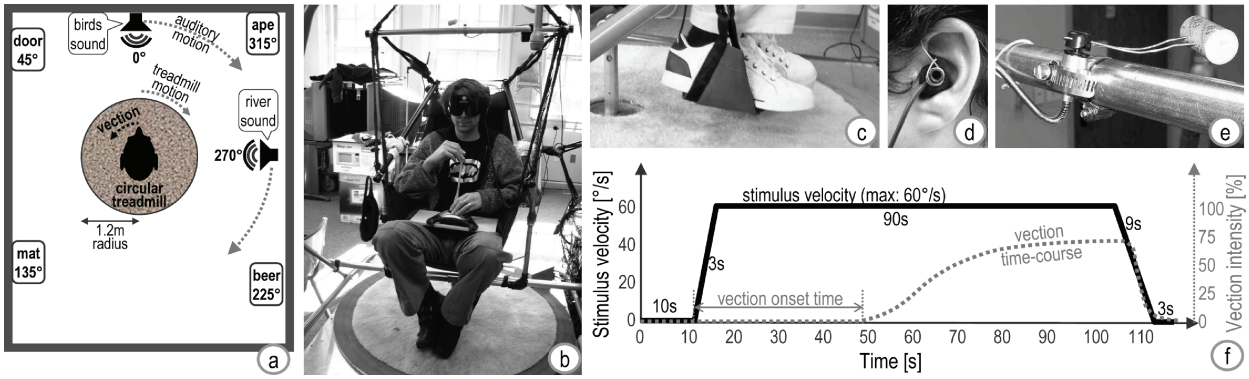

Fig. 1. (a): top-down schematic of the experimental setup (it is not drawn to scale). Note that treadmill motion was only used during the vection demonstration phase. (b): experimental setup showing the circular treadmill and a participant seated on the hammock chair with blindfold, noise-canceling headphones, and a pointing device used for a sound localization pre-experiment. Note that throughout the test phase, the treadmill was switched off and the hammock chair was fixed to prevent actual chair rotations. (c): side view of the experimental setup, showing a participant with his feet suspended in the footrest attached to the hammock chair ("movement possible" condition). (d): miniature microphones (Core Sound Binaural Microphone Set) positioned at the entrance of the ear canals during the binaural recordings (e): a USB fan was modified to act as an eccentric motor that provided barely noticeable vibrations to the hammock chair in half of the trials of Experiment 1. (f): time-course of the rotating vection-inducing sound field (solid black line) and hypothetical vection intensity (dashed gray line).

Sound Sources and Target Objects. As illustrated in Figure 1(a), two speakers were placed directly to the front (0 degrees, 2.3m away) and the right (270 degrees, about 3.3m away), respectively, of the participant seated in the hammock chair. During the binaural recordings (and only then), the 270 degree speaker displayed a custom-made mix of several river and waterfall noises, and the 0-degree 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 more pleasant than the white/pink noise stimuli that are sometimes used. As sketched in Figure 1(a), the room contained four target objects positioned at 45 degrees (door), 135 degrees (mat), 225 degrees (beer), and 315 degrees (ape) with respect to the observer seated in the default orientation.

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 degrees, and were passively rotated either counterclockwise or clockwise, at the velocity profile described in Figure 1(f) 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 degrees and 270 degrees displayed the bird and river sound mixes, respectively, throughout the recording. An additional binaural recording without any rotation later served as a control condition for the auditory motion perception pre-experiment (see Section 4). 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 1(d). 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 in Experiment 1 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. A compressed sound stimulus sample is available at http://www.sfu.ca/~ber1/web/auditoryVection/vectionStimulus_clockwise.mp3. Experiment 2 investigated whether nonindividualized recordings would show similar effects.

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 overall study comprises general preparatory stages (described in this section), two pre-experiments as described in Sections 3 and 4, and two main experiments described in Sections 5 and 6. The results are jointly discussed in Section 7. The whole study took about 4h and contained several breaks to reduce the effects of fatigue and declining alertness.

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").

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 Figure 1), 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 after it started rotating [Bles 1981; Pick et al. 1999; Rieser et al. 1995]. As expected, this procedure elicited compelling circular vection in all participants.

Calling Out Target Objects. Throughout the vection demonstration phase and Experiment 1 and 2, blindfolded participants were instructed to keep track of their orientation continuously with respect to the lab and the four targets positioned at 45 degrees, 135 degrees, 225 degrees, and 315 degrees. To obtain detailed measures of changes in participants' perceived facing direction while participants perceived 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 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 earlier, one for clockwise self-motion, one for counterclockwise self-motion, and one stationary recording.

3. PRE-EXPERIMENT 1: ASSESSMENT OF STATIONARY AUDITORY LOCALIZATION ABILITY

A first pre-experiment was performed to find out whether participants perceived the binaural sounds presented over headphone as externalized and spatialized so they could localize the sounds with

reasonable accuracy. In addition, we expected front-back localization confusions to occur more often with nonindividualized, as compared to individualized recordings Begault [1994], and Blauert and Allen [1997], and Shilling and Shinn-Cunningham [2002]. And so the pre-experiments also served as a baseline for Experiment 2, which explicitly compared the vection-inducing potential of individualized versus nonindividualized binaural sound.

3.1 Methods

We collected for each participant eight binaural recordings (10s duration) of one sound source (the birds sound) while participants were positioned at different orientations to provide recordings for self-to-sound angles of 0, 10, 45, 135, 180, −135, −45, and −10 degrees. Similar binaural recordings using the first author later served as the non-individualized sound stimuli for the experimental participants. For the localization pre-experiment and the subsequent auditory motion direction perception pre-experiment, participants were seated in the chair that was clamped to the 0° position. They wore headphones and blindfold and had their feet on the stationary floor. For the actual testing, participants were presented with different binaural stimuli and asked to point toward the perceived location of the sound source. Pointing was performed using a modified wireless Logitech Freedom 2.4 joystick that was mounted on a wooden board that was positioned on the participants' lap. The joystick handle was replaced by a longer 200 × 9mm Plexiglas rod to make it easier for participants to use as a pointing device, as depicted in Figure 1(b). Each participants completed 16 trials, corresponding to a factorial combination of 2 auralization conditions (individualized vs. nonindividualized recordings) × 8 sound source directions (0, 10, 45, 135, 180, −135, −45, and −10 degrees). The order of these 16 combinations was randomized to avoid systematic order effects.

3.2 Results

When presented with stationary binaural recordings of one sound source from different angles, all participants perceived the sound as externalized and spatialized, both for the individualized and non-individualized binaural stimuli.

3.2.1 *Analysis of Front-Back Reversals.* When asked to use the joystick to indicate the direction of origin of the sound source displayed via headphones, however, participants showed a considerable number of front-back reversals: The percentage of front-back confusions ranged from 4.5% when the sound source originated from ±135 degree (back left or back right) up to more than 30% when the sound originated from the frontal hemisphere (0, ± 10, or ±45 degrees), see Figure 2 (left). To investigate this phenomenon further, we conducted a repeated-measures within-subject ANOVA with the two independent variables of recording type (individualized vs. nonindividualized) × sound source direction (0, 10, 45, 135, and 180 degrees). The ANOVA results are summarized in Table I, together with a contrast analysis for the independent variable sound source direction that aimed at investigating the nature of the front-back reversals in more detail.

There was a marginally significant tendency toward more front-back reversals for the nonindividualized as compared to individualized binaural recordings. This trend is in agreement with the literature, where usage of individualized binaural recordings is often recommended in order to reduce front-back reversals. [Begault 1994; Blauert and Allen 1997; Shilling and Shinn-Cunningham 2002].

Although one might naïvely assume that front-back mirror-symmetric stimuli (e.g., 0 degree vs. 180 degrees or 45 degrees vs. 135 degrees) should show equal likelihood for front-back reversal, the data revealed that the occurrence of front-back reversals depended significantly on the direction of the sound source (see Figure 2 and Table I). In particular, the contrast analysis showed that sounds originating from the frontal hemisphere (0 degrees, ± 10 degrees, or ±45 degrees) were significantly

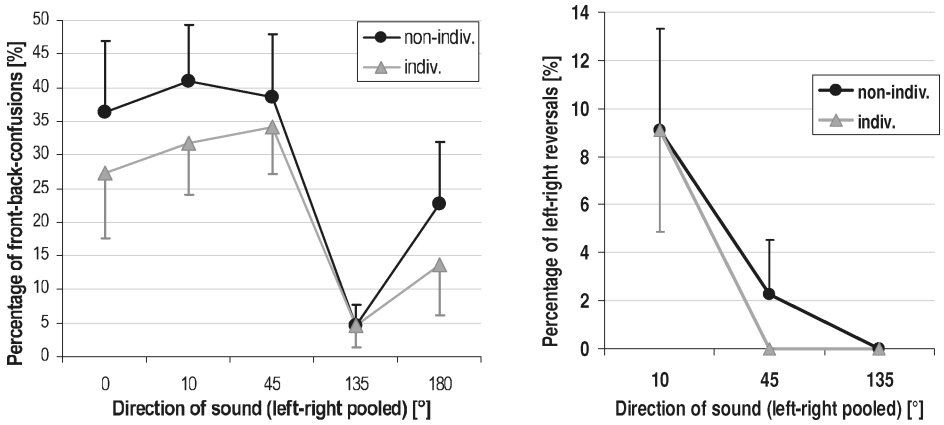

Fig. 2. Data from the auditory localization ability pre-experiments. Left: Mean percentage of front-back reversals for different sound source directions, plotted for the nonindividualized (dark line) and individualized binaural recordings (gray line). Whiskers indicate one standard error of the mean. Right: Mean percentage of left-right reversals for sounds positioned at ±10°, ±45°, or ±135°, plotted for the nonindividualized (dark line) and individualized binaural recordings (gray line).

Table I. ANOVA Results for the Stationary Sound Localization Pre-Experiment

Significant ($p \leq 5\%$) effects are typeset in bold, marginally significant effects ($p \leq 10\%$) in italics. The effect strengths partial η_p^2 indicates the percentage of variance explained by a given factor. The statistical power indicates the probability of finding a statistically significant effect if there was one (i.e., the probability that the statistical test will reject a false null hypothesis and thus will not make a Type II error).

	F	p	η_p^2	power
recording type (individualized vs. nonindividualized)	*F(1, 21) = 3.52*	*.074m*	*.144*	*.433*
sound source direction (SSD)	**F(2.24, 47.0) = 5.00**	**.009****	**.192**	**.819**
interaction recording type × SSD	F(2.61, 54.9) = .23	.849	.011	.088
SSD contrast front (0°, 10°, 45°) vs. back (135°, 180°) hemispheres	**F(1, 21) = 7.28**	**.013***	**.258**	**.730**
SSD contrast front (0°) vs. back (180°)	F(1, 21) = 1.30	.266	.058	.193
SSD contrast 45° vs. 135°	**F(1, 21) = 13.77**	**.001*****	**.396**	**.942**
SSD contrast 135° vs. 180°	**F(1, 21) = 5.86**	**.025***	**.218**	**.637**

more frequently front-back mislocated than sounds originating from the back hemisphere (±135 degrees or 180 degrees). Additional contrasts indicated that this difference can mainly be attributed to the low occurrence (4.5%) of back-front reversals for the ±135-degree (back right and back left) locations. In fact, the ±135-degree locations resulted in significantly fewer back-front reversals than both sounds originating from the front (0 degree) and behind (180 degrees), as indicated in Table I. Further studies are needed, though, to corroborate and further investigate these findings. In particular, it remains to be tested whether similar front-back confusion would occur for the real sounds (as compared to recordings presented through headphones).

3.2.2 *Analysis of Left-Right Reversals.* We initially intended to quantify localization ability using absolute and signed errors. Due to the high frequency of front-back reversals, which would have contaminated the error analysis, though, we refrained from a pointing error analysis and instead investigated the occurrence of left-right reversals, which are independent of front-back reversals. As indicated in the right subplot of Figure 2, participants rarely experienced left-right reversals. Even for the condition where they were asked to point to sound sources located just 10 degrees to the left or right, error rates were only 9.1%. This corroborates the overall reliability and quality of the binaural recordings and pointing procedure, and suggests that the main challenge with binaural recording/presentation

was related to specific front-back reversals, but not overall localization or left-right disambiguation problems.

4. PRE-EXPERIMENT 2: AUDITORY MOTION DIRECTION PERCEPTION

The first pre-experiment showed that all participants perceived sound sources properly externalized and spatialized. Despite occasional front-back confusion (between 4.5% and 40.9%, see Section 3.2), overall static localization ability was sufficient to proceed with the auditory motion direction perception pre-experiment, which aimed at investigating whether participants can properly determine auditory motion—which is a necessary prerequisite for the subsequent vection experiments. As the two pre-experiments directly compared individualized with nonindividualized binaural recordings for localization and motion detection ability, respectively, their results are also highly relevant for Experiment 2, which was designed to study the influence of individualizing binaural recordings on rotational self-motion illusions (see Section 4).

4.1 Methods

Participants were asked to use the joystick to continuously point toward the perceived origin of the bird sounds while listening to different 20s binaural recordings of moving or stationary sounds containing the same two sound sources as for the subsequent vection experiments. Each participant completed 12 trials, consisting of a factorial combination of 2 auralization conditions (individualized vs. nonindividualized recordings; randomized) $\times$ 3 sound source motion conditions (clockwise motion, counterclockwise motion, or stationary ([no motion, with the target sound source at 0 degrees and the other one at 270 degrees]); randomized) $\times$ 2 repetitions per condition. Although participants showed a high rate (54.5%, on average, see Section 4.2) of front-back confusions for the stationary recordings, all 23 participants could distinguish between stationary and moving sound sources without any errors and were thus admitted to the subsequent vection experiments. Due to partially missing data for one of the 23 participants in the pre-experiments, only data from the remaining 22 participants entered the later data analysis.

4.2 Results

Given that participants in the first pre-experiment showed considerable front-back confusion but virtually no left-right confusion for a static sound source, we can derive an interesting prediction for the second pre-experiment, which investigated moving sound sources: If we assume a sound source that is perceived as front-back reversed (e.g., at 180 degrees instead of 0 degrees, see Figure 3), than when the actual sound source starts rotating clockwise, it will become louder for the right ear and quieter for the left ear. Even if the sound is initially perceived front-back reversed, it will still become louder for the right ear and quieter for the left ear as it starts moving, such that participant's percept could either (i) swap to the nonreversed percept, such that participants will perceive the sound source properly localized and moving correctly counterclockwise (Figure 3(a)). Note that such as swapping from front-back reversed to nonreversed was indeed observed for some participants and trials, but apparently did not cause any confusion or discomfort; or (ii) remain front-back reversed, such that the sound would be perceived as rotating erroneously counterclockwise. This is illustrated in Figure 3(b). Thus, as the first pre-experiment demonstrated that participants showed virtually no left-right reversals, we can use the occurrence of erroneously perceived sound source motion directions in the second pre-experiment as an indication of an underlying front-back confusion. The continuous pointing procedure allowed us to confirm that sound source motion perception reversals indeed concurred with front-back reversals.

While the first pre-experiment used only recordings of one stationary sound source, the second pre-experiment investigated the perception of two concurrently moving sounds. Although adding a second

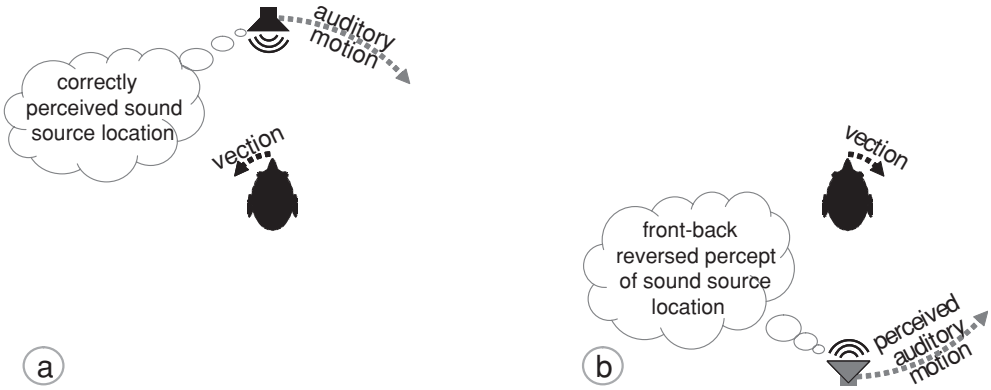

Fig. 3. Illustration of the potential effect of front-back reversal of sound source location on sound source motion perception. (a): If a sound source located at 0° and moving clockwise, it can result in counterclockwise auditory circular vection. (b): If the same moving sound source is instead perceived as front-back reversed (180°), it will still becomes louder at the right ear and quieter at the left ear, thus leading to the erroneous percept that the sound source is moving counterclockwise, which can eventually lead to clockwise auditory vection.

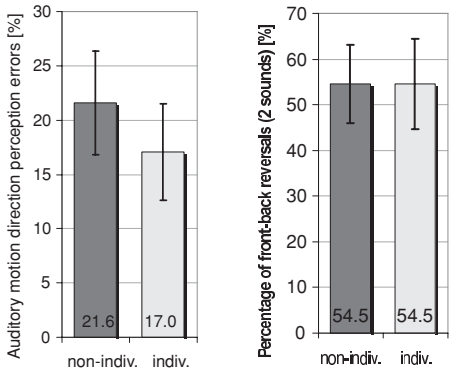

Fig. 4. Data from the auditory motion direction perception pre-experiments. Left: Mean percentage of auditory motion perception errors (i.e., misperception of clockwise vs. counterclockwise rotation) for the nonindividualized (left bar) and individualized (right bar) binaural recordings. Bars and whiskers indicate the arithmetic mean and one standard error of the mean, respectively. Right: Mean percentage of front-back confusions for the stationary recordings of two sound sources positioned at 0° and 270°. Participants were asked to point to the perceived location of the birds sound, which was always located at 0° (i.e., directly in front).

sound source was expected to decrease localization ability for the individual sounds, it is feasible that the dynamic information contained in the moving sound field might help participants to disambiguate anterior and posterior stimuli better and thus partially resolve front-back confusions. This would be reflected in lower front-back confusions (and thus motion direction perceived errors) for the moving stimuli than the static ones.

This was confirmed by the corresponding data plots in Figure 4 and by the statistical analysis: A repeated-measures within-subject ANOVA with the two factors recording type (individualized vs. nonindividualized) and sound movement condition (moving vs. stationary) and using the frequency of motion or front-back perception reversals as the dependent measure showed a significantly lower frequency of perceptual reversals for the moving sound stimuli, as compared to the stationary control condition,

F(1, 21) = 17.05, p < .0005***, η_p^2 = .448, power = .976. This suggests that providing moving instead of static sounds can indeed significantly reduce the number of front-back reversals (and consequently also the number of resulting motion direction misperceptions). This has important implications for vection experiments as well as auditory self-motion simulations in general, as it shows that the requirement of sound presentation fidelity can be relaxed if dynamic sound stimulation instead of static sounds are used.[2]

Although individualized binaural stimuli are often associated with reduced front-back reversals [Begault 1994; Blauert and Allen 1997; Shilling and Shinn-Cunningham 2002], the ANOVA for the current data revealed no such benefit (F(1, 21) = .410, p = .529, η_p^2 = .019, power = .094) and no interactions with the sound movement condition (F(1, 21) = .287, p = .598, η_p^2 = .013, power = .080). This lack of benefit for the individualized recordings might, in part, be related to our recording/presentation procedure and equipment, in particular the fact that we did not use an anechoic chamber for the recordings but instead recorded the whole, naturally occurring sound field including room reflections and reverberations. Consequently, participants in the static two-sound conditions showed front-back reversal rates of about 50% and were thus essentially at chance level, compared to a moving two-sound condition where the reversal rate dropped to about 20% (see Figure 4). Note that the static front-back reversal rate for the two sound sources in the second pre-experiment was also considerably larger than in the first pre-experiment, which used only one sound source.

5. EXPERIMENT 1: INFLUENCE OF VIBRATIONS AND THE POTENTIAL FOR ACTUAL MOTION ON AUDITORY CIRCULAR VECTION

Experiment 1 was designed to investigate if auditory circular vection could be enhanced by providing subtle vibrations and the potential for actual motion.

5.1 Methods

Participants. Our goal was to study how variations across our stimulus conditions influenced perceptual reports of circular vection. Nine of our original 23 participants did not reliably report circular vection under any of our conditions, so we excluded them from the statistical analysis to assess the effects of our stimulus conditions.[3] This ratio is in accordance with the literature, where auditory vection typically occurs only in about 20% to 60% of blindfolded observers [Lackner 1977; Väljamäe 2007]. The 14 participants (5 female) who reliably perceived auditory vection were between 18 and 51 years old (mean: 25.8) and had various occupational backgrounds.

Procedure. Participants were seated in the hammock chair that was fixed in the 0 degree position. They wore 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 Figure 1). Throughout Experiment 1, 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").

[2]Even better, though, would be to allow participants to move their head to disambiguate front-back confusions [Loomis et al. 1999]. We refrained from this option for the current study, though, as our experimental procedure required participants to keep their head stationary and to avoid the inherent technical difficulties of real-time individualized HRTF convolution.

[3]In the condition without vibrations and feet on the ground, 2 of those 14 participants who were included in the statistical analysis did not experience any auditory vection at all. For the condition without vibrations and feed suspended, one participant still did not experience any auditory vection. In the other conditions that included vibrations, all 14 participants perceived vection in at least some of the trials.

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 reanchor 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.

Posttrial Debriefing. At the end of each trial, participants were asked to rate the intensity of their perceived self-movement across these four questions: (i) "How intense was the onset of vection?" (ii) "How intense was the sensation of self-motion toward the end?" (iii) "How intense was the sensation of self-motion overall?", and (iv) "Did you really feel like you were rotating in the physical room?" Participants responded verbally using a continuous scale from 0% to 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.

Experimental Design. 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) $\times$ 2 vibrations conditions (jitter on vs. off; balanced order) $\times$ 2 feet conditions (feet on ground, "motion impossible" vs. feet suspended on the footrest, "motion possible"; balanced order) $\times$ 2 repetitions per condition. The order of the conditions was pseudobalanced across participants to avoid order effects.

5.2 Results

The data from the various dependent measures of Experiment 1 were analyzed using repeated measures within-subject 2 $\times$ 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 II, and the data are graphically represented in Figure 5.

Auditory vection was perceived in 67.9% to 98.2% of all trials, depending on the experimental condition (see Figure 5, top left). While 8 of the 14 participants always experienced vection, others perceived only occasional vection, and 2 of the 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 20.6% and 31.8% 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 (see discussion in, e.g., Riecke et al. [2009]).

Table II. Analysis of Variance Results for the Different Dependent Variables

Significant ($p \leq 5\%$) and marginally significant ($p \leq 10\%$) effects are typeset in bold and italics, respectively. The effect strengths partial Eta squared (η_p^2) indicates the percentage of variance explained by a given factor. The statistical power indicates the probability of finding a statistically significant effect if there was one (i.e., the probability that the statistical test will reject a false null hypothesis (that it will not make a Type II error). Note that adding subtle jitter facilitated vection in all dependent measures, whereas suspending one's feet by putting them on the footrest showed (marginally) significant benefits in only some of the vection measures.

	Jitter on/off				Feet on ground/suspended				Interaction jitter – feet			
	F(1,13)	p	η_p^2	power	F(1,13)	p	η_p^2	power	F(1,13)	p	η_p^2	power
Percentage of trials w/ vection	**6.05**	**.029**	**31.7%**	**.624**	*4.14*	*.063m*	*24.1%*	*.469*	1.16	.30	8.2%	.169
Estimated vection onset time	**7.13**	**.019**	**35.4%**	**.695**	*3.40*	*.088m*	20.7%	*.400*	.03	.87	.2%	.053
Realism of actually rotating	**12.96**	**.003**	**50.0%**	**.914**	*3.12*	*.098m*	*19.7%*	*.379*	.04	.843	.3%	.054
Vection intensity at onset	**8.94**	**.010**	**40.7%**	**.789**	1.89	.193	12.7%	.247	.42	.53	3.1%	.092
Vection intens. at end of trial	**9.65**	**.008**	**42.6%**	**.819**	**5.60**	**.034**	**30.1%**	**.591**	.005	.95	.0%	.050
Overall vection intensity	**10.31**	**.007**	**44.2%**	**.843**	*3.87*	*.071m*	*22.9%*	*.445*	.017	.90	.1%	.052

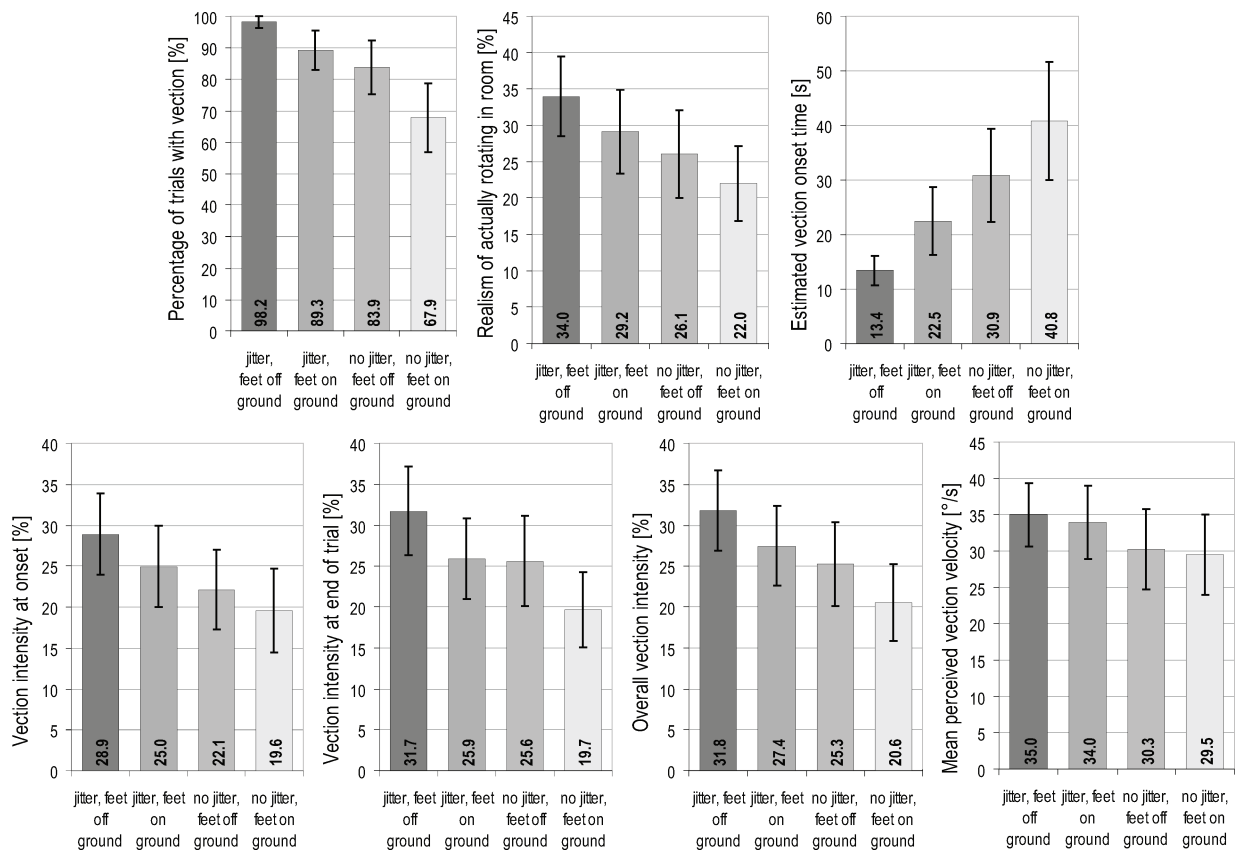

Fig. 5. Vection data for Experiment 1. The bars represent the arithmetic mean, the whiskers depict one standard error above and below the mean.

5.2.1 *Influence of Adding Jitter to Auditory Vection.* Table II 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 31% and 50%, indicating that between 31% and 50% of the observed variance in the data can be explained by the experimental manipulation of adding jitter.[4]

5.2.2 *Influence of Suspending Feet.* When participants placed their feet on the stationary floor (instead of suspending them on the chair's strap), their ratings of self-movement were reduced for all of the measures. This trend reached significance ($p \leq 5\%$) for the vection intensity at the end of the trial. Four of the other dependent measures reached marginal significance ($p \leq 10\%$). Between $\eta_p^2 = 19.7\%$ and $\eta_p^2 = 30.1\%$ of the variability in the data could be ascribed to the feet being suspended or not. These effect sizes can be described as medium to 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. This failure to find significant effects in some of the experimental measures might be related to a lack of power for this variable, indicated by power values below 60% [Cohen 1988]. Considering the relatively small number of participants tested, these results are already quite substantial, though.

5.2.3 *Interaction Jitter–Feet.* None of the dependent measures showed any significant interactions between the independent variables jitter and feet, 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.

5.2.4 *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 during the illusory self-rotation. The data from these 13 participants were used to estimate their perceived vection velocity (see Figure 5). Although there was a tendency toward higher perceived self-rotation velocities when jitter was added and one's feet did not touch solid ground, none of these effects reached significance ($F(1,12) = 2.11$, $p = .172$, $\eta_p^2 = 15.0\%$ and $F(1,12) = 0.42$, $p = .530$, $\eta_p^2 = 3.4\%$, respectively). Mean perceived vection velocities per condition varied considerably between participants, and ranged from 0°/s (i.e., no vection) for the no jitter condition up to almost 50°/s. Note that even the highest reported mean vection velocities were still slightly below the stimulus velocity of 60°/s, suggesting that participants' perceived self-rotation velocity was typically not "locked" to the auditory rotation velocity, at least not during the whole vection phase. This suggests that participants perceived the sound sources to be rotating with respect to the environment at the residual velocity, such that participants would have perceived both themselves and the sound sources as moving in opposite directions during vection. Although we did not systematically collect data to support this hypothesis, informal reports and observations indicate that while the room was never perceived to be rotating, the sound sources were perceived to be rotating with respect to the room and were, in fact, never perceived to be fully earth stationary. 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, such that one's perceived orientation with respect to the simulated scene remains constant

[4]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].

and the simulated scene is perceived to be earth stationary [Riecke et al. 2006, informal observations]. 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. 2005]. Interestingly, this did not seem to happen for the auditory stimuli used here, despite using a naturalistic sound field with clearly identifiable sound sources that participants saw and heard beforehand in the lab. Nevertheless, participants clearly updated the surrounding lab while being blindfolded and perceiving vection—albeit at a somewhat lower speed than the auditory rotation velocity.

6. EXPERIMENT 2: INFLUENCE OF INDIVIDUALIZED VS. NONINDIVIDUALIZED BINAURAL RECORDINGS ON AUDITORY CIRCULAR VECTION

Experiment 2 was designed to test if nonindividualized (other-ear) binaural recordings of a rotating soundfield are as effective in inducing circular vection as the individualized (own-ear) recordings that were used in Experiment 1.

6.1 Methods

Participants. The same 23 participants as in the previous experiments subsequently took part in Experiment 2. Compared to the 14 out of 23 participants who reliably perceived vection in the previous experiment, only 10 participants reliably experienced vection in more than one third of the trials in the current experiment. This reduction in the percentage of participants experiencing vection might, at least in part, be related to the lack of vection-facilitating vibrations in the second experiment. Data from the 13 participants that did not reliably experience vection were excluded from further analysis.

Stimuli and Apparatus. Stimuli and apparatus were identical to Experiment 1 apart from the changes described later in the text. While the first experiment presented only binaural recordings using participants' own ears ("individualized recordings"), the second experiment presented nonindividualized (other-ear) recordings in half of the trials. That is, we compared the individualized binaural recordings that were also used in Experiment 1 with nonindividualized recordings of the same sound field, that were generated by using the main author's ears and head-related transfer function for the recordings.

Experimental Design and Procedure. After performing two practice trials, each participant completed eight vection trials in one session of about 25 minutes. These trials were comprised of a factorial combination of 2 motion directions (clockwise vs. counterclockwise; alternating) $\times$ 2 auralization conditions (individualized binaural recordings vs. nonindividualized recordings) $\times$ 2 repetitions per condition. All conditions were balanced to avoid order effects.

6.2 Results

As in the previous experiment, a repeated-measures within-subject ANOVA was used to analyze the data, here with the single factor auralization condition (individualized vs. nonindividualized recordings). The statistical results are summarized in Table III, the corresponding data plots are presented in Figure 6.

Overall results for the individualized recordings were almost identical to the corresponding condition in Experiment 1 (no jitter, feet suspended), thus supporting the overall validity and consistency of the previous findings. Across our seven measures of vection, five did not show significant differences between the individualized versus nonindividualized recordings (see Table III). The two measures that did show a significant difference (namely, "realism of rotating in the room", and perceived rotation velocity) seemed paradoxical to us, because when participants listened to the nonindividualized binaural stimuli they rated the realism of rotating in the room more highly and rated the perceived velocity as closer to

Table III. ANOVA Results for the Different Dependent Variables of Experiment 2

Significant ($p \leq 5\%$) effects are typeset in bold. The effect strengths partial η_p^2 indicates the percentage of variance explained by a given factor. The statistical power indicates the probability of finding a statistically significant effect if there was one (i.e., the probability that the statistical test will reject a false null hypothesis (that it will not make a Type II error). Note that the nonindividualized binaural recordings unexpectedly resulted in slightly but significantly higher perceived realism of actually rotating in the experimental room and higher perceived vection velocity.

	Individualized vs. Nonindividualized Binaural Recordings			
	F(1,9)	p	η_p^2	Power
Percentage of trials with vection	1.00	.34	10.0%	.146
Estimated vection onset time	1.28	.29	12.5%	.174
Realism of actually rotating in room	**5.34**	**.046***	**37.3%**	**.541**
Vection intensity at onset	1.17	.31	11.5%	.163
Vection intensity at end of trial	2.11	.18	19.0%	.255
Overall vection intensity	.38	.55	4.1%	.086
Perceived vection velocity	**5.29**	**0.047***	**37.0%**	**.537**

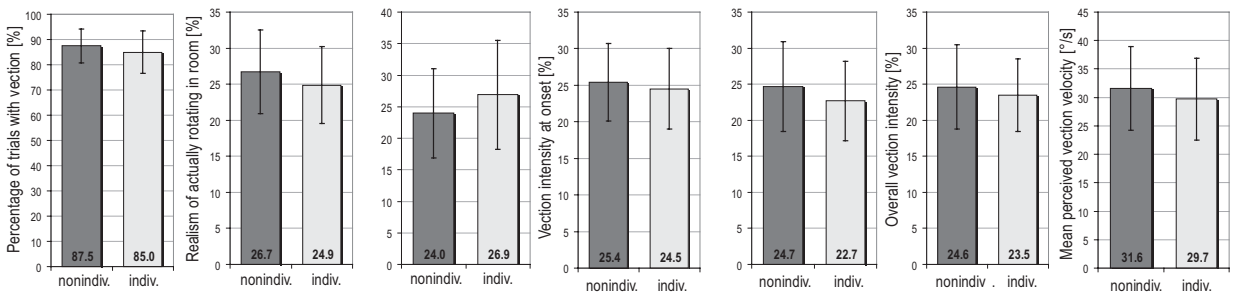

Fig. 6. Vection data for Experiment 2, plotted separately for the nonindividualized binaural recordings (darker left bars of each subplot) and individualized recordings (lighter right bars). Bars represent the arithmetic mean, whiskers depict one standard error of the mean.

the velocity specified by the auditory stimulus. We conclude from this that the extra work of making individualized sound recordings, which includes each listeners HRTF is not justified, for this purpose.

Note that while the absolute size of these effects was fairly small (a 7.4% increase in realism of actual rotation and a 6.3% increase in self-rotation velocity), the effect strengths partial η_p^2 of $\geq 37\%$ indicates a substantial effect [Cohen 1988], and 37% of the variability in these two vection measures could be attributed to the difference between non-individualized and individualized binaural recordings.

7. GENERAL DISCUSSION AND CONCLUSIONS

7.1 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, 2007], but it has never been shown that this procedure actually does facilitate

auditory vection. The current study provides the first evidence that such facilitation does indeed exist: Vection in Experiment 1 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 significantly facilitated reports of vection on some measures and marginally significant effects on other measures.

It is important to consider that this facilitation could have occurred via both 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 cues 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 or affect model selection, as discussed in Section 7.3 [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. 2005; Schulte-Pelkum and Riecke 2009; 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.

7.2 Vibrations Indicating Self-Movement Enhanced 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]. In Experiment 1, we investigated whether barely noticeable jitter might enhance auditory circular vection, in particular in situations where actual motion might seem possible.

Our results show that adding low-energy vibrations to the chair enhanced reports of circular vection for all seven of our measures. Väljamäe [2007], on the other hand, did not find that vibrations facilitated auditory circular vection. We do not know why our findings differ from his, but we suggest three possible reasons. First, our vibrations were low amplitude but just above the threshold of consciousness, whereas his were slightly below threshold. Second, our hammock chair was flexibly mounted. It moved slightly in response to the participant's body movements, and it all moved a bit in response to the low-amplitude vibrations we added to the situation. And third, Väljamäe [2007] exclusively used nonindividualized HRTF renderings, whereas we compared and contrasted individualized versus nonindividualized recordings. There are two reasons we do not believe that this accounted for the difference. One reason is that the effect of recording-type was nonsignificant for most of our measures. The other reason is that our nonindividualized recordings resulted in stronger reports of vection than our individualized recordings. In any case, our results show that low-frequency, low-amplitude vibrations, like the vibrations that occur when we physically rotate our hammock chair, resulted in significantly better reports of vection.

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.

7.3 Underlying Mechanisms for the Facilitation of Vection

We propose that vibrations might facilitate vection by reducing our perception and assumption of stationarity and thus supporting situational awareness of movability. 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. Alternatively, instead of conceptualizing the experimental manipulation (e.g., having one's feet on the floor) as a Bayesian prior, one could also conceptualize it as a gate on the possibility of different models being correct, thus posing the modeling challenge as an issue of model selection [Beierholm et al. 2008].

Now, why did 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 in the following text, such a framework seems simply unfeasible for our context: 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] or auditory and visual estimation of object location [Beierholm et al. 2008]). 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 visuohaptic 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: visuohaptic) 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 their 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 are simply no realistic methods of eliminating potentially interfering vestibular, proprioceptive, and biomechanical input under ordinary perceptual conditions. A further complication is the exponential decay of vestibular signals over time, which would require a time-dependent model [Mergner and Becker 1990].

7.4 No Benefit of Individualized Over Nonindividualized Binaural Recordings for Auditory Vection

Experiment 2 demonstrated that using nonindividualized instead of individualized binaural recordings did not reduce the vection-inducing power of the rotating sound field. Moreover, the velocity of the illusory self-rotation as well as the perceived realism of rotating in the actual room were even slightly but significantly increased for the nonindividualized recordings. These results were somewhat unexpected, as we used the exact same procedure and stimuli for the individualized and nonindividualized recordings, and thus expected overall improved sound fidelity, sound source localization, and externalization

[Begault 1994; Blauert and Allen 1997; Shilling and Shinn-Cunningham 2002]. The first pre-experiment showed indeed a tendency toward reduced front-back reversals for the individualized recordings when one static sound source was presented. When presented with two concurrent sound sources in the second pre-experiment, however, this trend disappeared and participants experienced comparable reversal rates for the individualized and nonindividualized recordings. While providing moving (as compared to static) soundfields reduced the overall reversal rate from about 50% (i.e., chance level) to about 20%, there still remained a considerable fraction of front-back reversals, which in turn led to motion direction perception reversals (see Figure 3).

The reasons for the lack of a clear benefit of individualized versus nonindividualized binaural stimuli in the current study are not fully understood and await further investigations. Note that only circular yaw motions were investigated here, and it remains to be investigated if other directions of motion (translations and pitch and roll rotations) would show a benefit of individualizing HRTFs. As suggested by Begault [1994], it might also be conceivable that listening with the ears of another person that is a good localizer might improve own's own localization ability, although there seems little support for this notion Begault [1994] and Moller et al. [1996]. Hence, further studies are required to investigate if non-individualized binaural recordings can indeed under certain circumstances provide an equal or even stronger sensation of auditory vection than individualized recordings—if this were the case, it would be of considerable theoretical as well as applied interest.

In conclusion, Experiment 2 demonstrated that nonindividualized binaural recordings can be as effective in inducing auditory circular vection as individualized recordings. This corroborates earlier findings by Väljamäe et al. [2004] who used synthesized binaural cues using HRTF convolution and found no difference in vection responses for individualized versus nonindividualized recordings. A recent study by Riecke et al. [2009] investigated the facilitatory effect of adding rotating sound fields to a visual circular vection stimulus, and found a small but significant auditory facilitation—auralization quality, however, did not seem to matter much, and a 5-channel binaural sound rendering provided the same vection facilitation as a high-quality 72-channel rendering.

Thus, the current findings contribute to the accumulating evidence that, at least with respect to auditory vection, the demands for accurate sound source localization are only moderate, and it seems not worth the effort to perform individual recordings for each participant. This has important implications for self-motion simulations (like car or flight simulations and many computer games), as many affordable off-the-shelf sound cards readily allow for real-time convolution with a generic HRTF, thus reducing overall simulation effort and cost.

7.5 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 nonauditory cues (like vibratory cues or having one's feet off the ground), even though these nonauditory cues did not provide any explicit self-rotation cues. This contributes to the growing interest in multimodal/multicue 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, 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. 2006; Schulte-Pelkum 2008; Wong and Frost 1981], or spatialized auditory cues that rotate in sync with the visual stimulus [Riecke et al. 2005a, 2009]. The requirements in terms of spatialization fidelity of the moving auditory seems to be only moderate for the context of self-motion perception, though, which corroborates recent studies by Väljamäe et al. [2004] and Riecke et al. [2009].

In conclusion, the current study provides the first evidence that adding vibrations can enhance auditorily induced circular vection. Furthermore, providing a perceptual/cognitive framework or situational awareness 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 multimodal 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 demonstrations showing that the cognitive belief that self-movement is possible facilitates visually induced vection [Lepecq et al. 1995; Riecke et al. 2005; Wright et al. 2006]. Furthermore, many applications 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, high-fidelity spatialized sound can be provided with ease and little expense and has been shown to induce self-motion illusions as well as facilitate visually or biomechanically induced vection [Riecke et al. 2009, 2008b]. The current study adds to the growing body of evidence highlighting the importance of consistent multimodal simulation embedded in a coherent perceptual and cognitive framework.

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