Spatialized Sound Enhances Biomechanically-Induced Self-Motion Illusion (Vection).

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ABSTRACT
The use of vection, the illusion of self-movement, has recently been explored as a novel way to immerse observers in mediated environments through illusory yet compelling self-motion without physically moving. This provides advantages over existing systems that employ costly, cumbersome, and potentially hazardous motion platforms, which are often surprisingly inadequate to provide life-like motion experiences. This study investigates whether spatialized sound rotating around the stationary, blindfolded listener can facilitate biomechanical vection, the illusion of self-rotation induced by stepping along a rotating floor plate. For the first time, integrating simple auditory and biomechanical cues for turning in place evoked convincing circular vection. In an auditory baseline condition, participants experienced only spatialized auditory cues. In a purely biomechanical condition, seated participants stepped along sideways on a rotating plate while listening to mono masking sounds. Scores of the bi-modal condition (binaural+biomechanical cues) exceeded the sum of both single cue conditions, which may imply super-additive or synergistic effects.

Author Keywords
Self-motion illusions, bio-mechanical and auditory circular vection, cue-integration

ACM Classification Keywords
H.5.1 [Information Interfaces and Presentation, HCI]: Multimedia Information Systems—Artificial, augmented, and virtual realities; J.4 [Social and Behavioral Sciences]: Psychology.

INTRODUCTION
Although self-motion illusions have been known and investigated for more than a century by psychologists (see [2,8,12] for reviews), they have only recently received increasing attention in the context of virtual environments and embodied human-computer interaction (see [8,4] for reviews). While modern computer graphics allow for stunning photo-realistic sceneries as evidenced by recent computer games and computer-animated movies, they nevertheless often lack a compelling embodied sensation of being in and moving through the depicted environment. That is, while visually depicted observer movements can be photo-realistic, they are not necessarily perceptually realistic and often do not evoke a life-like sensation of self-motion. This might limit overall perceived realism, immersion or user acceptance. We propose that investigating and utilizing self-motion illusions might be an affordable yet effective way of addressing this challenge.

The most prominent and well-researched method of inducing compelling self-motion illusions ("vection") is through large-field visual motion (see reviews in [2,4,8,12]). This can lead to compelling embodied self-motion illusions which can be indistinguishable from actual self-motion. Similarly, compelling biomechanical vection can be induced in blindfolded participants by stepping along a rotating floor plate while being stationary [1]. Although moving sound cues have long been known to induce vection in blindfolded listeners [3,6], the attention auditory vection received pales in comparison to the efforts invested in studying visual vection. Whereas visual and biomechanical vection can be quite compelling, auditory vection is much weaker, less compelling, and occurs only in 20-75% of participants (for reviews see [10,11]). Nevertheless, as high-quality sound can be provided at small cost using reliable and affordable off-the-shelf hardware, even a small benefit of adding sound could be easily justified. Indeed, recent studies showed that adding spatialized sound can significantly improve visually induced vection [10,11]. Surprisingly, however, it has to the best of our knowledge never been investigated if or to what degree auditory cues might benefit biomechanical vection. To close this gap, we investigated circular vection in stationary blindfolded participants induced by

(1) Rotating sound fields alone presented via binaural recordings through headphones (**auditory vection** condition)

(2) Stepping along a rotating floor plate and listening to mono masking sounds (**biomechanical vection** condition)

(3) Combined auditory and biomechanical stimulation (bi-**modal vection** condition)

Based on previous findings, we hypothesized that

H1: Auditory vection is weaker than biomechanical vection

H2: Bi-modal vection is stronger than biomechanical vection. In addition, we were interesting in the degree of cross-modal facilitation and potential synergistic effects.

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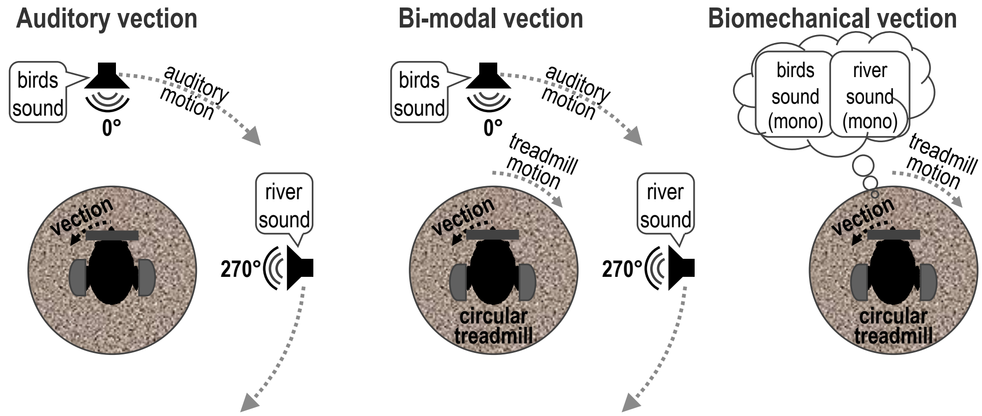

Figure 2: Top-down schematic view of the different vection conditions.

METHODS

A total of 19 participants (7 female) completed the experiment in exchange for monetary compensation at standard rates of $10 per hour. Participants were pre-screened for vestibular dysfunction using the Romberg test [5] and we asked them to rate how often they experience motion sickness in their daily lives on a scale between 0 (never) and 100 (very frequently). However, no participant was excluded because of motion sickness or vestibular dysfunction pre-screening. Due to the design of this experiment, we limited the scope to participants who were actually able to perceive auditory vection. Auditory vection occurs in only 25-75% of participants and thus, a auditory vection pre-screening method was used to select appropriate participants. All qualified participants had previously participated in an auditory vection experiment [9] and were thus familiar with the setup and overall procedure.

Stimuli and Apparatus

Throughout the experiment, participants were blindfolded and seated in a hammock chair mounted above a circular treadmill (Fig. 1a). Although fixed, the hammock chair allowed for minimal swaying movements, thus providing a cognitive-perceptual framework of movability, which has previously been shown to potentially facilitate vection (see reviews in [8,7]).

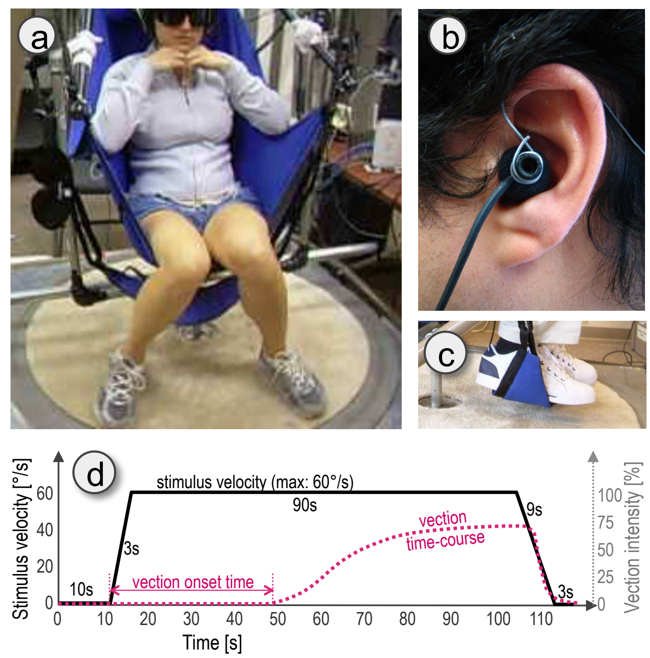

Figure 1: (a) Experimental setup showing a participant blindfolded and seated in the hammock chair mounted above the circular treadmill. (b) In-ear microphones used to create the binaural recordings that were later used to induce auditory vection. (c) For the auditory vection condition, participants' feet rested on a footrest and did not touch the rotating platform. (d) Stimulus velocity (platform and/or auditory rotation velocity) and sketch of vection time-course (red).

Biomechanical Cues

The biomechanical and bi-modal vection condition exploited proprioceptive cues from stepping along sideways on a rotating platter to evoke vection. To that end, participants were asked to comfortably step along sideways with the platform (Fig. 1a) which rotated according to the velocity profile depicted in Figure 1d.

Auditory Cues: Recordings

Auditory vection was induced by individualized binaural recordings of a rotating sound field presented through noise-cancelling headphones. Binaural recordings were obtained by placing miniature microphones (Core Sound Binaural Microphones) at the entrance of the ear canal (Fig. 1b). Two easily localizable and distinguishable sound sources (bird and river sound mixes) were positioned at 0° and 270°, respectively, around the observer seated above the circular treadmill (see [9] for details). For the recordings only, participants were then physically rotated using the velocity profile depicted in Figure 1d. Note that auditory and biomechanical rotation velocities were matched at 60°/s (Fig. 1d).

	ANOVA main effect			Contrast auditory vection vs. biomechanical vection			Contrast biomech. vection vs. auditory+biom. vection		
	FF(2,36)	p	η_p^2	F(1,18)	p	η_p^2	F(1,18)	p	η_p^2
Realism	**60.41**	**<.0005*** **	**.770**	**41.35**	**<.0005*** **	**.697**	**22.84**	**<.0005*** **	**.559**
Intensity	**69.64**	**<.0005*** **	**.795**	**44.36**	**<.0005*** **	**.711**	**33.95**	**<.0005*** **	**.654**

Table 1: ANOVA and pair-wise contrasts results. The effect strengths expressed as η^2 indicate the percentage of variance explained by a given factor. Effect sizes exceeded 50%, indicating large effect sizes.

Auditory Cues: Use in Conditions
During the auditory vection condition, participants were comfortably seated in the hammock chair and listened to rotating sound fields through noise cancelling headphones. Because participants were required to solely rely on auditory vection cues in this condition, we asked them to suspend their feet in a footrest to maximize the possibility of inducing purely auditory vection (Figure 1b). Auditory vection is commonly perceived as weak, so having the feet suspended should make self-motion more plausible [7,8].

During the biomechanical vection condition, a non-spatialized mono recording of the birds, river and platform sounds served as a masking sound. This ensured that participants did not perceive background noise from the lab that may conflict with the illusion of rotating. A mono recording was chosen to avoid any spatialization cues that might have affected biomechanical vection. A control experiment (unpublished) showed that monaural cues do not interfere with biomechanical vection Stimulus and perceived motion direction for each condition are illustrated in Fig. 2.

Experimental Design
As with all introspective measures, response bias cannot be excluded. However, within-subjects design has traditionally been used in vection research to reduce the typically large between-subject variability. The authors are not aware of any research showing systematic differences between within- and between-subject designs.

Participants completed 12 trials, consisting of a factorial combination of 3 vection conditions (auditory, biomechanical, and bi-modal) × 2 turning directions (left/right alternating) × 2 repetitions. Conditions were balanced among participants to avoid order effects. After each trial, participants verbally rated their vection experience using two dependent measures:

Perceived realism of rotation: "Did you feel like you were rotating in the physical room on a scale between 0-100%?"

Perceived vection intensity: "How intense was the sensation of self motion on a scale between 0-100%?"

RESULTS AND DISCUSSION
As predicted in hypothesis 1, auditory vection was overall fairly weak and only reported by 43% of the trials on average, whereas biomechanical and bi-modal vection was reported in 91% and 93% of the trials, respectively. Similarly, the perceived realism and intensity of auditory vection alone was significantly lower than in the biomechanical vection condition (see statistical results summarized in Table 1 and data plots in Fig. 3).

Although auditory cues themselves could not reliably induce compelling vection, adding rotating sound fields enhanced both the realism and intensity of biomechanical vection significantly, confirming hypothesis 2: Adding binaural rotating sound increased the perceived realism of rotating in the actual lab by 39% (effect size η^2 of 56%), and perceived vection intensity was increased by 37% (effect size η^2 of 65%).

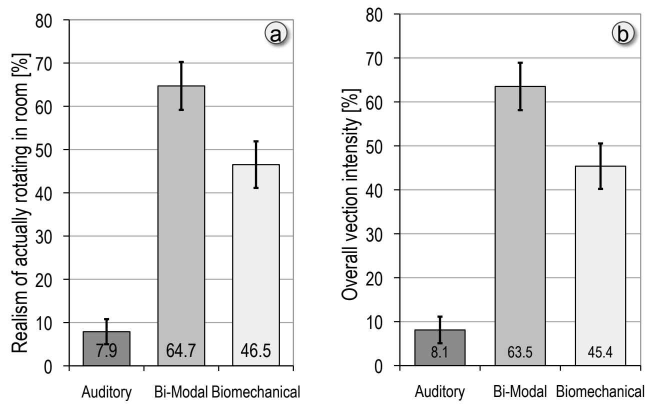

Figure 3: Means and standard error bars for the vection measures.

Interestingly, combining auditory and biomechanical vection showed a "super-additive", synergistic effect, in that the perceived realism and intensity of bi-modal vection was higher than the sum of the values observed for the pure auditory and biomechanical vection. This highlights the potential power of including high-quality spatialized sound for self-motion perception and cross-modal integration.

CONCLUSIONS
Apart from its theoretical relevance, the current findings have important implications for applications in, e.g., entertainment, gaming, and motion simulation: While spatialized sound seems not by itself sufficient to reliably induce compelling self-motion illusions, it can clearly support and facilitate biomechanical vection and has earlier

been shown to also facilitate visually induced circular vection [2] and thus support information from other modalities. Furthermore, high-fidelity, headphone-based sound simulation is not only reliable and affordable, but also offers an amount of realism that is yet unachievable for visual simulations: While even the best existing visual display setups will hardly be confused with "seeing the real thing", headphone-based auralization can be virtually indistinguishable from listening to the real sound and thus can provide a true "virtual reality".

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REFERENCES

1. Bles, W. Stepping around: circular vection and Coriolis effects. In J. Long and A. Baddeley, eds., *Attention and performance IX*. Erlbaum, Hillsdale, NJ, 1981, 47–61.

2. Dichgans, J. and Brandt, T. Visual-Vestibular Interaction: Effects on Self-Motion Perception and Postural Control. In *Perception*. Springer, 1978, 756 - 804.

3. Dodge, R. Thresholds of rotation. *J. Exp. Psychol. 6*, 2 (1923), 107-137.

4. Hettinger, L.J. Illusory Self-motion in Virtual Environments. In K.M. Stanney, ed., *Handbook of Virtual Environments*. Lawrence Erlbaum, 2002, 471-492.

5. Khasnis, A. and Gokula, R.M. Romberg's test. *J Postgrad Med 49*, 2 (2003), 169–172.

6. Lackner, J.R. Induction of Illusory Self-Rotation and Nystagmus by a Rotating Sound-Field. *Aviation Space and Environmental Medicine 48*, 2 (1977), 129-131.

7. Riecke, B.E. Cognitive and higher-level contributions to illusory self-motion perception ("vection"): does the possibility of actual motion affect vection? *Japanese Journal of Psychonomic Science 28*, 1 (2009), 135-139.

8. Riecke, B.E. Compelling Self-Motion Through Virtual Environments Without Actual Self-Motion – Using Self-Motion Illusions ("Vection") to Improve User Experience in VR. In *Virtual Reality*. Intech, 2011, 27 pages (book chapter in print).

9. Riecke, B.E., Feuereissen, D., and Rieser, J.J. Auditory self-motion simulation is facilitated by haptic and vibrational cues suggesting the possibility of actual motion. *ACM Trans. Appl. Percept. 6*, 3 (2009), 1-22.

10. Riecke, B.E., Väljamäe, A., and Schulte-Pelkum, J. Moving sounds enhance the visually-induced self-motion illusion (circular vection) in virtual reality. *ACM Trans. Appl. Percept. 6*, 2 (2009), 1-27.

11. Väljamäe, A. Auditorily-induced illusory self-motion: A review. *Brain Research Reviews 61*, 2 (2009), 240-255.

12. Warren, R. and Wertheim, A.H., eds. *Perception & Control of Self-Motion*. Erlbaum, New Jersey, London, 1990.