Vertical illusory self-motion through haptic stimulation of the feet

Nordahl, Rolf; Nilsson, Niels Christian; Turchet, Luca; Serafin, Stefania

Published in:
2012 IEEE VR Workshop on Perceptual Illusions in Virtual Environments (PIVE)

DOI (link to publication from Publisher):
10.1109/PIVE.2012.6229796

Publication date:
2012

Document Version
Publisher's PDF, also known as Version of record

Vertical Illusory Self-motion Through Haptic Stimulation of the Feet

Rolf Nordahl * Niels C. Nilsson † Luca Turchet ‡ Stefania Serafin §

Medialogy
Department of Architecture, Design and Media Technology
Aalborg University Copenhagen

ABSTRACT

Circular and linear self-motion illusions induced through visual and auditory stimuli have been studied rather extensively. While the ability of haptic stimuli to augment such illusions has been investigated, the self-motion illusions which primarily are induced by stimulation of the haptic modality remain relatively unexplored.

In this paper, we present an experiment performed with the intention of investigating whether it is possible to use haptic stimulation of the main supporting areas of the feet to induce vertical illusory self-motion on behalf of unrestrained participants during exposure to a virtual environment depicting an elevator. The experiment was based on a within-subjects design where all participants were subjected to identical visual and auditory stimuli. The participants experienced a total of four conditions. For three of the conditions a different signal was used to generate the haptic feedback while the final condition included no haptic feedback. Analysis of self-reports were used to assess the participants' experience of illusory self-motion. The results indicate that such illusions are indeed possible. Significant differences were found between the condition including no haptic feedback and the remaining three conditions.

Index Terms: H.5.2 [Information Interfaces and Presentation]: Input devices and strategies—Interaction styles; D.2.2 [Software Engineering]: Design Tools and Techniques—User interfaces

1 INTRODUCTION

A general experience is that of being on a motionless train, looking out the window at another stationary train in an adjacent track. As the second train departs from the station, a transient, yet compelling, illusion of being on the train which is moving is often experienced. This experience is a naturally occurring instance of visually induced illusory self-motion also referred to as vection [4]. The fact that we are susceptible to such illusions may at least in part be ascribed to the equivocal nature of visual motion stimuli [2]. That is to say, visual motion stimuli are open to not one, but two perceptual interpretations [1]. First, the moving stimuli may lead to exocentric motion perception the train passenger (falsely) perceives the surroundings as being stationary while he is moving. Secondly, the stimuli may lead to egocentric motion perception the passenger (correctly) perceives himself as being stationary in space while the train in the adjacent track is moving. Moreover, it is common to distinguish between linear and circular illusory self-motion. The former refers to the perceptual illusion of movement along some line, while the latter refers to the erroneous sensation of rotating about one or more of the three bodily axes [12]. Riecke et al. [7] summarize a number of bottom-up factors influencing the onset time, duration, and intensity of the vection sensation. These include, but are not limited to, the movement speed of the stimulus, the area of the visual field occupied by the display and the perceived depth structure of the visual stimulus. This, however, does not mean that vection is solely induced by bottom-up factors. It has been shown [9, 6, 14] that both circular and linear vection may be influenced by whether participants are seated in a chair that potentially could move as opposed to one that is immovable. It has also been shown that vection under some circumstances may also be influenced by whether the participants are asked to attend to the sensation of self-motion or objects' motion before being subjected to visual motion stimuli [5]. Notably, illusory self-motion may also be induced auditorily during deprivation from visual stimuli [12]. Sound sources moving relative to the position of an individual may induce a sensation of self-motion. However, auditory motion stimuli may, just as their visual counterparts, be open to perceptual interpretations and thus lead to either exocentric or egocentric motion perception.

While visually and auditorily induced illusory self-motion are studied extensively, the influence of the haptic modality remains relatively unexplored territory. The limited attention assigned to self-motion illusions induced purely through haptic stimulation may presumably be ascribed to the nature of the motion cues provided by haptic stimuli. It seems meaningful to distinguish between stimuli providing explicit and implicit motion cues. Explicit motion cues provide information about the relative position and movement of the perceiver and objects in the surrounding environment. In the visual modality, optic flow is responsible for providing this information which can be used to estimate both the velocity and direction of the self-motion [3]. Contrarily, implicit motion cues do not provide any information regarding the relative position and movement of the perceiver and the surrounding environment, but still suggest that movement may be occurring. Commonly experienced implicit motion clues include engine sounds or the subtle vibrations experienced during commute with a motorized vehicle. Notable, it would seem that explicit motion cues relies on bottom-up factors while explicit motion cues largely achieve their significance do to the perceivers expectations to, and interpretation of, the stimuli, that is, top-down factors [8]. With that being said, it does seem plausible that haptic stimuli also may qualify as a bottom-up factor. For example, haptic stimulation of the feet might be perceived as the ground being unsteady and possibly moving, rather than simply bring about associations of a running engine.

As suggested the haptic stimuli experienced during everyday interactions is unlikely to provide any explicit motion cues and thus provide no information about the relative position of the perceiver and the surroundings.

In this paper we describe an experiment performed with the intention of investigating whether it is possible to induce illusory self-motion along the longitudinal axis by means of haptic stimuli in a virtual environment (VE) devoid of any explicit motion cues. To find out we created a lab scenarion, where the goal was to determine whether it would be possible to create the illusion of being in a moving elevator where no visual or auditory information related to the velocity and direction of the movement were presented.

*e-mail: rn@create.aau.dk
†e-mail:ncn@create.aau.dk
‡e-mail:tur@create.aau.dk
§e-mail:sts@create.aau.dk

IEEE VR Workshop on Perceptual
Illusions in Virtual Environments 2012
5 March, Orange County, CA, USA
978-1-4673-1218-9/12/$31.00 ©2012 IEEE

2 Related Work

Research on the influence of haptic stimuli in relation to illusory self-motion is rather limited. Moreover, the experiments involving haptic feedback have generally focused on whether this form of stimuli positively influences an illusion of movement facilitated by stimulation of another modality [8, 13].

Vaaljamaae and colleagues [13] describe a study performed with the aim of investigating whether sensation of auditorily induced linear illusory self-motion may be intensified by the addition of vibrotactile feedback delivered by means of low frequency sound and mechanical shakers. The authors of that study found that the self-motion illusion was significantly higher during exposure to the mechanically induced vibration. Notably their results also showed that the auditory-tactile simulation of a vehicle engine was as effective as illusions induced via auditory feedback including explicit motion cues, i.e., moving sound fields. Riecke et al. [8] similarly describe an experiment investigating whether physical vibrations of the perceivers' seat and footrest enhance visually induced circular vection. They found that the addition of this form of vibrotactile feedback entailed a slight, yet significant, enhancement of the self-motion illusion.

As it is the case for the influence of haptic feedback on illusory self-motion, also vertical self-motion illusions, that is, perceived movement along the longitudinal axis, remains almost unexplored. One such study, performed by Wright and colleagues [14], aimed at investigating the vestibular and visual contributions to vertical illusory self-motion. More specifically they exposed the experiment's participants to different combinations of explicit visual motion cues and 0.2 Hz vertical linear oscillation. Amongst other things they found that visual motion cues, indicating low amplitude oscillatory motion, were able to induce sensations of vertical self-oscillation in the absence of any actual inertial motion. A more general conclusion drawn from the study was that vestibular sensations were subordinate to visual motion cues when these cues originate from a visual scene that mimics the appearance of the physical test environment.

Notably, it would appear that illusions of vertical self-motion may be induced purely through haptic feedback. To be more exact, Roll and colleagues [10] performed a study of whether tactile information from the main supporting areas of the foot influences body posture awareness and body representation in blindfolded subjects who are physically restrained at the shoulder and hip levels. While all ten participants experienced illusory full-body leaning, seven also reported kinesthetic illusions along the longitudinal axis of the body, that is, they experienced upward movement.

The experiment described in this paper attempts to determine whether it is possible to induce a similar self-motion illusion within the context of a virtual environment without physically restraining the participants. Roll et al. [10] do not disclose detailed information about the signals used to drive the haptic stimulation. Our experiment remains relatively explorative in nature. That is to say, in addition to investigating whether such illusions would be possible in the first place, the aim was to compare a small selection of different types of haptic feedback.

3 Experiment Design

The experiment was performed using a within-subjects design and included four conditions. In three of the conditions a different signal was used to generate the haptic feedback while the fourth and final condition included no haptic feedback (AV). The three types of signals were white noise (N), a sawtooth waveform (S) and a combination of the two (SN). Identical visual and visual stimuli were used for all four conditions.

3.1 Experiment Setup and Stimuli

The virtual elevator was simulated using a multimodal architecture originally developed for simulating walking-based interactions through visual, auditory and haptic stimuli [11].

3.1.1 Simulation hardware

The user interacts with the system by performing natural movements registered by the system. The position and orientation of the participants head is tracked by means of a 16 cameras Optitrack motion capture system (Naturalpoint) and the forces exerted during foot-floor interactions are registered by a pair of customized sandals augmented with actuators and pressure sensors [11]. Two FSR pressure sensors (I.E.E. SS-U-N-S-00039) are placed inside the sole of each sandal at the points where the toes and heel come into contact with the sole. The analogue values of each of these sensors were digitalized by means of an Arduino Diecimila board. The actuators responsible for delivering the haptic feedback are placed at roughly the same positions. Each sandal is embedded with four of these electromagnetic recoil-type actuators (Haptuator, Tactile Labs Inc., Deux-Montagnes, Qc, Canada), which have an operational, linear bandwidth of 50 to 500 Hz and can provide up to 3 G of acceleration when connected to light loads. Figure 1 illustrates the placement of the pressure sensor and actuators in the heel of one sandal.

The visual feedback is delivered through a nVisor SX head-mounted display, with a resolution of 1280x1024 in each eye and a diagonal field of view of 60 degrees. While the multimodal architecture in its original form is capable of delivering auditory feedback using a surround sound system composed by 12 Dynaudio BM5A speakers, a set of headphones (Sennheiser HD 600).were used during the current experiment. The reason being, that the actuators generate sound while activated, which might make up an undesirable bias. Thus the headphones both served the purpose of providing auditory feedback and masking out the undesired sounds.

Figure 1: Placement of a pressure sensor and two actuators in the heel of one sandal.

Figure 2: A screenshot of the virtual elevator.

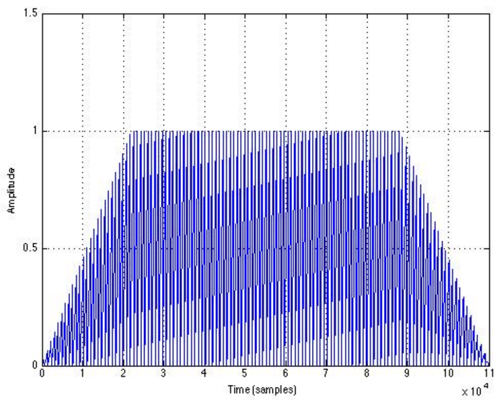

Figure 3: Time domain waveforms for one of the three stimuli used in this experiment: Sawtooth (S)

3.1.2 Simulation software

The virtual elevator (see Figure 2) was produced in the multiplatform development environment Unity 3d which facilitates stereoscopic viewing by the placement of two cameras within one environment. Dynamic eye convergence was simulated by means of a simple raycasting algorithm ensuring that the cameras are always aimed at the closest object immediately in front of the user. The choice of using an elevator with opaque walls was a deliberate one, since this ensured that the participants were deprived of any explicit and more detailed visual motion cues. The auditory feedback was similarly designed to deprive the participants of any explicit motion cues and consisted consisted of a one minute recording of a moving elevator but not rendered in spatial audio. The auditory feedback was delivered using the Max/MSP realtime synthesis engine, which also was used for both delivery and synthesis of the signals used to control actuators delivering the haptic feedback.

The signal used for the condition N was white noise and the sawtooth waveform used for condition S had a frequency of 50 Hz. This frequency was chosen by experimenting with different values which could represent the motion sensation experienced in an elevator. A symmetric trapezoidal temporal envelope was used for both signals, to simulate the starting and ending sensation of motion. Condition SN comprised of summing S and N. All three stimuli lasted one minute, with attack and decay of the trapezoidal envelope of 5 seconds. The three waveforms can be seen in Figure 3, 4 and 5.

The data obtained from the pressure sensors was used to ensure that vibration only was activated when the foot is in contact with the ground. A schematic drawing the multimodal architecture used

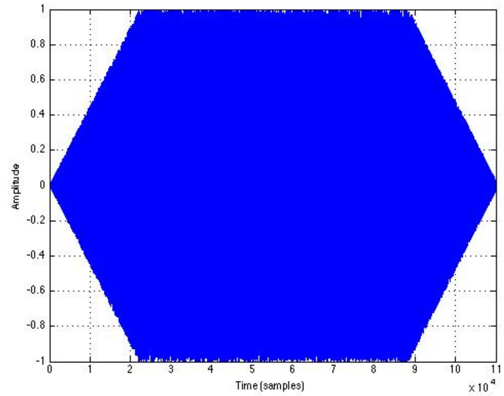

Figure 4: Time domain waveforms for one of the three stimuli used in this experiment: noise (N)

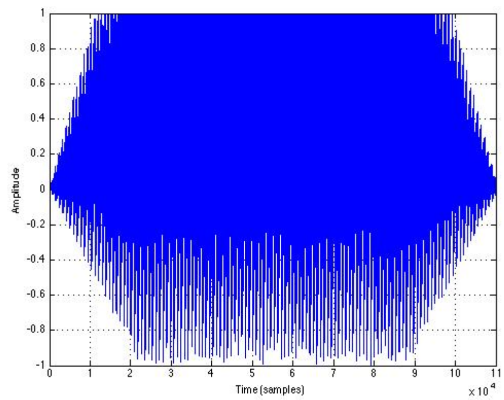

Figure 5: Time domain waveforms for one of the three stimuli used in this experiment: noise plus sawtooth (SN).

to simulate the virtual elevator can be seen on Figure 6.

3.2 Measures of Illusory Self-motion

The participants' experience of illusory self-motion was assessed by means of existing measures of self-motion illusions, namely, analysis of reported self-motion illusion per stimulus type, illusion compellingness, intensity and onset time [12].

The reported self-motion illusion per stimulus type simply corresponds to a binary measure of whether illusory self-motion were experienced or not. The compellingness (or convincingness) of the illusion was assessed by asking the participants to rate their sensation on a magnitude estimation scale from 0 to 5 where 0 signified no perceived movement and 5 corresponded to fully convincing movement.

The intensity of the illusion was measured by asking the participants to estimate the magnitude of the displacement on a scale familiar to them (meters or feet). No experienced movement would correspond to a displacement of zero meters. It should be noted that past experiments where intensity has been operationalized as the magnitude of the displacement [14], have included stimuli providing information about the distance to, or size of, objects based on which estimates of distance could be made. The illusion onset time (or latency) was measured as the time elapsed from the onset of the stimuli until the onset of the illusion. The measures of both compellingness, and intensity were adapted from [14]. Finally the

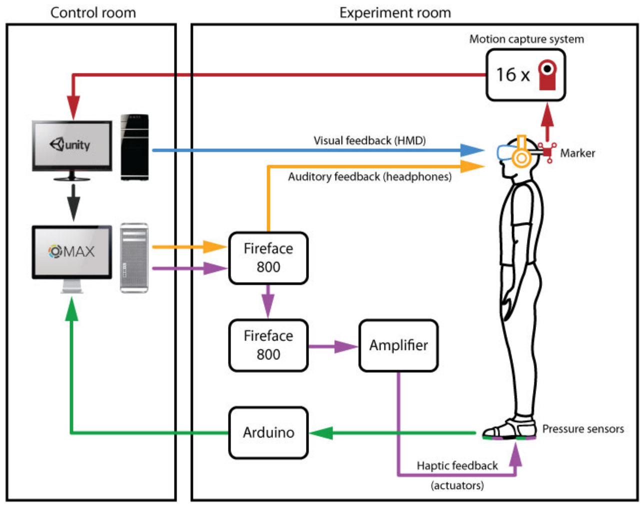

Figure 6: A schematic drawing of the multimodal architecture used to simulate the virtual elevator.

AV	N	S	SN
6	18	23	18

Table 1: Reported self-motion illusion per stimulus type.

participants were also asked to estimate the direction in which the elevator was moving.

3.3 Participants and procedure

A total of 28 participants took part in the experiment (22 men and 6 women) aged between 21 and 33 years (mean = 25.0, standard deviation = 3.1). Before exposure to the VE, the participants were introduced to the scenario they were about to experience and were asked to attend to the sensation of movement. Moreover it was stressed that we were interested in the participants honest opinion rather than answers brought about by any assumptions regarding the demand characteristics of the experiment. During the four exposures to the virtual elevator the participants were placed on a wooden platform, which they were made to believe might move during one or more of the conditions. The participants were unable to see the experimental setup for the duration of the experiment. This was done since it has been shown that the convincingness of self-motion illusions significantly increases when subjects believe that actual motion may occur [9]. The participants were exposed to all four conditions for one minute and after each exposure the participants were asked to answer the provided questions verbally. The order of the conditions was randomized so as to control potential order effects.

4 Results

Table 1 shows the results pertaining to the reported self-motion illusion per stimulus type, that is, the number of participants who experienced a self-motion illusion across the four conditions. A comparison by means of a Cochrans Q test yielded a significant difference between the four conditions ($Q(3) = 7.814, p = 0.0001$). Subsequent pairwise comparison using McNemar's tests revealed that the audio visual condition differed significantly from the remaining three conditions while the three did not differ significantly from one another.

Table 2 summarizes the results obtained from the measures of illusion onset time, compellingness, and intensity. The bar charts presented in figures 9 and 8 provide a graphical overview of these

	Compellingness	Intensity (meters)	Onset time (sec.)
AV	0.61 ± 1.31 (28)	1.46 ± 4.14 (26)	23.65 ± 17.90 (5)
N	1.64 ± 1.54 (28)	9.82 ± 13.80 (17)	25.35 ± 18.62 (12)
S	2.43 ± 1.55 (28)	16.26 ± 16.37(19)	13.64 ± 12.97 (18)
SN	1.64 ± 1.54 (28)	9.52 ± 11.57 (21)	17.05 ± 18.17(14)

Table 2: Mean ± one standard deviation pertaining to three of the measures of illusory self-motion. Values in parenthesis indicate the number of reports based on which the mean and standard deviations were determined.

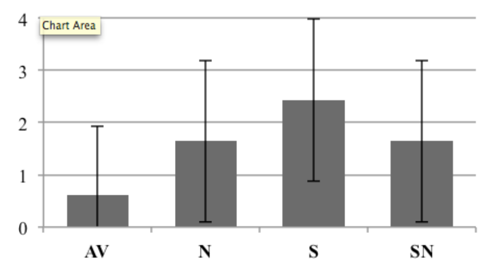

Figure 7: Mean compellingness ratings. Error bars indicate ± one standard deviation.

three sets of results. One-ways analyses of variance (ANOVAs) were used to compare the averages obtained from the measures of the compellingness and intensity of the self-motion illusion across the four conditions Significant differences was found in relation to both compellingness ($F(3,79) = 5.96, p = 0.001$) and intensity ($F(3,108) = 7.02, p = 0.0002$). Subsequently post-hoc analyses were performed by means of Tukeys procedure. In relation to both measures this pairwise comparison of the means revealed that conditions AV and S differed significantly while no significant differences were detected amongst the remaining means. No significance tests were used to compare the means pertaining to illusion onset time. The reasons being that, the number of registered onset times differed greatly from condition to condition, since a large number of participants neglected to report the onset time and no times recorded when no illusion was experienced.

Finally, Table 3 summarizes the results pertaining to the question of what direction the elevator was moving in. It should be noted that one participant reported having had the sensation that elevator was moving backwards rather than up or downwards after being exposed to condition S.

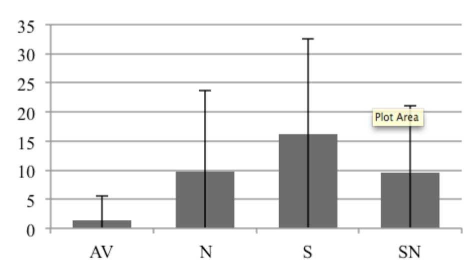

Figure 8: Mean illusion intensity in meters. Error bars indicate ± one standard deviation.

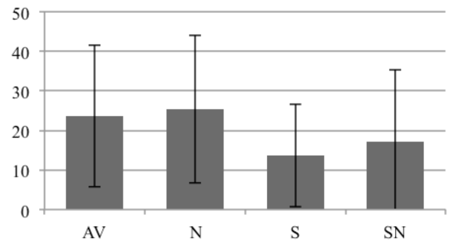

Figure 9: Mean illusion onset time in seconds. Error bars indicate ± one standard deviation.

	Upwards	Downwards	Unsure
AV	4	1	1
N	10	8	0
S	9	9	4
SN	7	6	5

Table 3: Frequency of the participants' estimates of the elevator' s direction of movement across the four conditions.

5 Discussion

The reported self-motion illusion per stimulus type suggests that all three employed signals were more likely to produce self-motion illusions compared to sound and visuals alone. Notably the haptic feedback driven by the sawtooth waveform produced self-motion illusion on behalf of the largest number of participants while the noise and the combination of noise and the sawtooth waveform elicited an identical number of illusions.

The mean ratings pertaining to compellingness and intensity painted a similar pictured. These suggest that exposure to a virtual elevator including haptic feedback based on the sawtooth waveform facilitates a significantly more compelling and intense illusions, compared to the experience of a virtual elevator devoid of haptic feedback. While the two sets of results do seem to be consistent, one cautionary reminder should be added. Unlike past experiments, where intensity has been operationalized as the magnitude of the displacement , the current experiment did not include stimuli providing information about the distance to, or size of, objects based on which estimates of distance could be made. Indeed, many of the participants did express that they find it difficult to estimate the displacement.

The number of registered onset times did as suggested differ greatly across the four conditions, which in turn makes it difficult to rely on the associated results. With that being said, it is worth mentioning these results do show somewhat similar tendencies. That is to say, the illusion onset time was lowest when the participants were exposed to haptic stimuli driven by the sawtooth waveform.

Finally, no tendencies seem readily apparent when it comes to the experienced direction of movement. Thus, it would seem that the different types of stimuli were equally likely to elicit an experience of upwards or downwards movement. The fact that just one participant experienced backwards rather than up or downwards movement hardly came as a surprise. However, it is an interesting anomaly since it illustrates that this form of haptic stimuli indeed may open to a multitude of different interpretations in relation to the direction of movement. This can most likely be ascribed the fact that haptic stimuli, unlike the auditory and visual counterparts, does not provide any explicit motion cues. The fact that only one participants experienced movement in any direction other than up or downwards, may be interpreted as an indication of the influence which the context the elevator have had on the participants interpretation of the stimulation.

One possible explanation for why the sawtooth waveform gave rise to the strongest illusions of self-movement is that this signal provided a more discernible stimulation of the feet. Several participants reported experiencing a tingling sensation during expose to the noise condition, but many added that it barely was noticeable. It seems likely that the combination of white noise and the sawtooth waveform similarly have been experienced as less discernible. That is, the ramps and drops of the sawtooth wave may have been experienced as less noticeable. Alternatively, it does seem possible that the haptic feedback produced from the sawtooth wave felt more like a real elevator. Here it should be stressed that one interpretation does not preclude the other. The differences in experience may both have been influenced by the discernibility and familiarity of the stimuli. The results related to the AV condition experienced did as suggested indicate that few participants experienced illusory self-motion when no haptic feedback was presented and the ones that did found the illusion less compelling and less intense. Despite hereof, it is interesting to note that this condition was able to elicit self-motion illusions in the first place. This can presumably be ascribed the influence of top-down effects, that is, self-motion illusions may be influenced by "expectations as well as the interpretation or associated meaning of the stimuli" [9]. Last, but not least it is worth mentioning that the experience of the virtual elevator entailed an unexpected perceptual illusion on behalf of a small number of participants. Four participants explained that the sensation of movement at times had been accompanied by the sight of moving lights in the narrow slit between the elevators doors, similar to those one might see when passing a series of floors without coming to a halt.

6 Conclusion

In this paper we have described an experiment performed with the intention of investigating whether it is possible to use haptic stimulation of the main supporting areas of the feet to induce vertical illusory self-motion on behalf of unrestrained participants during exposure to an immersive simulation of an elevator. The experiment was based on the a within-subjects design and all 28 participants thus experienced the same four conditions, Three conditions where different signals were used to generate the haptic feedback and one condition where no haptic feedback was provided. The participants sensation of movement was assessed by means of self-reported measures of illusory self-motion, namely, namely, reported self-motion illusion per stimulus type, illusion compellingness, intensity and onset time. Finally the participants were also asked to estimate the experienced direction of movement. Significant differences were found between the condition devoid of haptic feedback and one or more of the remaining conditions. Based on these results we feel reasonably confident when concluding that haptic feedback delivered at feet level may elicit vertical self-motion illusion, albeit with different levels of intensity and compellingness.

References

[1] T. Brandt, J. Dichgans, and E. Koenig. Differential effects of central versus peripheral vision on egocentric and exocentric motion perception. *Experimental Brain Research*, 16(5):476–491, 1973.

[2] E. Goldstein. *Sensation and perception*. Wadsworth Pub Co, 2009.

[3] M. Lappe, F. Bremmer, and A. Van den Berg. Perception of self-motion from visual flow. *Trends in Cognitive Sciences*, 3(9):329–336, 1999.

[4] K. Lowther and C. Ware. Vection with large screen 3d imagery. In *Conference companion on Human factors in computing systems: common ground*, pages 233–234. ACM, 1996.

[5] S. Palmisano and A. Chan. Jitter and size effects on vection are immune to experimental instructions and demands. *PERCEPTION-LONDON-*, 33:987–1000, 2004.

[6] B. Riecke, D. Feuereissen, and J. Rieser. Auditory self-motion illusions (circular vection) can be facilitated by vibrations and the poten-

tial for actual motion. In *Proceedings of the 5th symposium on Applied perception in graphics and visualization*, pages 147–154. ACM, 2008.

[7] B. Riecke, J. Schulte-Pelkum, M. Avraamides, M. von der Heyde, and H. Bülthoff. Scene consistency and spatial presence increase the sensation of self-motion in virtual reality. In *Proceedings of the 2nd symposium on Applied perception in graphics and visualization*, pages 111–118. ACM, 2005.

[8] B. Riecke, J. Schulte-Pelkum, F. Caniard, and H. Bülthoff. Influence of auditory cues on the visually-induced self-motion illusion (circular vection) in virtual reality. In *Proceedings of Eigth Annual Workshop Presence*, 2005.

[9] B. Riecke, D. Västfjäll, P. Larsson, and J. Schulte-Pelkum. Top-down and multi-modal influences on self-motion perception in virtual reality. In *HCI international*, 2005.

[10] R. Roll, A. Kavounoudias, and J. Roll. Cutaneous afferents from human plantar sole contribute to body posture awareness. *Neuroreport*, 13(15):1957, 2002.

[11] L. Turchet, R. Nordahl, S. Serafin, A. Berrezag, S. Dimitrov, and V. Hayward. Audio-haptic physically-based simulation of walking on different grounds. In *Multimedia Signal Processing (MMSP), 2010 IEEE International Workshop on*, pages 269–273. IEEE, 2010.

[12] A. Valjamae. Auditorily-induced illusory self-motion: A review. *Brain research reviews*, 61(2):240–255, 2009.

[13] A. Väljamäe, P. Larsson, D. Västfjäll, and M. Kleiner. Vibrotactile enhancement of auditory induced self-motion and presence. *Submitted to Journal of Audio Engineering Society*, 2005.

[14] W. Wright, P. DiZio, and J. Lackner. Perceived self-motion in two visual contexts: dissociable mechanisms underlie perception. *Journal of Vestibular Research*, 16(1):23–28, 2006.