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Vibrotactile Inputs To The Feet Can Modulate Vection

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ABSTRACT

Vection refers to the illusion of self-motion when a significant portion of the visual field is stimulated by visual flow, while body is still. Vection is known to be strong for peripheral vision stimulation and relatively weak for central vision. In this paper, the results of an experimental study of central linear vection with and without vibrotactile feet stimulation are presented. Three types of vibratory stimuli were used: a sinusoidal signal, pink noise, and a chirp signal. Six subjects faced a screen looking at a looming visual flow that suggested virtual forward motion. The results showed that the sensation of self-motion happened faster and its intensity was the strongest for sinusoidal vibrations at constant frequency. For some subjects, a vibrotactile stimulus with an increasing frequency (a chirp) elicited as well a stronger vection. The strength of sensation of self-motion was the lowest in the cases when pink noise vibrations and no vibrotactile stimulation accompanied the visual flow stimulation. Possible application areas are mentioned.

Index Terms: H.1.2 [User Interfaces]: Haptic I/O—Theory and methods; I.2.10 [Vision and Scene Understanding]: Motion—Perceptual reasoning

1 INTRODUCTION

The sensation of self-motion is inherently multimodal. Inputs from the vestibular system, proprioception, touch, audition, and vision all contribute to experiencing a sensation of self-motion. Among the illusions of self-motion, vection is the illusory experience of self-motion given by the presence of visual flow in the absence of the other sources of motion information. Vection is most effectively induced when significant portions of the visual field provide motion information while the body is still [5]. Vection is known to be stronger than when the peripheral visual field is stimulated [2]. Vection may also be elicited when the central visual field is stimulated [1, 21]. Owing to the strong contributions of vestibular inputs to the sensation of self-motion it is customary to distinguish 'linear vection' from 'circular vection'.

Numerous studies about vection and self-motion perception have been carried and motivated by the many opportunities afforded by virtual reality applications, training systems, computer games, and telepresence systems [15, 13, 3]. However, the illusory sensation of self-motion is often reported to be weak or to fail to be elicited since it is an inherently bistable percept that can switch between a sensation of self- or external motion. It was shown, for instance, that vection fails to occur when two visual flows are superimposed [10]. The ability to experience vection depends on size of the display, on the occlusions in the visual flow and other factors such as the spatial and temporal frequencies present in the stimulus [21, 19, 18].

There is, therefore, a strong incentive to leveraging inputs from other sensory modalities in order to enhance the occurrence of vection, such as audition [17, 23, 22, 14]. Force feedback applied to the hands can also be used for this purpose, where the force intensity is adjusted in accordance to the visual flow during navigation in a virtual environment [7, 11, 4]. Low-frequency vibration stimuli can also applied through a chair on which subjects are sitting, concomitantly with auditory inputs [12]. Artificial air flow on the skin was also used together with visual flow enhance the effect [20]. Floor stimulation to the feet is another approach that can be employed to enhance the perception of motion [24]. It was shown that tactile stimulation of the feet results in illusory perceptions of whole-body leaning [16]. A haptic footstep interface provided the sensation of mechanical impacts during virtual walking [6]. Vibrations of 50 Hz applied to the feet, together with visual and auditory stimuli, was used to generate vertical illusory self-motion [9]. Similar studies investigated the influence of the feet vibration on the strength of the illusion according to different visual and auditory contexts [8].

In the aforementioned studies employing vibrotactile inputs, neither the amplitude nor the spectral characteristics of the vibration stimulus were related to the parameters of the optical flow. There was no physical dependency between the type and the parameters of vibration/tactile stimuli and visual flow, only the effect of the existence or the absence of a stimulus was investigated. In real life all sensory inputs arising from the environments with which we interact are related through the laws of physics. In the present study, we wondered whether vibrotactile stimulation combined with visual stimulation would enhance the experience of vection if a correlation was introduced between the visual flow and the spectral characteristic of the vibration.

We now present the results of a pilot study where the effects of different vibratory inputs on linear vection combined with the same visual stimulus were compared to each other. The visual stimulus was of the frontal type with a looming optical flow. This type of stimulus creates a rather weak vection effect that can be easily adjusted by varying the subject-display distance, that is the angular size of the stimulated visual field. It is typical to only experience a 'Star Wars credits' effect where the environment is perceived to be moving, but where the percept can also switch to vection.[1] Vection studies are often difficult to carry out and the results are hard to analyze because there is no straightforward manner to measure the sensation of self-motion. Typical approaches resort to introspection—either one feels or fails to feel self-motion. Quantification of the effect must rely on verbal reports about its strength, on reporting the time-to-onset of the effect, and on comparing the effects felt in different conditions. It is also typical to encounter very large inter-subject differences owing to the important contribution of attention, volition, and other endogenous states or inputs to the experience of self-motion.

2 METHODS

2.1 Experimental Setup

The experimental setup comprised two vibrating foot stimulators placed on the floor in front of a video display (LCD screen, 101 cm in diagonal), a personal computer, an audio amplifier (PylePro,

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[1] `https://www.youtube.com/watch?v=RFc3daZVN2I`

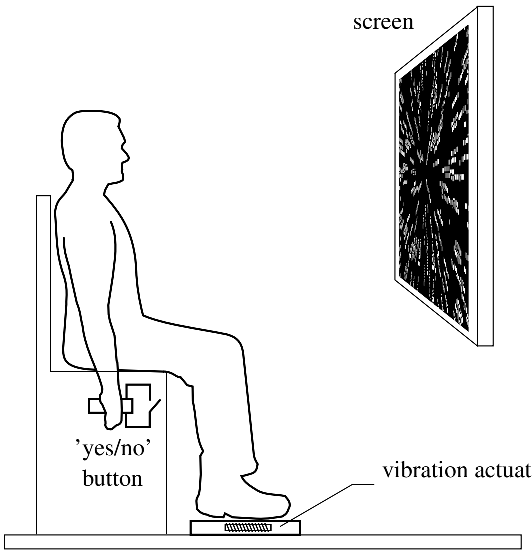

Figure 1: General view of the experimental setup.

model PCA1), and a handle-held press-button. The subjects were seated in front of the screen with their feet placed on the foot platforms. The general view of the setup is shown in Fig. 1.

Visual stimulus. The visual stimulus was synthesized from a set of a thousand white dots streaming out of a central focus to create a radial visual flow (see Fig. 1). The laws of perspective projection were used to generate the movement of the dots on the screen as a function of the virtual velocity of the viewer. Such stimulus is known to generate a sensation of movement in space [26]. The trajectories $[x_t(t), y_k(t)]$ of each point, $k = [1, \cdots, 1000]$, on the screen were calculated as follows,

$$x_k(t) = \frac{X_0}{Z_0 + v_z t}, \qquad y_k(t) = \frac{Y_0}{Z_0 + v_z t},$$

where (x_k, y_k) are the coordinates of the points on the screen at discrete time instant $t = t_k$; (X_0,Y_0,Z_0) are the randomly distributed initial coordinates of the points in 3D space; v_z is the velocity of motion in the 3D virtual environment along the z-direction orthogonally to the plane of the screen. The 3D coordinates of each point were initially randomly generated within sufficiently large ranges as well as each time the projections escaped the limits of the screen. The position, velocity and acceleration time history of the points are shown in Fig. 2a (left panel). This velocity was used for all trials. Each visual stimulus lasted 10 s. Display was operated at 35 frames per second.

Haptic stimuli. The haptic stimuli were provided to subjects through the vibration of each foot. Each foot platform was equipped with two custom-designed electromagnetic inertial actuators (haptuator-type [27]) attached as shown in the Fig. 3. The platforms were free to vibrate horizontally and the same time able to support the weight of a person without significant attenuation of the signal.[2] The actuators were driven by a computer-generated signal through the sound card's analog output and the audio amplifier. Four types of haptic/vibration signals were used: sinusoidal wave ('sine'), pink noise ('random'), sinusoidal wave with increasing frequency ('chirp') and no vibration stimulation ('still') (see the types of the signals in Fig. 3, bottom row, respectively). The 'sine' signal had frequency of 90 Hz. The frequency of the 'chirp' signal varied from 70 to 110 Hz. The profile of the varying frequency was same as the velocity profile of the optical flow (Fig. 2a, velocity plot). The values of the frequencies were selected empirically during several pre-tests in order to be in the working range of the stimulator. Duration of each haptic stimulus was same with the visual stimulus duration. Output signals from the computer were amplified to achieve a desired level of platform acceleration which was monitored with an accelerometer (model ADXL330K, bandwidth 500 Hz) attached in the center of the foot platform., see Fig. 2b-d.

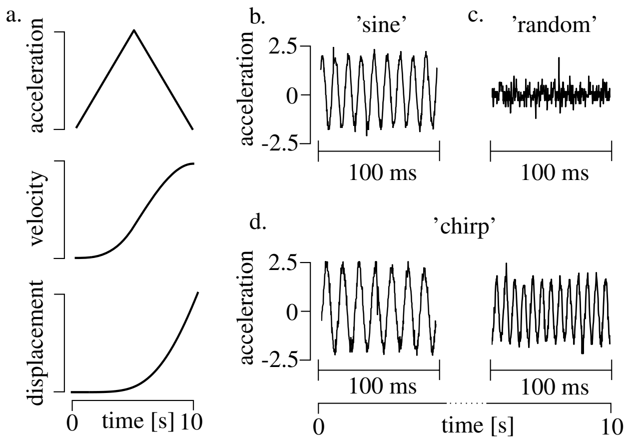

Figure 2: Time history for visual acceleration, velocity and displacement (a); measured acceleration of the foot platform for the 'sine' stimulus (b), the 'random' stimulus (b), and the 'chirp' stimulus (d).

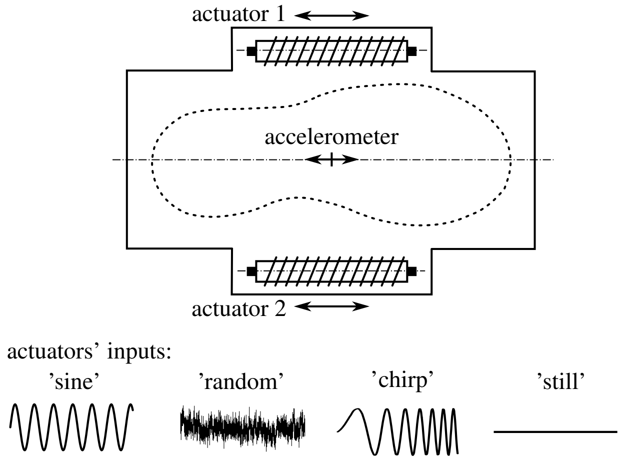

Figure 3: Schematic top view of vibration platform for the left foot (left panel) and four types of vibration signals (right panel).

2.2 Experimental Procedure and Protocol

Six healthy adults took part in the study (5 male, 1 female, age: 27-40). The subjects were seated in front of the screen with their feet placed on the foot platform as shown in Fig. 1. The distance between the subjects head and the screen was approximately 1.5 m. The field of view covered by the screen was about 33^o and 18^o for horizontal and vertical planes, respectively. The subjects were instructed about the procedure and had short trial sessions before the experiments. All experiments were performed in a darkened room and the subjects wore sound isolation headsets.

A two-alternative forced-choice method was employed. During the experiment, subjects were exposed to a sequence of two visual-haptic combined stimuli for 10 s each with a pause of 3 s in be-

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[2] These devices were designed by George Dietz and Amir Berrezag at ISIR UPMC and their technical characteristics documented internally only.

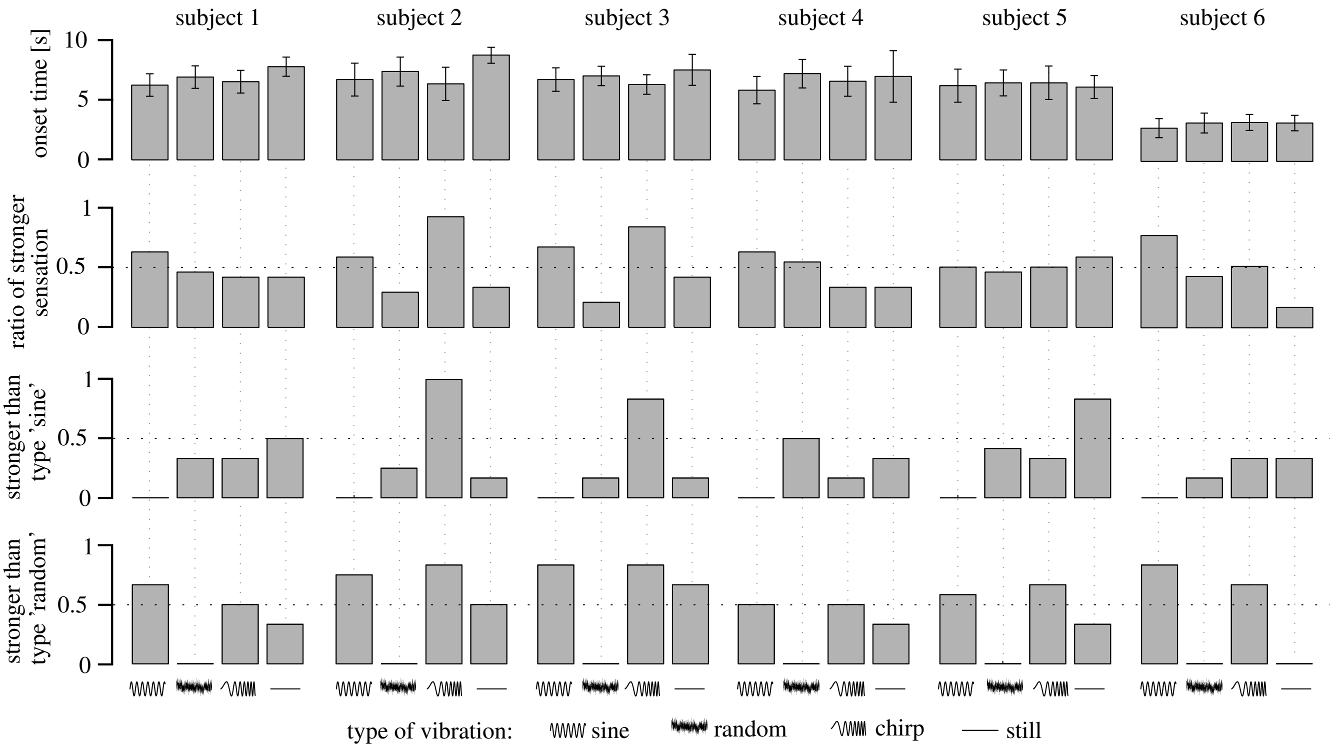

Figure 4: Overall results.

tween. Subjects were asked to push and release the press-button if the first stimulus evoked a stronger feeling of self-motion. The subjects compared the effect of a stimulus of type 'sine' with the effect of a stimulus of type 'random', 'chirp', or 'still', and a stimulus of type 'random' with the three other possibilities. The stimuli of type 'sine' and 'random' were selected to serve as reference in two-alternatives comparisons because sinusoidal vibrations are the most common types of vibrations used in experimental studies and pink noise vibrations occur frequently in real world physical interactions [25]. The stimulus with no vibration was not used as a references since it would be possible for the subjects to subjects be biased simply by the sudden occurrence of a vibration.

The procedure was repeated 36 times for each subject. In total, 72 visual-haptic stimuli were provided to each subject. Six permutations of stimulus presentation were used, each permutation displayed six times. Stimulus occurrences across trials were: 'sine' (24/36), 'random' (24/36), 'chirp' (12/36), 'still' (12/36). The visual stimulus was always the same. The experimental sequence for combinations of the stimulus was generated randomly using the Latin square rule.

During each trial subjects were also asked to push the button whenever the illusion of self-motion was experienced. The onset time for self-motion perception was measured for each combination of a visual-haptic stimulus. Subjects were asked to release the button once the stimulation was over.

Experiments were performed in two sessions of ten minutes long for each subject (36 stimuli per session). Adjustment of the vibration platforms was done before every session for every subject. Sinusoidal signal was used to drive the foot platform with a human subject on it while amplifier's gain was adjusted to achieve magnitude of the foot's acceleration 2.0 m/s^2. This was done to ensure that the same vibration amplitude as presented to each subject. The actuators' inputs, the state of the subject's response button and time were also recorded during the experiment.

3 RESULTS

A summary of the collected results from six subjects is shown in Fig. 4. Means and standard deviations of the time-to-onset within each subject for the four types of haptic stimuli are presented in the top row. Average time-to-onset of vection was the shortest with constant frequency stimuli ('sine') for subjects 1, 4 and 6, while stimuli with increasing frequency ('chirp') provided the shortest time-to-onset for subjects 2 and 3. The mean values of time-to-onset for subject 5 did not differ as much as for other subjects. A paired t-test procedure ($\alpha = 0.05$) with Bonferroni correction was used to compare the mean difference between the time-to-onset measurements for each subjects. The time-to-onset was significantly longer when no vibrotactile stimulation was used compared to any other stimulus for subjects 1, 2 and 3 ($p < 0.016$). Subjects 1 and 4 perceived vection significantly faster when 'sine' stimulus was used as compared to 'random' stimulus ($p < 0.022$). There was no significant difference between 'sine' and 'chirp' stimulus for all subjects ($p > 0.072$).

The second row of the Fig. 4 presents the normalized number of 'stronger' responses for the forced choice method. For each stimulus and each subject, the total number of responses when a particular stimulus elicited a stronger sensation of vection was divided by the number of occurrences of this stimulus. In other words, if the value reported on the plot a particular stimulus, X, is higher than 0.5 (50%), then stimulus X evoked a stronger perception of vection in more than 50% of the trials. The stimuli with a constant frequency ('sine') and with an increasing frequency ('chirp') provided stronger feeling of vection than the noisy stimulus ('random') or no stimulus ('still'). Vection enhanced with the 'sine' stimulus was the strongest for subjects 1, 4 and 6. Vection enhanced with the 'chirp' stimulus was stronger for subjects 2 and 3. Pink noise vibration ('random') and no vibration ('still') were never the most effective, except for subject 5. A paired t-test ($\alpha = 0.05$) with Bonferroni correction for the mean values of all six subjects' responses ratio showed that the number of responses when 'sine' stimulus evoked stronger vection was significantly higher when compared to 'random' ($p = 0.012$) and 'still' ($p = 0.01$) stimulations. In addition, a one-sample t-test ($\alpha = 0.05$) was used to check if the values of subject's responses ratio were significantly higher than 0.5 (a 50% response ratio when particular stimulus was stronger). The test showed the significant difference for the 'sine' stimulus ($p = 0.007$) and no significant difference for 'random', 'chirp' and 'still' cases ($p = 0.954$, $p = 0.213$, and $p = 0.962$, respectively).

The normalized number of responses when one of the stimuli evoked a stronger vection a constant frequency stimulation ('sine') is presented in the third row of the Fig. 4. For each stimulus ('random' or 'chirp' or 'still') and each total number of responses when one of these stimuli enhanced vection more than a 'sine' stimulus was divided by number of occurrence of pairs when this particular stimulus compared to a 'sine' stimulus. A vibration stimulus with increasing frequency ('chirp') provided a stronger vection for subjects 2 and 3, compared to the constant frequency vibration stimulus ('sine'). Subject 2 reported that increasing frequency vibration ('chirp') evoked stronger effect in all cases (100%) of the comparisons between the stimuli 'chirp' and 'sine'. Subject 3 reported that increasing frequency stimulus ('chirp') evoked a stronger effect in 80% of the cases of the comparisons between the stimuli 'chirp' and 'sine'. For subject 5, the absence of vibration ('still') evoked a stronger vection when compared to the stimulus with a constant frequency vibration, 'sine'. It is likely that the visual attention of this subject was distracted by the vibrations felt in the feet.

The last row of Fig. 4 show the normalized number of responses when one of the stimuli evoked stronger vection as compared to the stimulus with random frequency ('random'). The values indicated by the plots were calculated as mentioned above. Vibrations with constant frequency ('sine') evoked stronger vection in more than 50% of the cases for subjects 1, 2, 3, 5 and 6, when compared to the 'random' stimulus. For subjects 3 and 6, the 'sine' stimulus was more effective than the 'random' stimulus in 80% of the cases. Stimuli with an increasing frequency ('chirp') evoked stronger vection in 80% of the comparisons for subjects 2 and 3, and 70% for subjects 5 and 6.

4 DISCUSSION

The results show that providing vibrotactile stimulus to the feet magnified perception of vection. The time-to-onset for vection was decreased for five out of six subjects when 'sine' or 'chirp' vibrations were used as stimuli. Stimuli with a constant frequency of vibration provided the strongest vection for five subjects. Stimuli with increasing frequency of vibration provided strong vection for four subjects, as well. Random frequency and the 'still' stimuli were the weakest, and did not facilitate the perception of self-motion.

Vibrotactile stimulation of the feet is a simple and effective way to modulate vection in humans. These present results support the hypothesis that the vection effect is sensitive to the type of the vibration felt by the feet. Good stimuli should be well structured, as a constant frequency signal or a chirp signal. Random vibrations do not seem to have a measurable effect on the perception of self-motion. In real life situations, motion of the self usually happens in transportation vehicles (bicycles, trains, busses, cars, airplanes) or during locomotion. Haptic stimulation from the foot is an important source of motion information in all these cases. A train passenger standing in a moving car may detect absolute changes in the velocity of the train through the vibrations of the floor on which he/she stands. The frequency and the magnitude of the vibrations are correlated with the actual movements of the train. In our study we investigated a special stimulus where the frequency of the vibrations is proportional to visual low velocity. Yet, we found out that vibrating the feet at constant frequency vibration was sufficient to enhance vection. One of the possible interpretation for this is that interactions in real-world situations are strongly multimodal, including vestibular inputs, while in our experiment we restricted the sensory inputs to a basic visual flow foot stimulation only.

5 CONCLUSION

The study presented in this paper showed that the vibrotactile feet stimulation is an effective way to promote the illusion of self-motion. Achieving vection can be an important element of immersive human-machine interfaces for training or entertainment purposes and in other applications such as telepresence. We did not employ large visual display as in virtual reality caves nor did we place the screen close to subjects. In doing so, we attempted to show that vection could be facilitated with vibrotactile stimulation even in the presence of a weak effect due to frontal visual flow. The results showed that vection could be achieved faster and stronger with the vibrotactile inputs and without the necessity of high-end virtual reality systems. The use of vibrotactile stimulation to the feet can be helpful and effective for vehicle or plane simulators that are widely used for civil and military purposes. A promising application area could be the rapidly growing computer gaming and entertainment industry where a gratifying user experience is important. Modulating vection may be also be useful in human-machine interactions in telerobotics. For instance, vibrotactile stimulation of the feet could provide a human-operator important information about the motions of a remote robot and could be correlated to net velocity, net acceleration, or the vibrations of the robot frame, and as a result, evoke sensations of self-motion in the operator as if she or he was riding on the robot. Often such information is hard or even impossible to convey to the human-operators through the visual flow from a robot's camera alone. Such simple foot haptic displays could cost-efficient to increase the sensation of telepresence. However, as indicated in the results of this study, only certain vibrotactile stimuli seem to be able to modulate vection effectively. Future research will be dedicated to study in greater depth the most efficient characteristics of vibrotactile stimuli. Evoking the sensation of self-motion perception depends on many properties of the sensory inputs and the simple stimuli that we have explored leave a lot of room for improvement.

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