A Preliminary Study on Full-Body Haptic Stimulation on Modulating Self-Motion Perception in Virtual Reality

Francesco Soave, Nick Bryan-Kinns, and Ildar Farkhatdinov

School of Electronic Engineering and Computer Science,
Queen Mary University of London, London E1 4NS, UK
f.soave@qmul.ac.uk

Abstract. We introduce a novel experimental system to explore the role of vibrotactile haptic feedback in Virtual Reality (VR) to induce the self-motion illusion. Self-motion (also called vection) has been mostly studied through visual and auditory stimuli and a little is known how the illusion can be modulated by the addition of vibrotactile feedback. Our study focuses on whole-body haptic feedback in which the vibration is dynamically generated from the sound signal of the Virtual Environment (VE). We performed a preliminary study and found that audio and haptic modalities generally increase the intensity of vection over a visual only stimulus. We observe higher ratings of self-motion intensity when the vibrotactile stimulus is added to the virtual scene. We also analyzed data obtained with the igroup presence questionnaire (IPQ) which shows that haptic feedback has a general positive effect of presence in the virtual environment and a qualitative survey that revealed interesting and often overlooked aspects such as the implications of using a joystick to collect data in perception studies and in the concept of vection in relation to people's experience and cognitive interpretation of self-motion.

Keywords: Haptic Feedback · Virtual Reality · Self Motion · Sound

1 Introduction

Vection is a condition for which a visual stimulus can induce a strong and embodied sensation of locomotion relative to the fixed surrounding environment, even when the body is not physically moving [15]. The traditional real-life example used to describe vection is the sensation of motion that arises when observing a departing train on a neighbouring railway track. Although visual stimulus is traditionally the one that elicits the strongest self-motion, Keshavarz [4] found that auditory stimuli increase compellingness of visual vection and confirmed that self-reported auditory vection happens in about 25-60% of participants. The literature on auditorily and haptically induced vection is rather scarce and highly heterogeneous in terms of settings and setups. For instance, some studies on auditory-haptic vection do not have a visual component and participants are simply blindfolded [5,10]. Notably Valjamae [14] did not find haptic feedback to facilitate or increase the intensity of self-reported vection, while Riecke did [10]. Furthermore, the role of vibrotactile stimuli often seems to be just a marginal addition to auditory and/or visual cues. Some researchers [2, 8] explored the influence of haptic feedback applied to the feet of a person. However these studies are hard to compare. Riecke [10] haptic feedback was generated by adding a small USB fan to a hanging hammock chair to produce "barely noticeable" vibrations at 7Hz. Participants were blindfolded and the study focused on circular vection. On the other hand, Farkhatdinov et al. [2] designed a visual optical flow, while Nilsson [8] had standing participants in a realistic visual context (e.g. a train and a lift).

Our experimental setup is concerned with producing a so called "whole-body" vibration. Research on full body haptics often focuses on audio-haptic cross modal mappings and multisensorial integration, which is regarded as a key point on building consistent VR experiences [1]. For example, Lindeman et al. [6] designed and implemented a wearable suit made of multiple individually addressable vibrotactile actuators placed on the upper body of a user. Recently, Merchel and Altinsoy [7], used vertical vibrations to explore vibrotactile feedback influence on music perception and enjoyment.

Vection has often been linked to presence (the feeling of "being there") in virtual environments [13]. A number of studies, [5, 12, 14] explored correlations between self motion and presence in virtual environment, and how understanding vection can be fundamental to improve the user experience of a VE. Most results show correlation between vection intensity and onset times with ratings of spatial presence and involvement [11].

In this paper we describe our hardware setup for whole-body haptic vibration and a user study to investigate the role of haptic feedback on linear forward vection in VEs under normal viewing conditions (e.g no fixation point) and specifically when the vibrotactile signal is dynamically produced by the sound. We hypothesize that:

- H1 Every condition (visual, audio and haptic) produces at least a minimum amount of vection, as found in previous research; [8]
- H2 The addition of fully body haptic feedback, produces the highest vection intensity, similarly to how visual and auditory vection has been shown to be stronger than visual-only conditions [4];
- H3 Full body haptic feedback increases ratings of presence similarly to how Larsson [5] reported higher presence by adding sound to visual stimulus.

2 Methods

2.1 Experimental setup

We designed a virtual scene of a person sitting on a train and moving linearly at constant speed inside a tunnel. The idea of the train was used by other researchers before and intuitively it is correlated with the traditional paradigm

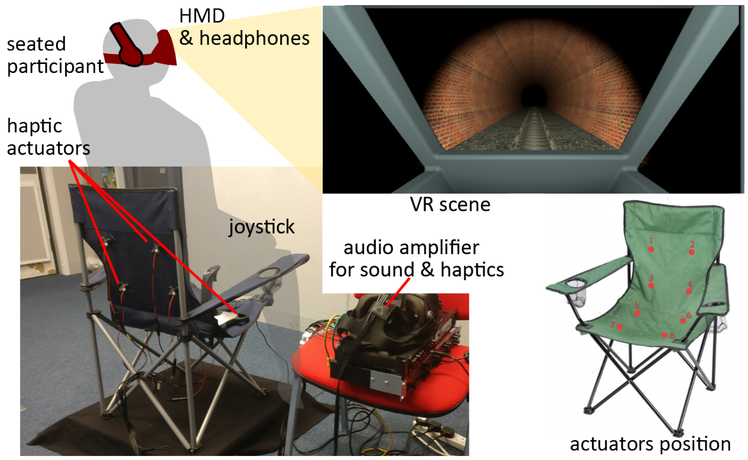

Fig. 1. Experimental setup for studying self-motion perception in virtual reality with visual, audio and haptic feedback modalities.

used to explain vection in the previous chapter, that is the train departing from the platform. The VE was implemented in Unity3D (www.unity.com) and played through an HTC Vive headset. The audio is processed in Pure Data (puredata.info) which triggers the sound at the start of the trials and applying a fifth order Butterworth Low Pass filter (cutoff 120Hz) and sends the signal to the actuators. We used a Motu 828 Mk3 and Behringer Powerplay Pro XL to output the audio signals. The haptic feedback is produced by eight Lofelt L5 (www.lofelt.com) actuators (frequency range 35-1000Hz). We designed and 3D printed a custom holder for each of them to ease the placement of the actuators which were then sewed to the back and seat of the chair in 4x2 design similar to [3].

2.2 Procedure

Twelve unpaid postgraduate students (6 males; age 29±4.2) participated each in one session of 45 minutes. Eight of them rated their experience with VR applications at level 3 on a scale 1 to 5. In a mixed experimental design, each participant was exposed to three conditions (*visual* V, *visual-audio* VA, *visual-audio-haptic* VAH). The between factor was the ordering of conditions therefore each participant was randomly assigned to one of three sets, based on Latin Square design. The experimental sets were 1) V, VA, VAH; 2) VA, VAH, V; 3) VAH, V, VA. Each participant experienced 15 trials of 60 seconds duration each (5 trials per stimuli type). The task was described as "rate the intensity of your sensation of self-motion". We stressed our interest in their honest report and to only move the joystick if vection was perceived. They were made believe the platform on which the chair was mounted, could slightly move during the

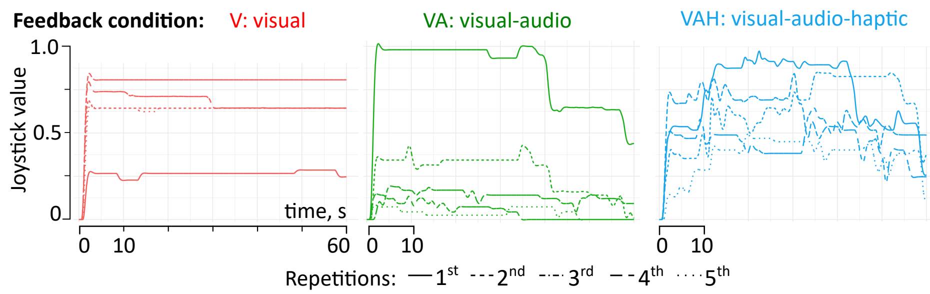

Fig. 2. Recorded joystick data of a typical participant for three different conditions. Each line corresponds to one repetition.

trials. This was done in accordance with previous studies [5,9] that demonstrated how the actual possibility of physical movement increases the intensity of the self-motion sensation. An initial test scene was designed so participants could get used to the joystick range of motion. There was a 5 second pause between each repetition to avoid stimuli carryover effect. The study was approved by the University Research Ethics Committee (ref. 2207).

2.3 Measurements

Participants were asked to use a joystick (Logitech Extreme 3D Pro) to rate the intensity of vection, while immersed in the VE. After each set of conditions (V, VA, VAH) they were asked to fill the standard IPQ presence questionnaire. At the end of the study the participants were also asked to fill a qualitative survey with questions on their experience and on the task itself.

3 Results

3.1 Self-motion intensity reported with joystick

Figure 2 shows the joystick data recorded for a typical participant. Variability across conditions and repetitions is easily observed.

In Figure 3(left) we compared the joystick values for self-motion intensity across the three conditions for all subjects. The highest self-motion intensity is reported in condition VAH with the highest mean (0.49) across conditions. The lowest variation and mean (0.19) is reported in condition V.

Figure 3(right) shows the results reported with joystick across all subjects for each experimental set. It is important to consider these results as we were interested in exploring potential ordering and learning effects. Figure 3(right) highlights that the greatest difference between V and VAH happens in the experimental set 3 when VAH is presented first and followed by condition V.

The interaction plots in Figure 4 show the VAH condition points are always above the others (except for the $4th$ repetition in Set 1). There is a visible positive

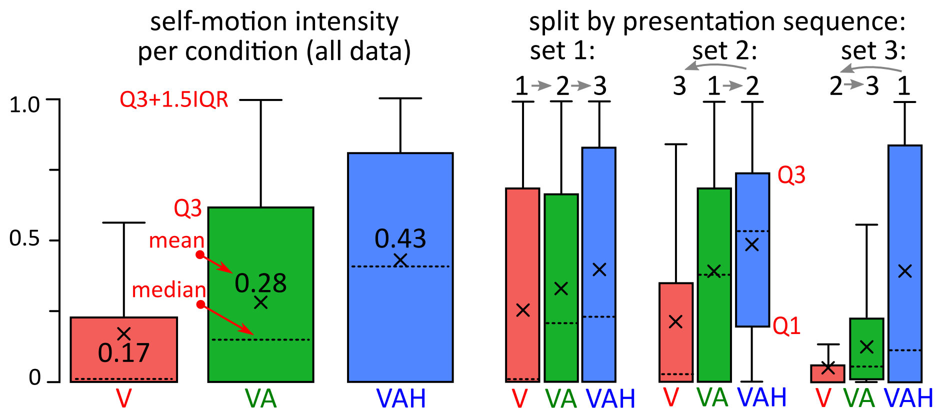

Fig. 3. Full joystick recordings of reported self-motion intensity across all participants for visual (V), Visual-Audio (VA) and Visual-Audio-Haptics (VAH) feedback modalities (left panel). Right panel demonstrates the results split by three presentations sets (order sets). Notations for mean, median second and third quartiles (Q2 and Q3) and 1.5 interquartiles range (IQR) limit are indicated in the left panel.

trend, especially for conditions VA and VAH, particularly in Set 3, where the V condition also shows a negative slope. Additionally, the Set 3 plot shows highest and lowest absolute means for VAH and V respectively.

3.2 Haptic effect on presence

The standard iGroup Presence Questionnaire was presented three times to each participant, once after each type of condition (V, VA, VAH). The questions are grouped in four areas: Involvement, sense of Being There, Spatial Presence and Realism. Figure 5 shows the results for each area. Three out of four subgroups benefited from haptic feedback: “Being there”, “Involvement”, ”Spatial Presence”. “Being There” is the subgroup with the largest difference in median between VAH (M = 4.67) and V/VA (M = 2.33). The “Realism” subgroup instead reports unexpected result in which the VAH condition seems to be less consistent with the corresponding real-world experience, compared to condition V. This subgroup has opposite medians to those of “Being There” (M(V) = 4.67, M(VA/VAH) = 2.33).

3.3 Qualitative survey

Due to a technical issue two responses had to be excluded. We summarize the main findings in four key-points:

P1 Vection is not a uniquely understood concept. Most literature on vection seem confident in the fact that people understand and interpret the expressions “self-motion”, “illusion of motion”, “vection”, “sensation of motion”,

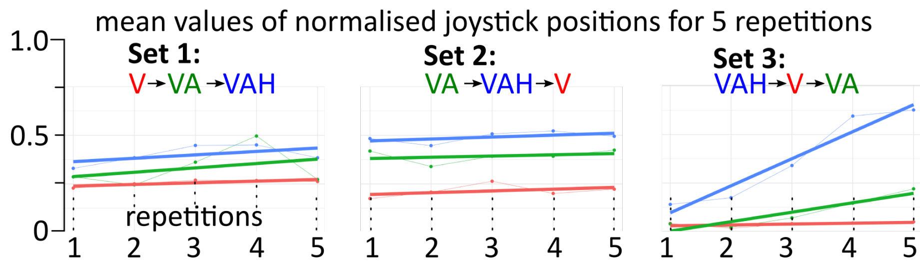

Fig. 4. Regression lines for each condition, in relations to sets and repetitions. Each data point is the mean of joystick values in a repetition.

"speed" interchangeably. In our case, we found that most participant do not find these wording to be the same at all, actually some reported how the traditional description of vection (the train motion illusion) does not seem coherent with the description of "sensation of self-motion".

P2 Seven participants reported how the full congruency between sound and haptics was fundamental to the experience. However, six participants reported that the sound did not appear to be correlated with the visual and how this affected realism of the VE. Three participants questioned whether their sensation of motion was due to the additional modalities or just the duration of the visual animation.

P3 The usage of joystick to report self-motion intensity introduces a series of questions that should be considered. One participant reported how using a joystick automatically made him feel as if he "had to" or "was" controlling the animation. Four people reported they were not aware of the current position of the joystick and that it was hard to tell if they were pulling the lever or not and how precise it was.

P4 Every participant stated that haptic stimuli increased the realism of the VE and it made the experience unique and engaging ("*the haptic experience was quite visceral, I felt like having a 2D screen on my legs*"). Those who first experienced the VAH condition reported being "bored" by the others. This might confirm the order effect visible in the Set 3 of the other measures.

4 Discussion

All the conditions used in the study seem to have elicited self-motion confirming hypothesis H1. Comparing the means and maximum values of the whiskers in our joystick data, it is visible how the haptic seem to confirm our second hypothesis (H2) that haptic feedback enhances the intensity of self-motion perception. This is true both for the comparison between V and VAH and also between VA and VAH conditions. The interaction plots show the regression line of VAH condition being constantly above the others. Figure 3 reveals how the difference between conditions V and VAH seem to be much stronger when multisensorial stimuli

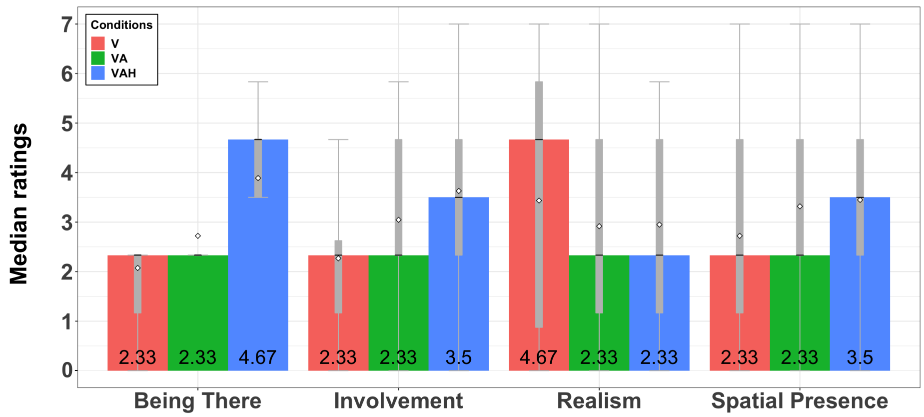

Fig. 5. Questionnaire subgroups. Every question was answered on a 0-7 Likert scale. Each subgroup is divided by the 3 conditions. Each bar represents 1 condition of the subgroup. The median value of each condition is shown at the bottom of each bar. White squares are the means. Whiskers are the min/max values -/+1.5 * interquartile range.

is experienced before a plain visual condition. A similar result was previously found by Riecke [10] and Nilsson [8].

The effect of haptic addition on presence is reported through the IPQ questionnaires which confirm that vibrotactile stimulus indeed increases sense of presence, involvement and spatial presence. Unexpectedly, the data reports low ratings of realism (e.g. "how real did the virtual world feel to you") which is in contrast with previous studies [5, 12]. One possible explanation might come from the qualitative survey (P2): while every participant felt sound and vibration to be crossmodally congruent, this did not always happen with the visual stimulus. Some participants reported that the vision did not seem to necessarily match the audio. One hypothesis might be that haptic feedback increased the incongruities between visual and auditory stimuli, which produced a "less realistic" simulation when compared to the V and VA condition.

The qualitative survey also reports interesting findings. First, it is very hard to discern between participants who experience vection as in the "train illusion" example, from those who just focused on the speed or intensity of movement (P1). This is mostly because it seems not trivial to convey the idea of vection, especially in studies under normal viewing conditions, in that vection might be harder to induce. Some studies report how they initially have the participants experience real vection. Riecke [9] was able to physically rotate their own chair thus inducing real motion illusion in the participant before the study. This of course provides a safe method to ensure participants can later refer to the sensation, but it still does not acknowledge the semantic differences in wording and additionally it requires a specific hardware setup. If we only rely on self-reported vection during the simulation, the illusion it is known to be reported in as low at 20% of cases which makes it even harder to observe. The use of a joystick can introduce variables such as learning effect and variations in participant's expressivity (P3): the same amount of joystick movement might have a different meaning, if performed at the beginning or later in the study. Furthermore the joystick is not visible while immersed in the VE and this makes it hard to know where in the movement range you "are". On one hand this issue could be circumvented by adding a visual representation of the current joystick position in the visual animation, but it is likely that doing so would heavily conflict with the visual stimulus. In addition, a physical lever might not the best device to rate a human "sensation". Finally, haptic feedback might suffer from novelty effect (P4). Every participant reported positively on the intensity and precision of the vibratory stimulus. Although this is a positive feedback towards our hardware, it might also influence the data produced by a study. This condition might have induced participants to do or rate "more" no matter the "what".

5 Conclusion

Self-motion has been traditionally explored by means of quantitative analysis of self-reported and joystick values. Our participants reported some insights on how we frame the study of the illusion of self-motion that has not been often acknowledged in literature. We argue that if self-motion perception has to play a major role in the User Experience design of VEs then it is fundamental to include a qualitative perspective in the topic. Future research will engage with an in-depth statistical analysis, investigate the semantic relations of congruency between sound as visual in our context and focus on alternatives to joystick or self-reported measures.

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