Exploring the Effect of Vibrotactile Feedback through the Floor on Social Presence in an Immersive Virtual Environment

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ABSTRACT

We investigate the effect of vibrotactile feedback delivered to one's feet in an immersive virtual environment (IVE). In our study, participants observed a virtual environment where a virtual human (VH) walked toward the participants and paced back and forth within their social space. We compared three conditions as follows: participants in the "Sound" condition heard the footsteps of the VH; participants in the "Vibration" condition experienced the vibration of the footsteps along with the sounds; while participants in the "Mute" condition were not exposed to sound nor vibrotactile feedback. We found that the participants in the "Vibration" condition felt a higher social presence with the VH compared to those who did not feel the vibration. The participants in the "Vibration" condition also exhibited greater avoidance behavior while facing the VH and when the VH invaded their personal space.

Index Terms: H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems—Artificial, Augmented, and Virtual Realities; J.4 [Computer Applications]: Social and Behavioral Sciences—Psychology

1 INTRODUCTION

Previous research has shown that virtual humans (VHs) can provide users with a sense of "being together" and facilitate social interaction with the VHs similar to the behavior people would exhibit with real humans (RHs) in the real world [2, 3, 13]. Researchers often use the terms *social presence* and *co-presence* to describe this phenomenon [11]. Blascovich et al. define *social presence* both as a "psychological state in which the individual perceives himself or herself as existing within an interpersonal environment" and "the degree to which one believes that he or she is in the presence of, and dynamically interacting with, other veritable human beings." [9, 10]. For the consistency within this paper, we use *social presence* to indicate such a phenomenon.

Historically, work related to social presence has primarily focused on VH appearance, intelligence, verbal and nonverbal behaviors [14, 15, 39]. These efforts are aimed at making VHs similar enough to RHs that, in turn, RHs respond to them in a socially plausible (perhaps "realistic") way—similar to how they would respond to a RH. However, in the real world, social interaction not only involves RHs, it also involves the surroundings where the social interaction takes place. For example, people might hold a door open for others who are approaching, knock on a table to catch one's attention, or stomp their feet on the floor to express their anger. As such, social interaction associated with the environment can be an important aspect of an interactive system when VHs and RHs are present in a shared space, such as an augmented or immersive virtual environment (IVE) [24].

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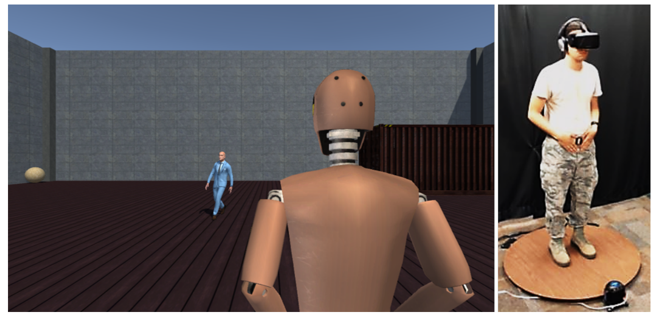

Figure 1: Each participant inhabited the virtual dummy shown in the left image, and observed the virtual environment from the dummy's perspective. The participant's head position/orientation were tracked and applied to the dummy's body posture to induce a virtual body-ownership illusion. Participants were asked to put both hands on their waist during the experiment, to avoid breaks in presence (shown in the right image).

Humans perceive their surroundings not only via the senses of sight and hearing, but also via other body senses. In particular, proprioception and tactile feedback enable humans to perceive vibrations that are propagated through the surface of an object in contact with their body. In interpersonal situations, slight vibrations propagated through the floor or furniture can support one's awareness of another person. For example, if a person is approaching us from behind, our body senses might pick up on the slight vibrations of the floor, making us aware of the person's presence. Similarly, if we know that someone is standing behind us and we start feeling vibrations through the floor, we assume that the person has started to move, which is then usually confirmed during social interaction via the visual sense by turning the head.

While it is not always possible to provide vibrotactile feedback through arbitrary surfaces, the floor is not only the most common shared object in social interactions, it is also relatively easy to stimulate. In this paper, therefore, we explore the effect of vibrotactile feedback via a floor shared with a VH on social presence in an immersive virtual environment.

2 RELATED WORK

2.1 Haptic/tactile Feedback in Social Interaction

To the best of our knowledge, prior research related to haptic/tactile feedback on feet in virtual environments has focused on realistic walking sensations [33, 36, 38], or the use of haptic/tactile feedback as secondary feedback to users when feet were used as an input method, such as for navigation [22, 30, 40]. While we are unaware of prior work exploring the intentional inclusion of vibrotactile feedback through the floor as a means to increase social presence, there is some research that is relevant to our approach.

Midas touch refers to the phenomenon where casual touch, such as a tapping on one's shoulder, promotes altruistic behaviors and willingness to comply with the one who touched [16]. In general, interpersonal touch is known to elicit positive responses [12]. Researchers have conducted studies to find effects of interpersonal touch when it is mediated via electromechanical devices. Basdogan et al. found that a haptic sensation of other participants through a shared virtual object (e.g., pulling/pushing) in a collaborative task increased the task performance as well as the sense of togetherness [5]. Similarly, Sallnäs reported that haptic feedback on a shared virtual object increased presence, social presence, and the perceived performance when participants in two remote places passed a virtual object in a shared virtual environment [34]. Researchers have also examined the effects of touch interaction with social agents—physically embodied and purely virtual. Kotranza et al. developed a virtual patient that responded to touch [25], and touched back to real human [26] in a mixed reality medical simulation. They found that the touch-enabled virtual patient increased the quality of the communication and was treated more like a real human. Bickmore et al. found that squeezing behavior, conveyed by an air bladder, of a mannequin-based virtual agent was associated with the perception of affect arousal or valence [7]. Huisman et al. similarly used a vibrotactile device to convey interpersonal touch with a VH in an augmented reality setup [20]. They found that the VH who touched participants was rated higher in affective adjectives. Although how the haptic/tactile feedback induced such effects is uncertain, the sensorimotor conflict might account for the increased feeling of the other person's presence [8] as similar to sensorimotor integration could induce the illusion of body ownership [23].

2.2 Behavioral Responses to Virtual Humans

Slater postulated that people would respond realistically to a VE when both *place illusion* and *plausibility* occur [37], and research has demonstrated that VHs in IVEs could possibly induce a social behavior to the VHs from people [1, 2, 35] or even alter their behavior in the real world after the IVE experience [43]. Here, we briefly review research relevant to behavioral responses to IVEs and VHs. Proxemic behavior addresses how humans maintain their surrounding space. In [35], participants in an experiment with an obstacle avoidance task in an IVE maintained a greater distance to anthropomorphic obstacles compared to inanimate obstacles. Similarly in [1], participants maintained more space around a VH than they did for a human-sized cylinder. When participants were approached by VHs, their physiological arousal was increased [29]. Proxemic behavior can also be affected by a VH's behavior. For example, Bailenson et al. found that participants preserved longer distance with VHs when the VHs approached from the front direction. In their experiment, participants also gave more personal space to VHs when the VHs exhibited mutual gaze behavior [1, 2]. In a social context, people often use gaze for nonverbal communication. In [32], participants tended to look more at a VH with a happy face than a VH with an angry face, and social anxiety was correlated with avoidance gaze behavior associated with the angry VH. Similarly, Social Avoidance and Distress (SAD) scores were correlated with participants' intent not to disturb VHs in a library setting [13]. The researchers also utilized physiological measures—electrodermal activity (EDA) and heart rate—and found an increase in EDA in the library room where VHs were studying, compared to the training room. Heart rate increased in a condition where VHs looked at the participant. In [4], people used less force with a VH compared to a non-human object, and they touched the VH's face with less force than the VH's torso. Also in their study, people used less force for female VHs than male VHs.

3 Hypotheses

As outlined in the previous section, prior work has shown that haptic/tactile feedback affects one's perception of the interaction partner whether it is a real human or an agent (e.g., a robot or a VH). However, these findings were mostly in situations where the interaction partner directly touched the participant's body, which rarely happens in everyday interactions. Instead, we often perceive kinetic forces exerted by the other person through an object we are both touching. For example, if a person is walking on a rope bridge, one can become aware of a person behind of him/her via vibrations transmitted through the shared bridge. We therefore believe that interpersonal haptic/tactile feedback that is propagated through a shared object, such as the floor, could be more practical [28].

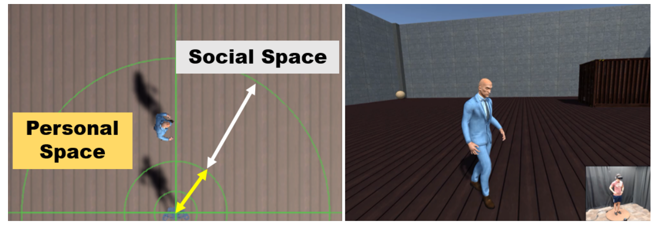

Figure 2: The Virtual Human (VH) was pacing back and forth in the social space (left). While pacing, the VH invaded the participant's personal space multiple times [17]. The right image shows a participant's view when the VH is pacing in the social space.

Based on the related work, we thus formulated the following two hypotheses:

- **H1:** Participants feel higher social presence with a VH when they experience vibrotactile feedback of the VH's footsteps through a shared floor in an IVE.
- **H2:** Participants exhibit more realistic social behavior with a VH when they experience vibrotactile feedback of the VH's footsteps through a shared floor in an IVE.

4 Footstep Experiment

To investigate the effects of vibrotactile feedback through the floor, i.e. perceived at the soles of one's feet, on social presence, we built an immersive virtual simulator with a platform that can generate vibrotactile feedback. Participants were standing on the platform while observing the virtual environment. In this section, we describe details of the experiment.

4.1 Participants

We recruited 41 undergraduate and graduate students within our university community (15 female, 26 male, mean age: 24.2, age range: 19–34 years). All participants received $15 as a compensation for their participation. The average duration of the experiment was about forty minutes.

4.2 Materials

4.2.1 Virtual Environment

Our virtual environment for this experiment comprised of a square space with a wooden floor surrounded by cement brick walls. Participants inhabited the virtual dummy shown in Figure 1, and observed the virtual space from its perspective. The participants wore an Oculus Rift DK2 head-mounted display (HMD) tracked by the Oculus tracking camera, and motion was applied to the dummy's head. The body—mainly its neck, spine, thighs, knees—was controlled based on the head motion using inverse kinematics. We placed a directional light that cast a shadow of the body in the front direction such that the participant could see their body motion from the shadow. The virtual space included a ball, a shipping container, a ladder on the right wall, and a VH. The ball and the VH were the only virtual entities that moved over the floor during the simulation. The shipping container hid the ball and the VH from the participants' view at the beginning of the experiment. The VH did not make any conversation with participants. Instead, the

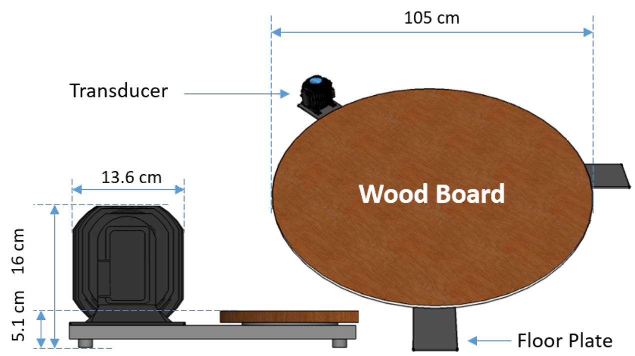

Figure 3: Footstep platform: We placed a round wooden board on top of three floor plates. For added stability we added rubber support bumpers between each plate at the boundary. A low frequency audio transducer was mounted at one of the floor plates. Participants stood in the center of the platform during the experiment.

VH exhibited "walking", "pacing back and forth", and "looking vacantly in a direction" behaviors (see Figure 2). Prerecorded footstep sounds—footstep sounds on a wooden floor as seen on the HMD—were played when the VH's sole touched the floor. In addition to the internal 3D sound setting of the Unity engine, we used the footfall distance of each gait to control the volume of the footstep sound such that the volume matched the VH's pacing behavior.

4.2.2 Footstep Platform

We designed and built a wooden platform to stimulate the soles of the participants' feet with vibrational feedback that can be observed when standing on a wooden floor. The platform comprises a round wooded board around one meter in diameter. Three equally-spaced floor plates support the wood at the curved boundary. Each plate has four rubber legs for vibration isolation, and one thin rubber pad to reduce vibration noise. The thin rubber pad covered roughly half of the top surface. The wood is mounted on top of the thin rubber pads (see Figure 3). We added a rubber support bumper between each plate for added stability. We used the ButtKicker LFE transducer [1]. The transducer was firmly mounted on the front floor plate (see Figure 4) as the VH approached from the front. An amplifier included in the Buttkicker LFE kit was used to amplify the sound source. We configured the amp such that participants could feel the footsteps gently when the VH paced in the social space. The amp configuration was the same for all participants.

4.2.3 Setup

This experiment was conducted in a laboratory room prepared as shown in Figure 4. We placed a wooden platform near an edge of the experimental space. On the other side of the space, the Oculus Rift DK2 tracking camera was slightly tilted down and placed about 1.7 *m* above the floor using a tripod. We attached the ButtKicker low frequency audio transducer to the front side of the platform. We used the Alesis MultiMix4USB[2] audio mixer to split the audio source from the graphics workstation on which the Unity engine was running. One branch of the audio source was amplified and fed to the transducer while the other branch of the audio source was fed to a Bose QuietComfort 15 acoustic noise canceling headphone[3] that was worn by the participants in the experiment in order to block out noises from the real world. The experimenter was able to selectively turn on/off each branch of the audio source depending on the experimental condition.

[1] http://www.thebuttkicker.com/
[2] http://www.alesis.com/
[3] http://www.bose.com/

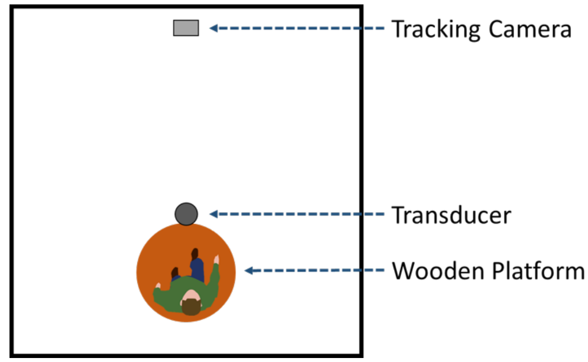

Figure 4: We used a 3.25 *m* (width) $\times$ 3.43 *m* (length) space surrounded by black curtains. The footstep platform was 105 *cm* in diameter. The distance between the center of the platform and the tracking camera was 2.46 *m*. The tracking camera was placed at 1.7 *m* above the floor. The transducer was attached to the front side of the platform. Participants were guided to stand in the center of the platform (cf. Figure 1).

4.3 Method

4.3.1 Study Design

We used a between-subjects design for this experiment. Participants were randomly assigned to one of the three conditions described below.

- **Mute**: The footstep sounds were not played in this condition, and vibrotactile feedback was not supplied.
- **Sound**: The footstep sounds were played, but the vibrotactile feedback was not supplied (we turned off the transducer).
- **Vibration**: The footstep sounds were played, and the vibrotactile feedback associated with the footsteps were generated.

In all conditions, the noise canceling functionality of the headphone was active.

4.3.2 Scenario

At the beginning of the experiment, the ball and the VH were placed near the right side wall behind the shipping container and were thus hidden from the participant's view. As the simulation started, the ball started rolling toward the left wall slowly. Once the ball hit the left wall and stopped, the VH started walking toward the participant, making a gently curved path. When the VH entered the participant's social space (3.6 *m* distance from the participant [17]), the VH started pacing back and forth for about a minute (see Figure 2). At the beginning of the pacing phase, the VH slightly invaded the participant's personal space (1.2 *m* distance from the participant [17]) five times. After the pacing phase, the VH stopped and looked at the left wall vacantly (from the participant's viewpoint) for about twenty seconds. Then, the VH returned to the container from where it started (see Figure 5).

4.3.3 Measures

Subjective Measures We measured presence and social presence primarily with a combination of post-experiment subjective surveys. We used the social presence questionnaire by Bailenson et al. [2] and the presence questionnaire by Witmer and Singer [42]. Participants responded in seven-point Likert scales for each question. Since our experiment did not involve 3D navigation, object manipulation, questions specific to those aspects were removed from the Witmer and Singer presence questionnaire. We measured social presence indirectly through questionnaires that assessed two possible correlates of high social presence, affective attraction (or

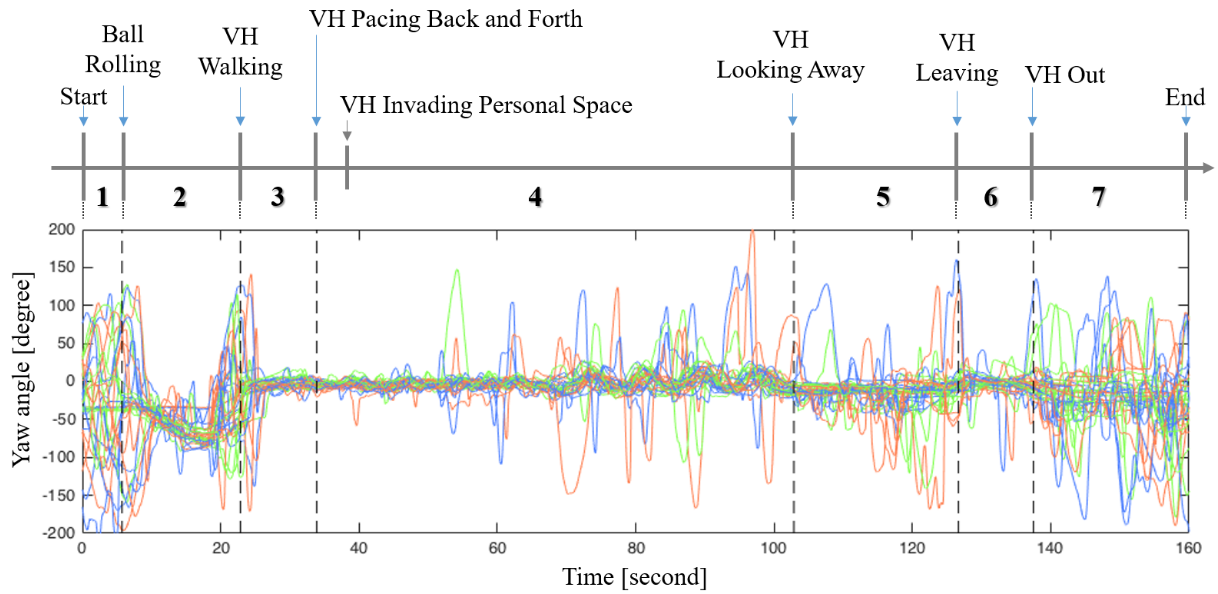

Figure 5: Simulation timeline (up): Starting times for major events were marked on the timeline. We divided the simulation into seven phases for behavior analysis. We named each phase for the sake of convenient reference as follows: 1 – Start, 2 – Ball rolling, 3 – VH face, 4 – VH pace, 5 – VH stop, 6 – VH back, 7 – End, from 3 to 6 – VH visible; Participants' head gaze behavior (down). Yaw angle difference between the head gaze direction and the VH's head position (0°: VH's head position, negative: left, positive: right) were plotted (Mute: blue, Sound: green, Vibration: orange).

liking) [19] and anxiety [41]. We also performed a manipulation check, a measure often used in a social science study to determine whether an independent variable varies in ways researchers expect; Participants answered yes/no to questions asking whether they heard footstep sounds and perceived vibrotactile feedback associated with the footsteps in the survey. Lastly, participants provided informal comments on the interaction verbally and on paper.

Behavioral Measures During the experiment, the participant's head was tracked with the Oculus Rift DK2 tracking system. From the head position and orientation we derived the following behavioral measures.

Kinetic Energy: We calculated the kinetic energy of the participants' head motion by assuming the head as a solid sphere having average human head mass ($5kg$) and size ($56cm$) for all participants.

Dwell Time on VH/Ball: We converted head gaze—a proxy to eye gaze—into yaw and pitch angles from the VH's head and the Ball positions respectively. Then, we calculated the duration where both yaw/pitch angles were below a threshold angle ($10°$) per each phase (see Figure 5) [21].

Avoidance Magnitude: As described above, the VH invaded the participant's personal space during the "VH pace" phase. We calculated a backing away head distance—a proxy to making a step backward in the real world—for the first personal space invasion. We measured the distance within a two seconds time range—one second before/after the invasion moment.

Skin Conductance Response: We used the Empatica E4[4] (a wrist-worn physiological monitoring device) to measure the participants' skin conductance response (SCR). We used the Ledalab[5] Matlab-based software to decompose the SCR into continuous signals of tonic and phasic activities [6]. We calculated a summed phasic activity for the first personal space invasions (sum of phasic activity from the moment the VH invaded to four seconds after).

[4]http://www.empatica.com/

[5]http://www.ledalab.de/

4.3.4 Procedure

When participants arrived we asked them to read and sign the informed consent, and fill out a demographics questionnaire. Then, we guided them to the experimental space and explained that their task was to stand in the center of the platform and observe the virtual space. We instructed them to place both hands on their waist, and not to move their feet during the experiment. After the instruction, participants donned the physiological sensor (a wrist band) and the HMD. An experimenter helped them to don the noise canceling headphones over the HMD. The participants were asked not to look around until the experimenter told them to start. The experimenter told them to start through the headphones, and the participants experienced the simulation as described above. When the simulation was done, the experimenter helped them doff the devices, guided them to the questionnaire area, had them complete a post-questionnaire, and gave them the compensation.

5 Results

We performed Kruskal-Wallis H tests on each measure with Dunn's tests with Bonferroni correction for the post-hoc pairwise comparisons. We removed participants who did not pass the manipulation check (seven participants) and who did not complete the survey (two participants). We analyzed data from 32 participants (mute: 11, sound: 11, vibration: 10).

5.1 Subjective Measures

5.1.1 Social Presence

The results of Bailenson's social presence questionnaire are shown in Figure 6 (left). We analyzed the questionnaire by averaging the five responses—scores for question 3 and 5 were inverted (c.f. [2]). A higher value indicates that the participants estimated the VH as conscious, aware, and alive. We conducted a Kruskal-Wallis H test on the averaged scores at the 5% significance level. We found a significant main effect of the conditions on social presence, $\chi^2(2) = 6.09, p < 0.05$. Post-hoc comparisons indicated that the

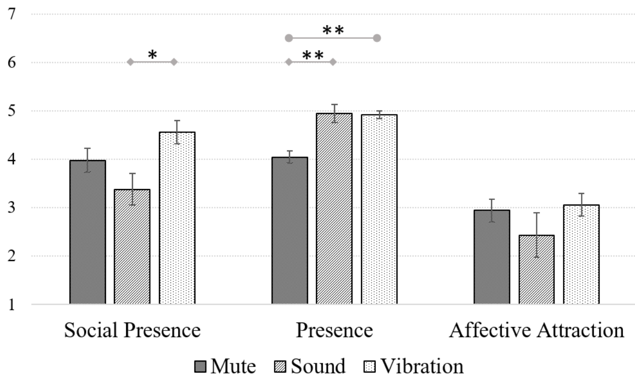

Figure 6: Means of social presence, presence, and affective attraction scores for each condition. Error bars represent the standard error, * ($p < 0.05$) and ** ($p < 0.01$) indicate statistically significant differences.

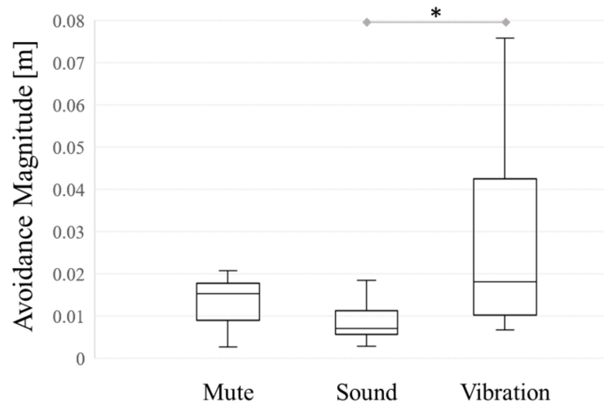

Figure 7: Avoidance magnitude for the personal space invasion for each condition. * ($p < 0.05$) indicates statistically significant difference.

social presence score in the vibration condition was significantly higher than in the sound condition ($p < 0.05$).

5.1.2 Presence

The results of the presence questionnaire are shown in Figure 6(center). As described in the measurements section, we used a subset of questions from the Witmer-Singer questionnaire [42]. We averaged the scores, computing an aggregated presence score. We used a Kruskal-Wallis H test on the aggregated scores at the 5% significance level. We found a significant main effect of the conditions on presence, $\chi^2(2) = 15.2, p < 0.001$. Post-hoc comparisons indicated that the mean score in the mute condition was significantly lower than in the sound condition ($p < 0.01$) as well as in the vibration condition ($p < 0.01$).

5.1.3 Affective Attraction and Anxiety

The participants' attraction to the VH in terms of the affective attraction items from [19] are shown in Figure 6 (right). The five sub-items were rated on seven-point Likert-scales. We averaged all items to construct an aggregate affective attraction score. We conducted Kruskal-Wallis H tests on the aggregated affective attraction scores as well as on the aggregated anxiety score at the 5% significance level. We found no significant main effect of the conditions on affective attraction, $\chi^2(2) = 3.73, p = 0.16$. However, note that in all conditions the mean values were below four, which means that the participants rated the VH with strong negative affect in general. Also, we found no significant main effect of the conditions on aggregated anxiety scores, $\chi^2(2) = 0.85, p = 0.65$.

5.2 Objective Measures

5.2.1 Avoidance Magnitude

Figure 7 shows the calculated backward head translation for the VH's first invasion of the participant's personal space. The backward head motion was calculated in a time range between one second before/after the invasion moment. A Kruskal-Wallis H test was conducted on the back-away distance. We found a significant main effect of the conditions on the back-away distance, $\chi^2(2) = 8.04, p < 0.05$. Post hoc comparisons indicated that the mean distance for the vibration condition ($M = 2.7cm, SD = 2.3cm$) was significantly different from the sound ($M = 0.9cm, SD = 0.5cm$) conditions ($p = 0.016$).

5.2.2 Gaze Behavior

Figure 5 shows all participants' head motion in yaw angle during the simulation. We computed a Kruskal-Wallis H for each variable, e.g. the dwell time on the VH during the VH pacing. We found no significant main effect of the conditions on the dwell times and the kinetic energies for all time periods.

However, when we analyzed the head gaze behavior (yaw and pitch angles—see Figure 8) we found a difference in participants' pitch behavior for the time periods "VH visible" and "VH stop". Two outliers were omitted. We used the common rule of 1.5 interquartile ranges to detect the outliers [31]. For the pitch variance during "VH visible", we computed a Kruskal-Wallis H which showed a significant main effect, $\chi^2(2) = 7.02, p < 0.05$ and post hoc comparisons showed a significant difference in pitch variance between the sound condition and the vibration condition ($p = 0.031$). For the "VH stop" period, a Kruskal-Wallis H and post hoc comparisons showed a significant main effect, $\chi^2(2) = 7.68, p < 0.05$, and a significant difference between the sound and vibration conditions ($p = 0.017$).

5.2.3 Skin Conductance Response

Similar to the avoidance magnitude, we generated a phasic SCR sum for the first social space invasion (cf. Section 4.3.3). The time window used for the SCR sum was from the invasion moment to four seconds after as there was a delay between a SCR and stimulus [6]. We computed a Kruskal-Wallis H on the phasic SCR sum. The result showed no significant main effect of the conditions on skin conductance, $\chi^2(2) = 0.94, p = 0.63$.

6 Discussion

Overall, the results show strong support for our hypotheses, which underline the importance of vibrational haptic feedback in VEs.

Bailenson's questionnaire showed a significant increase in social presence in the "vibration" condition compared to the "sound" condition, which supports H1, although we did not find a significant difference between the "vibration" and the "mute" condition. Regarding the surprisingly low social presence score in the "sound" condition, we speculate that this might be related to a violation of sensorimotor contingency (between sound and vibration), i.e., a situational implausibility that sound could be heard but not felt in this environment [37].

Regarding the behavioral responses, we found a significant difference in participants' gaze behavior in terms of head pitch movements between the conditions. Participants in the "vibration" condition exhibited more pitch motion than the other conditions when looking at the VH. We speculate that the negative affective attraction to the VH and the increased social presence might have led participants to avoid looking at the VH's face directly, resulting in

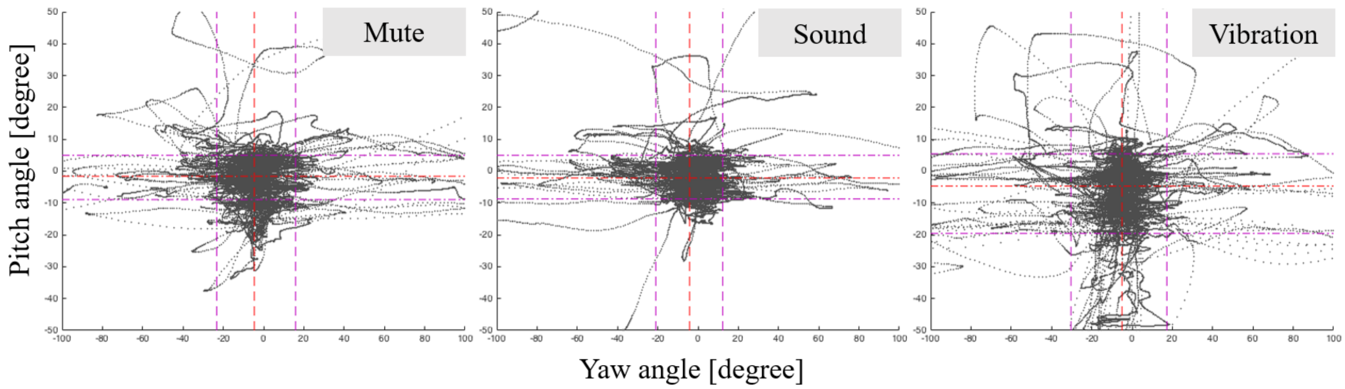

Figure 8: Participants' head movement trajectories relative to the VH during the "VH visible" phase of the interaction, i.e. phases 3–6 in Figure 5. The polar origin (0,0) of each plot corresponds to the direction from the participant's head to the VH; the pitch (up-down) and yaw (left-right) motion represent head excursions away from the VH. The standard deviations (purple lines) and medians (red lines) are indicated.

greater pitch head motion, which is similar to results found in [32] when participants avoided looking at a VH with an angry face. We also analyzed participants' avoidance behavior when the VH invaded their personal space [2]. Participants in the "vibration" condition exhibited stronger avoidance behavior compared to the other conditions. We consider these two findings as support for H2.

Regarding skin conductance, we did not see any significant differences between the conditions. This could be explained by the results from [29]. In their experiment, they found that the skin conductance was increased in both a VH approaching condition and a human-sized inanimate object approaching condition, despite of the profound difference in qualitative response. Therefore, we consider the skin conductance response might not be an appropriate measure for the socially realistic behavior in this experiment.

We had considered including an additional "vibration only" condition in the experiment to examine the interaction effect between sound and vibration. However, vibrational platforms as the one developed for this experiment tend to generate a solid-borne noise due to the transducer and the vibrating wooden board such that a "vibration only" condition would have been confounded due to the low noise. By applying a low pass filter, the noise from the transducer could be reduced for the experiment, but the solid-borne sound from the wooden board could not. With regard to the ball, it was originally introduced to see the difference in participants' behavioral toward a VH and an inanimate object. However, due to the short animated period of the ball compared to the VH, we did not perform any comparison. Most participants kept track of the ball once they found it moving.

While debriefing the participants we noticed that some of them stated that they did not notice the vibrations. It seemed to happen when they wore shoes with thick soles. We had considered this before running the experiment, but we had not wanted to produce an artificial situation by having them stand barefoot on the wooden platform. Even though the strength of the vibrations might have been reduced due to the shoes, the results still indicate a strong benefit of this condition over the others. We believe that by adjusting the strength of the vibrations based on the user's shoes might further strengthen this effect.

Overall, based on our observations and findings in this experiment, we suggest the following implications and guidelines for future foot-related vibrotactile setups:

- A transducer such as the ButtKicker can produce mechanical noise that can penetrate noise canceling headphones. Superior headphones or masking sounds should be used.
- Each individual has a different sensitivity to the floor vibration, but the sensitivity is also affected by the user's shoes, which can be compensated for.

7 Conclusions and Future Work

In this paper we presented the first study that examined the effects of vibrotactile feedback through a shared floor on social presence in an IVE. For that, we built a vibrotactile feedback platform, the footstep platform, which can be easily adopted in other IVEs that exploit social interaction with VHs.

Our experiment revealed that the vibrotactile feedback of a VH's footsteps, when it was accompanied by appropriate sounds, can increase social presence of a VH in both subjective feelings and behavioral responses, compared to sounds only. We found that participants who experienced both the footstep sounds and vibrations exhibited a greater avoidance behavior to the unfavorable looking VH, e.g., avoided looking at the VH's face directly and moved their head backward more when the VH invaded their personal space.

Future work should focus on improving the footstep platform for diverse situations in IVEs. First, here we tested a wooden floor case only, in which people would expect vibrations of the VH's footstep from their real-world experience. It could have violated users' expectation if the same vibrations were rendered when the floor was a concrete floor. In this regard, vibration propagation signatures in different materials should be carefully considered. Second, in this study the VH approached from the front, which roughly matched the location of the transducer. However, if the VH approached from a side or the back, it could eliminate the visual dominance effect, leading to apparent violation of sensorimotor contingency [18]. To mitigate this issue, the use of multiple transducers should be considered [27].

Acknowledgements

The work was supported in part by the Office of Naval Research (ONR) Code 30 under Dr. Peter Squire, Program Officer (ONR awards N00014-14-1-0248 and N00014-12-1-1003), and in part by the Florida Hospital Endowed Chair in Healthcare Simulation.

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