VRsneaky: Increasing Presence in VR Through Gait-Aware Auditory Feedback

Matthias Hoppe[1], **Jakob Karolus**[1], **Felix Dietz**[1], **Paweł W. Woźniak**[2], **Albrecht Schmidt**[1], **Tonja Machulla**[1]
[1]LMU Munich, Munich, Germany, {firstname.lastname}@ifi.lmu.de
[2]University Utrecht, Utrecht, the Netherlands, p.w.wozniak@uu.nl

ABSTRACT

While Virtual Reality continues to increase in fidelity, it remains an open question how to effectively reflect the user's movements and provide congruent feedback in virtual environments. We present *VRsneaky*, a system for producing auditory movement feedback, which helps participants orient themselves in a virtual environment by providing footstep sounds. The system reacts to the user's specific gait features and adjusts the audio accordingly. In a user study with 28 participants, we found that *VRsneaky* increases users' sense of presence as well as awareness of their own posture and gait. Additionally, we find that increasing auditory realism significantly influences certain characteristics of participants' gait. Our work shows that gait-aware audio feedback is a means to increase presence in virtual environments. We discuss opportunities and design requirements for future scenarios where users walk through immersive virtual worlds.

CCS CONCEPTS

• **Human-centered computing → Auditory feedback**; *Virtual reality*; *Sound-based input / output*;

KEYWORDS

Auditory feedback; virtual reality; gait awareness; presence.

ACM Reference Format:
Matthias Hoppe, Jakob Karolus, Felix Dietz, Paweł W. Woźniak, Albrecht Schmidt, Tonja Machulla. 2019. VRsneaky: Increasing Presence in VR Through Gait-Aware Auditory Feedback. In *CHI Conference on Human Factors in Computing Systems Proceedings (CHI 2019), May 4–9, 2019, Glasgow, Scotland UK*. ACM, New York, NY, USA, 9 pages. https://doi.org/10.1145/3290605.3300776

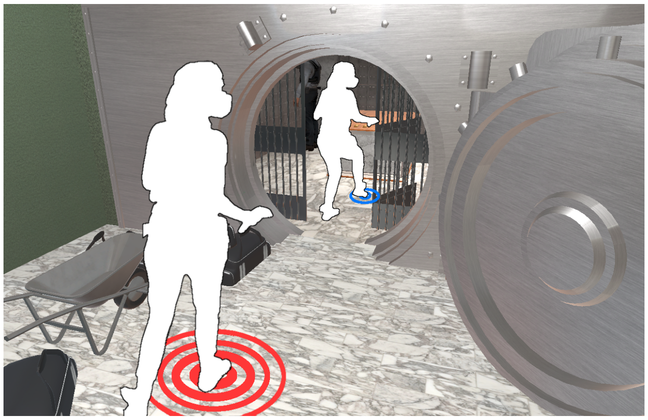

Figure 1: Depiction of a user in our virtual environment. *VRsneaky* detects the user's gait — heavy (red) vs. light (blue) footsteps — and provides congruent auditory feedback.

1 INTRODUCTION

"Press shift to sneak"

Players often read these words during the tutorial of a video game. The example illustrates that applications on classical plattforms such as the desktop computer are typically limited to user input through a keyboard, mouse or controller. In contrast, applications in Virtual Reality (VR) can leverage much more fine-grained sensory input from their users. Tracking the user's body enables higher immersion [18, 21], resulting in an increased sense of presence for the user.

Nevertheless, body tracking and — more importantly — providing effective virtual representations of the effects of bodily movements still remains a challenge, particularly in terms of veridical auditory and haptic feedback.

While the visual sense dominates human perception, research has shown that other sensory channels play an important role when it comes to the user's perceived presence in VR [14]. Simple feedback cues like walking sounds modify how users perceive their own speed and weight or the surface that they are walking on [13, 22]. However, non-congruent feedback cues can easily reduce the user's sense of presence and ultimately lead to motion sickness [5].

In this paper, we focus on the auditory aspect of VR immersion. We introduce *VRsneaky*, a system with force-sensing resistors attached to the user's shoe sole. It tracks the user's

---

CHI 2019, May 4–9, 2019, Glasgow, Scotland UK

ACM ISBN 978-1-4503-5970-2/19/05…$15.00
https://doi.org/10.1145/3290605.3300776

stride length and enables us to deliver synchronized footstep sounds as well as infer the user's current gait to adjust sound playback accordingly. This improves the congruence between sensory information across different sensory modalities compared to state-of-the-art approaches, where walking sounds are played independently of the user's actual stepping patterns.

To verify our approach, we evaluated *VRsneaky* in a playful "bank robbery" scenario where participants needed to make use of different gaits to remain undetected. We use this scenario as an exemplary application of gait-aware soundscape design for VR applications. In our study with 28 participants, we evaluate the impact of different sound types on the participants' perceived presence and their behavior in virtual reality. We found that using *VRsneaky* led to increased presence and influenced how participants moved while interacting in our VR scenario. Based on our results, we present opportunities and requirements for VR systems that allow users to walk through virtual worlds.

We conclude that synchronized and gait-aware step sounds in VR applications (1) increase the sense of presence by (2) helping users be more aware of their own posture and gait; thus (3) influencing certain gait characteristics, such as stride length and walking speed.

2 RELATED WORK

Research has shown that environmental factors in the virtual world have an influence on how users perceive themselves. Visually altering body weight impacts one's self-observation while dealing with eating disorders [12]. Different cultural representation creates illusions that change our way of interacting with the virtual world. As showcased by Kilteni et al. [6], where the activity during a musical performance changes when participants are embodied in morphologically different avatars.

While development is still ongoing, a certain level of fidelity in VR components has been achieved. Yet, realistic locomotion in virtual environments and how to reflect it are still challenging. As physical walking space is usually limited, other forms of player movement need to be considered. An early example of this has been showcased in the seminal work by Slater et al. [19], presenting an approach where the user is able to take steps in the same spot and traverse the virtual world at the same time. Recent work by Boysen et al. [3] and Wilson et al. [24] demonstrated approaches to overcome limited tracking areas by either upscaling the user's size or the speed of movement.

An important aspect in solving the locomotion challenge is to provide realistic and congruent feedback to the user in VR. Zhang et al. [28] used a shoe-based sensor system of accelerometer and force-sensing resistors to classify eight classes of activities, e.g. sitting, standing and walking. As not only the sounds of walking influence the experience, RealWalk lets one feel the resistance of the virtual surface while walking by changing the viscosity in a shoe-like device attached to the user's feet [20]. Other modalities such as sound, e.g., through the binaural sense of hearing, are important for localizing objects, actions, and oneself in virtual environments. Action planning and execution are both affected by accompanying sounds, influencing the user's interactions in the virtual world [1].

As shown by Podkosova et al. [13], realistic spatial sound that includes reflections and reverb can help the user "to adjust to [...] game[s] faster and provides them more support in avoiding virtual obstacles" [13]. The project *Cingo* [11] aims to develop more immersive sound by simulating alterations of sound that get reflected off walls and other objects while traveling through the virtual space. Combined with tracking systems, audio can be placed at exact spatial positions, such as the user's feet to create footstep sounds underneath the user. Even though sounds can create a sense of presence and help users orient themselves, they are often not enough to recognize a place only by its soundscape [15]. As the creation of adaptive soundscapes for games or VR scenarios is more challenging than their static movie counterparts, Lopes et al. [8] present a system that autonomously generates soundscapes and selects sounds from a library based on crowdsourced annotations.

Altered locomotion sounds can create illusory perception of one's virtual self as shown by Tajadura-Jiménez et al. [22]. Modified walking sounds change the user's perceived body weight and induce a related gait pattern. High frequencies of walking sounds lead to the perception of having a thinner body. This results in an enhanced motivation for physical activity and a more dynamic swing and a shorter heel strike.

Additionally, realistic sound samples are required to achieve high auditory immersion. Serafin et al. [16] present two different setups where microphones are either mounted on the participant's shoes or attached to the floor, the sounds then get synthesized and played back to the user. While the latter limits the method to room-scale VR scenarios, attaching the microphones to the shoes enables a bigger traversing area. However, the authors remark that the resulting airflow from a walking user induces noise artifacts.

3 VRSNEAKY

In our work, we draw on the playful usage of VR to evaluate the idea of congruent audio feedback for walking in a virtual environment. In the following section, we elaborate on the design considerations for such a prototype and the technical implementation details.

Based on related work, we identify three requirements to be considered in the design of our prototype, *VRsneaky*. Firstly, *VRsneaky* must not hinder the user's **freedom of**

movement in either the virtual or real world. As such, the system needs to be wearable and connected via wireless technology. Secondly, the system should be **easily deployable** and **deliver robust input** for the virtual environment. Based on these factors, we decided to employ force-sensing resistors (FSRs) that we attached to the user's shoe sole.

Contrary to vision-based approaches, such as current VR tracking systems, FSRs do not suffer from occlusion and are able to reliably track subtle changes in the user's gait. Importantly, the amount of pressure exerted over time is a clear indicator of when a person changes their mode of stepping — for instance, stepping more cautiously to avoid making sounds. Thus — compared to inertial sensors — FSRs provide a direct response to the user's gait.

Our third design consideration focuses on the usage of appropriate sound samples for the user's stepping noise. As outlined by related work, **realistic sound samples** and **sound placement** is vital for high presence. Yet, directly sourcing audio from microphone recordings has been problematic in the past [16]. Hence, in our work, we rely on prerecorded sound samples to circumvent noise artifacts and randomly select sound samples from a set to account for natural variance, as proposed by Turchet et al. [23]. Furthermore, we place the virtual location of the sound source underneath the user's feet to reinforce perceived spatial congruence between sensing one's own steps through hearing and proprioception.

We utilize the force sensor input in two ways. Firstly, we detect the exact moment when the user's foot touches the ground, which is the beginning of the foot's natural rolling movement. Over the course of this movement, we monitor sensor values and calculate two distinct moments for sound playback: when the heel touches the ground and when the ball of the foot touches it. Secondly, we measure the amount of pressure the user exhibits over the whole motion to predict their gait. The played footstep sounds are triggered by two pressure thresholds, one for the heel and one for the ball of the foot. Each sound is randomly chosen from an array that offers a variety of stepping sound for each gait. Based on the collected data, the weight distribution over time can be used for footstep feature analysis. For our scenario, a simple threshold-based approach was sufficient, but more elaborate features and gait adaptations are imaginable.

We implemented the prototype by attaching a Raspberry Pi Zero W, that acts as a control unit, to each of the user's legs. The electronics were protected by a 3D-printed case (see Figure 2). The modules were powered via a USB powerbank placed in the user's trouser pockets. The array of FSRs (Interlink FSR402) was embedded in textile and attached to each of the user's shoe soles (see Figure 3). We adapted the placement of FSRs suggested by Zhang et al. [28] and placed one sensor underneath the big toe, three distributed over the ball of the foot and one at the heel.

Figure 2: VRsneaky prototype: Raspberry Pi Zero W control unit mounted on a participant's leg. Force-sensing resistors (FSRs) used for gait awareness were placed under the shoe.

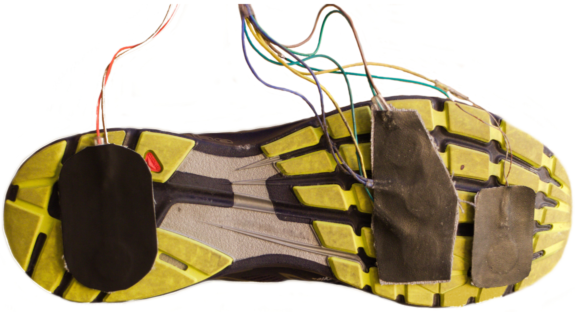

Figure 3: Placement of FSRs: One underneath the big toe, three distributed over the ball of the foot and one at the heel; placement of FSRs adapted from Zhang et al. [28].

4 EVALUATION

To evaluate our system, we employed a one-factorial (*Sound Modality*) within-subject design with four conditions (see Table 1). *No Sound* and *Equidistant* represent the current state-of-the-art of most VR applications, where stepping sounds are either completely absent or emulated at fixed distances, and therefore serve as a baseline. With our prototype, we introduce the novel conditions *Synchronized* and *Synchronized & Gait-Aware*, where stepping sounds are synchronized with the user's footsteps. In addition, *Synchronized & Gait-Aware* distinguishes between two different variants of a user's gait: normal and cautious stepping (sneaking). This concise set of variables allows for tight experimental control and assures that the user study can be conducted within a reasonable timeframe per user. Also, we excluded some easily distinguishable traits, such as jumping and running, due to restrictions imposed by the tracking space.

Condition	Explanation
No Sound	No footstep sounds played.
Equidistant	Footstep sounds every 70 *cm*; based on average stride lengths [9, 10].
Synchronized	Footstep sounds synchronized with the participant's footsteps.
Synchronized & Gait-Aware	Same as *Synchronized* but different sounds depending on the participant's gait.

Table 1: Different conditions for *Sound Modality* during the study.

We approached data collection from three directions: 1) we extracted objective gait metrics, 2) we measured presence using a well-established presence questionnaire (PQ) [25, 26], and 3) we asked participants follow-up questions to capture aspects of the experimental experience that are not covered by the PQ. The latter are analyzed using thematic analysis and reported in a narrative, rather than numeric, format. More details are provided in the following sections.

Task and Procedure

To provide a motivating and engaging task in our user study, we chose a bank robbery that had to be carried out. We asked our participants to steal the money and gold that was on a table in the middle of the vault. Outside the vault, was a wheelbarrow, in which the money had to be stored. As there was a guard standing inside the vault, the participants had to move silently to avoid being detected. We told our participants that they had to sneak inside the vault, but could walk normally near the wheelbarrow, since the guard would not be able to hear them outside. The task ended after all of the money and gold items had been placed in the wheelbarrow. At the start of the experiment, we asked our prospective participants to provide informed consent for the participation in our study. Afterwards, we introduced the participants to our system and the VR setup, giving them time to adjust and recorded data from the pressure sensors of their preferred gait for cautious stepping (sneaking) and walking normally. The order of conditions was randomized using a Latin square approach. After each run (when all the money and gold was inside the wheelbarrow), participants were advised to remove the headset and answered a questionnaire to measure their perceived presence in the VR scenario. Furthermore, we logged behavioral measures during the whole experiment for further analysis.

Measures

The questionnaire consisted of the 19 core questions from Witmer's and Singer's presence questionnaire [25, 26], including the auditory subscale group (see Table 2). Additionally, we added four free text questions to query the perception of the utilized footstep sound (see Table 3). After completing all conditions, participants filled out a final questionnaire, stating their most and least favorite form of footstep sound during the experiment.

Auditory subscale questions
How much did the auditory aspects of the environment involve you?
How well could you identify sounds?
How well could you localize sounds?

Table 2: Auditive subscale questions by Witmer and Singer [26] on a 7-item scale.

Free text questions
How convincing was the played stepping sound?
How did the stepping sound affect your awareness of yourself?
How did the stepping sound affect your awareness of the environment?
How did the stepping sound affect how you moved?

Table 3: Additional questions in our applied questionnaire; all free text.

Additionally, we logged the participants' spatial position in each trial and their gait over time. Based on these logs, we calculated several behavioral measures for each run that were submitted for statistical analysis: stride length, task completion time (TCT), proportion of cautious stepping (sneaking) and their head height.

Apparatus

We created a VR scenario with Unity3D that was run on a Windows 10 PC with an i5-7500, GTX1080 and 16GB RAM. The HTC Vive VR HMD was connected to the PC via TPCast wireless transmission to ensure the participant's freedom of movement in the $2x4\,m$ tracking space. The data from the FSRs were sent to Unity via WiFi and were used to classify the participant's gait. Based on the classification result and employed condition, gait-adjusted stepping sounds were played back to the user.

We equipped our participants with active noise-canceling headphones to prevent them from hearing their own footsteps. Additionally, we added white-noise from a running ventilator that was present during the experiment[1](both in the virtual and real environment). The sound volume was set to a predetermined value for the whole study. To eliminate varying factors and to simplify the task, the participants were only given one controller that they carried in their preferred hand. After picking up money or gold the guard cleared his throat and mumbled within two seconds, reminding the participant of his presence and the danger of getting caught.

Participants

We recruited 33 participants (11 females) from our university through mailing lists. The data of 28 ($M = 24.07\,y$, $SD = 4.30\,y$) were submitted for further analysis. We excluded 5 participants due to technical problems and motion sickness. All participants reported normal or corrected-to-normal sight and hearing. Eleven of our participants had little VR experience (less than two hours). Nine had extended experience and 8 had no VR experience at all. Most participants (18) had extensive video gaming experience, two had little experience and 8 none. After the experiment, each participant was either paid an allowance of 10 Euros or given course credit for their study program.

5 RESULTS

We report on the statistical analysis of the behavioral measures and the presence questionnaire. Furthermore, we present a qualitative analysis of our own questionnaire (see Table 3) and report on the free text questions at the end of the experiment.

Behavioral measures

To detect systematic variability in the objective performance data, we examined the data for trends across the four experimental conditions by performing a set of orthogonal polynomial contrasts (tests for linear, quadratic, and cubic trends). As the conditions can be ordered along a dimension of increasing auditory realism (*No Sound* < *Equidistant* < *Synchronized* < *Synchronized & Gait-Aware*), we predicted that each of the dependent measures (TCT, proportion of cautious stepping, stride length, and head height) should exhibit some covariation along this axis, in particular a linear trend. In other words, we expected the dependent variables to increase or decrease systematically along the dimension of auditory realism. The data analysis was performed by fitting four linear mixed effect models; one for each of the four objective performance measures. In each model, the performance measure of interest served as the dependent variable, while the condition served as a fixed factor in form of an ordered categorical variable and participant as a random factor. This modelling approach performs a variant of a regression with condition as a categorical ordered predictor and a performance measure, such as TCT, as the outcome variable. Results are reported in the following, with an emphasis on linear trends.

We find that increasing auditory realism significantly influences some characteristics of participants' gait. In particular, we find that stride length decreases by $2.17\,cm$ with each level of auditory realism (linear component of the orthogonal polynomial contrasts; $t(193) = -2.29, p = 0.023$) and overall TCT increases by $2.7\,sec$ (linear component of the orthogonal polynomial contrasts; $t(81) = 2.02, p = 0.044$). The latter effect also reaches a ceiling for the conditions with higher realism (quadratic component of the orthogonal polynomial contrasts; $t(81) = -2.23, p = 0.027$). These findings are illustrated in Figure 4 (Subfigures A and B). This result is consistent with the interpretation that, with increasing auditory realism, participants more often adopt a gait pattern commonly associated with "stealth" — short, non-accelerated stepping. There is no influence on participants' posture in terms of head height (linear component of the orthogonal polynomial contrasts; $t(193) = 0.25, p = 0.8$), nor on the second gait parameter, proportion of cautious stepping (linear component of the orthogonal polynomial contrasts; $t(193) = -0.77, p = 0.44$) as depicted in Figure 4 (Subfigures C and D).

Presence Questionnaire

To analyze the gathered data from the presence questionnaire, we aggregate the results from individual questions into one presence score metric. Using an analysis of variance of aligned rank transformed data as introduced by Wobbrock et al. [27], we identified significant differences among the conditions.

For the overall presence score, we aggregated the result of all questions, yielding a possible maximum score of 154. The grand mean of this score was 122.60 ($SD = 15.79$). The highest average score ($M = 129.46, SD = 13.80$) was achieved using condition *Synchronized & Gait-Aware*, while the lowest average score ($M = 117.18, SD = 18.32$) occurred in condition *Equidistant.* The distribution is depicted in Figure 5. We identified a significant effect for the *Sound Modality*, $F(3, 81) = 9.49, p < 0.001$. A Tukey post hoc test revealed significant differences between *Synchronized & Gait-Aware* and all other conditions: *No Sound* ($p < 0.001$), *Equidistant* ($p < 0.001$) and *Synchronized* ($p < 0.05$). No further pair-wise statistically significant differences were found.

---

[1] The ventilator not only served as a cooling device during the hot summer days, but also concealed outside noises to minimize possible distractions.

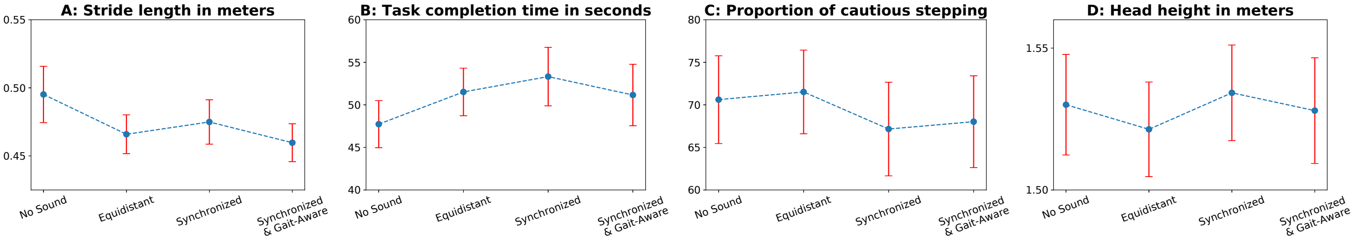

Figure 4: Behavioral measures (mean values) recorded during the experiment given *Sound Modality*. Subfigure A shows the participants' stride length; Subfigure B their task completion time; Subfigure C depicts the percentage of cautious stepping and Subfigure D shows the head height.

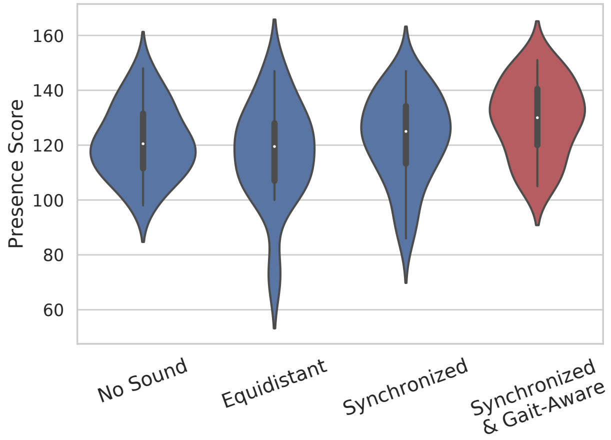

Figure 5: Violin plots showing the distribution of the presence score metric given the respective conditions. The group marked in red (*Synchronized & Gait-Aware*) is pairwise significantly different to all other groups.

Qualitative Feedback

We analyzed the textual feedback provided by the users in the post-run form (see Table 3) after each condition. As we wanted to understand specific aspects of the experience of *VRsneaky*, we used a structured top-down approach. Three researchers used affinity diagramming to identify positive and negative aspects of the user experience within each of the questions [2]. We also opted to count coded statements to give the reader an impression of the prevailing opinions. Results are structured according to the questions in the response form. We provide the gender and age of the cited participants.

How convincing was the played stepping sound?
For the condition *Synchronized & Gait-Aware*, 11 participants (in total 28) found that the used sounds for footsteps were appropriate and convincing. We identified that especially the sound for a sneaking motion was appreciated more (7):

> "quite convincing, especially when I walked slowly" [P20, f, 19 y]
> "The sound was very convincing and exact" [P23, f, 19 y]

The other 10 participants were leaning more towards it being an unrealistic sound that did not fit well given the floor in the real and virtual world. This was also evident for the condition *Synchronized*, where participants criticized the lack for gait awareness (8):

> "The sound was the same volume whether I walked normally or walked on my tiptoes." [P31, f, 21 y]

We could identify that negative comments mainly resulted from inappropriate sounds in the floor environment (13). Some participants were okay with odd sounds as long as they were synchronized with their actual footsteps (7). This finding is more evident for *Equidistant* where 22 participants reported that the timing of the footsteps was off and delayed. This irritated most of our participants, which can be observed in one comment coming from the condition *No Sound*:

> "there was none [condition *No Sound*] but this was better than having an unrealistic sound as in *Equidistant*. (...)" [P30, f, 28 y]

For the condition *No Sound*, most participants (21) reported that they heard no sounds at all, yet 6 participants remarked that they could notice their own footsteps, as they were physically aware of and heard their own footsteps in the real environment.

How did the stepping sound affect your awareness of yourself?
When using *Synchronized & Gait-Aware*, 16 of our participants reported that they felt like a "part" of the game and enjoyed using the different gait types, while 5 reported that they felt an increased awareness of themselves:

> "Very much! The sneaking felt way more realistic and tense. I was really aware of my movement!" [P25, f, 21 y]

Only 7 participants reported that they felt slight to no change. For the *Synchronized* condition, 11 participants reported that the lack of gait awareness negatively influenced their own movement. They commented that the sound seemed too loud when they were sneaking. In this condition, only 6 participants perceived the step sound as helpful and realistic, while the rest (11) indicated little to no change. Similar to the first question, participants (12) felt that the *Equidistant* condition negatively affected their awareness of themselves as the timing of the played footsteps was off and not in sync. Again, 11 participants felt little to no change. For *No Sound*, most participants (20) experienced no difference. However, two remarked that they could notice their own footsteps and be more focused due to the missing step sounds (4).

How did the stepping sound affect your awareness of the environment?

Ten participants reported that the condition *Synchronized & Gait-Aware* had no effect on their awareness of the environment, 5 noticed slight changes, whereas 9 participants perceived the environment as more realistic:

> "I felt like a bank robber. I was more aware of the guard." [P25, f, 21 y]
> "Environment became more realistic; I could anticipate how to move." [P18, m, 27 y]

Four participants commented on the volume of the sounds being too high:

> "I had the feeling of being extremely loud compared to my environment." [P32, f, 19 y]

For *Synchronized*, we received similar feedback. Ten participants commented that they were more aware, especially of the guard, and tried to make as little noise as possible. Another 10 participants reported no changes, while 2 reported slight changes. Due to the missing gait awareness, 6 participants reported that the sounds were unfit for their gait.

> "I did not perceive that my movement was affected by steps." [P18, m, 27 y]

For *Equidistant* and *No Sound*, participants mainly reported little to no changes (12 and 19), while also paying more attention to other stimuli — mostly visual — in the environment (7 and 6). In *Equidistant*, seven participants again mentioned the effect of misplaced footstep sounds.

> "I was paying more attention (visually) to the guard." [P15, m, 29 y]
> "It was contradictory to the experience. The sounds were too loud, hard and unrealistic." [P30, f, 28 y]

How did the stepping sound affect how you moved?

Out of 28 participants, 24 reported a positive effect in *Synchronized & Gait-Aware*. They used the sound feedback to adjust their gait and be as quiet as possible:

> "It gave me some feedback, if my sneaking was "sneaky" enough." [P16, m, 19 y]
> "I tried out different postures and took care to sneak when close to the guard. I walked and sneaked." [P25, f, 21 y]

Only 4 participants stated that the stepping sound did not affect their movement. For the *Synchronized* condition, 11 participants reported positive changes, but also remarked negatively (7) on the missing distinction between sneaking and walking.

> "I intentionally took big steps to limit the amount of noise I made. Overall, I moved very cautiously." [P2, m, 24 y]
> "I tried to be quiet but it did not work." [P27, f, 19 y]

Eleven participants reported that the footstep sounds had no effect on how they moved. For the remaining conditions, most participants reported no changes to their gait, 11 for *Equidistant* and 21 for *No Sound*.

> "Not careful anymore. Only tiptoed because it was in the rules of the game. I didn't care how many steps I took." [P2, m, 24 y]

Again, participants (6) perceived asynchronous footstep sounds as disturbing, but tended to ignore them:

> "I tried to move as expected, but was not too particular since the sound did not match." [P10, f, 24 y]
> "As there was no correlation between sound and the way I walked, it was harder to focus on my movements." [P30, f, 28 y]

Concluding Questions

At the end of the experiment, we asked every participant to rate their favorite and least favorite *Sound Modality* and provide additional comments if desired. Of our 28 participants, 82% rated the condition *Synchronized & Gait-Aware* as their favorite one.

> "(..) It let me feel I was performing well at controlling my steps." [P10, f, 24 y]
> "It gave me a realistic experience of movement and position in virtual space. Sneaking felt more intense and important." [P25, f, 21 y]

Three participants preferred *No Sound* stating that the played footstep sounds seemed mostly unrealistic. *Synchronized* was chosen once, while *Equidistant* was never selected. One participant stated that "(...) all [conditions] were unrealistic" [P4] and did not choose one.

Eleven participants rated *Equidistant* as their least favorite *Sound Modality*.

> "Not in sync with my steps, very confusing." [P13, m, 24 y]

Seven voted for *No Sound* reporting that "it felt like there was something missing." [P9, f, 23 y] and one each for *Synchronized* and *Synchronized & Gait-Aware*. The results from 8 participants were excluded due to unclear ratings.

6 OPPORTUNITIES AND REQUIREMENTS FOR GAIT-AWARE SYSTEMS

Our analysis of the presence questionnaire indicates that participants felt an increase in perceived presence in the virtual environment when presented with synchronized footstep sounds tailored to their gait. We reason that synchronized gait sounds gave the users the ability to orient themselves better in the virtual environment, thus creating an increased sense of presence. **Moreover, the addition of being able to interact with and perceive different sounds based on gait has created an increase in auditory involvement.**

Comments from our participants reinforce this finding as most users enjoyed the feedback condition with synchronized step sounds and gait awareness the most. Especially the ability to alter one's soundtracks by modifying the gait was appreciated and noted as highly realistic by the participants. By being more aware of their own positioning and posture, participants explained that the sound modalities affected their preferred way of moving. In the condition *Synchronized & Gait-Aware*, **the sound feedback helped them find an optimal posture, reducing the amount of noise created**.

This finding is supported by our analysis of the participants' behavioral measures. While the proportion of sneaking during the experiment showed no significant increase, the participants' stride length and walking speed (measured via TCT) decreased. This is consistent with the reports on **heightened awareness of their own gait**. Since participants were instructed to be sneaky, we reason that the *Synchronized & Gait-Aware* condition gave participants the ability to accurately control their sneaking and adopt a "stealthy" way of sneaking: short, non-accelerated stepping.

For other sound modalities, reports stated that participants tended to ignore the feedback after a while since it didn't match their gait. Furthermore, we also identified that asynchronous step sounds were even more detrimental to the user's perceived presence than no sounds at all. This indicates that **users were prone to neglect their own body posture and gait if the virtual environment did not react to it**. Hence, only verifiable feedback that is in accordance with the user's own perception is beneficial.

This phenomenon can be exploited in a number of ways to **create a feeling of increased reality, but also create illusions** by manipulating the user's step sounds [22]. In a creative way, this may be used for entertainment in VR, designing a perceptual illusion that the users know is not real, but they just cannot help experiencing it as reality [17].

Sound is another modality that can be used for presence manipulation. Altering footstep sounds can be used to create the illusion of different body weight, posture and gait. This effect can be beneficial for health related applications, e.g. to help train correct body posture, motor rehabilitation and gait after an accident, as already reported by Lamson [7] and Holden [4].

7 CONCLUSION

In *VRsneaky*, we address a topical shortcoming of current VR systems. While visual fidelity steadily increases, providing realistic auditory feedback for user movement is still an open question. In this paper, we present an easily deployable step detection system that implements synchronized footstep sounds and is aware of the user's current gait. We found that using *VRsneaky* significantly increased the users' perceived presence in the virtual environment, while also helping them to be more aware of their own body posture and gait. Furthermore, gait-aware footstep sounds had a direct impact on the users' behavior in VR by influencing their stride length and walking speed.

We identified that footstep sounds play an important role in achieving a high presence in VR. Improper sounds, however, can easily break that feeling of presence. Thus, it is essential to properly adjust playback sound for footsteps to environmental factors of the virtual and real environments.

We envision that through easy deployment of systems like *VRsneaky*, developers will be able to leverage the direct input of a user's gait. This offers creative opportunities for immersive virtual environments and provides the capabilities to raise the user's feeling of "being in another world" to a new level.

8 ACKNOWLEDGEMENTS

This work was supported by the European Union's Horizon 2020 Programme under ERCEA grant no. 683008 AMPLIFY. We would also like to thank the reviewers and ACs for their work and valuable feedback.

REFERENCES

[1] Elena Azañón, Luigi Tamè, Angelo Maravita, Sally A Linkenauger, Elisa R Ferrè, Ana Tajadura-Jiménez, and Matthew R Longo. 2016. Multimodal contributions to body representation. *Multisensory Research* 29, 6-7 (2016), 635–661.

[2] Ann Blandford, Dominic Furniss, and Stephann Makri. 2016. Qualitative HCI research: Going behind the scenes. *Synthesis Lectures on Human-Centered Informatics* 9, 1 (2016), 1–115.

[3] Yannic Boysen, Malte Husung, Timo Mantei, Lisa-Maria Müller, Joshua Schimmelpfennig, Lukas Uzolas, and Eike Langbehn. 2018. Scale & Walk: Evaluation von skalierungsbasierten Interaktionstechniken zur natürlichen Fortbewegung in VR. *Mensch und Computer 2018-Tagungsband* (2018).

[4] Maureen K Holden. 2005. Virtual environments for motor rehabilitation. *Cyberpsychology & behavior* 8, 3 (2005), 187–211.

[5] Behrang Keshavarz, Bernhard E Riecke, Lawrence J Hettinger, and Jennifer L Campos. 2015. Vection and visually induced motion sickness: how are they related? *Frontiers in psychology* 6 (2015), 472.

[6] Konstantina Kilteni, Ilias Bergstrom, and Mel Slater. 2013. Drumming in immersive virtual reality: the body shapes the way we play. *IEEE Transactions on Visualization & Computer Graphics* 4 (2013), 597–605.

[7] Ralph J Lamson. 2002. Virtual reality immersion therapy for treating psychological, psychiatric, medical, educational and self-help problems. US Patent 6,425,764.

[8] Phil Lopes, Antonios Liapis, and Georgios N Yannakakis. 2017. Modelling affect for horror soundscapes. *IEEE Transactions on Affective Computing* (2017).

[9] MP Murray, RC Kory, and SB Sepic. 1970. Walking patterns of normal women. *Archives of physical medicine and rehabilitation* 51, 11 (November 1970), 637–650. http://europepmc.org/abstract/MED/5501933

[10] Melissa P Murray, A B Drought, and R C Kory. 1964. Walking Patterns of Normal Men. *The Journal of bone and joint surgery. American volume* 46 (1964), 335–60.

[11] Juhani Paasonen, Aleksandr Karapetyan, Jan Plogsties, and Ville Pulkki. 2017. Proximity of Surfaces-Acoustic and Perceptual Effects. *Journal of the Audio Engineering Society* 65, 12 (2017), 997–1004.

[12] Concepción Perpiñá, Cristina Botella, R Baños, H Marco, M Alcañiz, and Soledad Quero. 1999. Body image and virtual reality in eating disorders: is exposure to virtual reality more effective than the classical body image treatment? *CyberPsychology & Behavior* 2, 2 (1999), 149–155.

[13] Iana Podkosova, Michael Urbanek, and Hannes Kaufmann. 2016. A Hybrid Sound Model for 3D Audio Games with Real Walking. In *Proceedings of the 29th International Conference on Computer Animation and Social Agents (CASA '16)*. ACM, New York, NY, USA, 189–192. https://doi.org/10.1145/2915926.2915948

[14] Maria V Sanchez-Vives and Mel Slater. 2005. From presence to consciousness through virtual reality. *Nature Reviews Neuroscience* 6, 4 (2005), 332.

[15] G Serafin and S Serafin. 2004. Sound design to enhance presence in photorealistic virtual reality. Georgia Institute of Technology.

[16] Stefania Serafin, Luca Turchet, and Rolf Nordahl. 2009. Extraction of ground reaction forces for real-time synthesis of walking sounds. *Proc. Audiomostly* (2009).

[17] Mel Slater. 2018. Immersion and the illusion of presence in virtual reality. *British Journal of Psychology* (2018).

[18] Mel Slater and Maria V Sanchez-Vives. 2016. Enhancing our lives with immersive virtual reality. *Frontiers in Robotics and AI* 3 (2016), 74.

[19] Mel Slater, Martin Usoh, and Anthony Steed. 1995. Taking steps: the influence of a walking technique on presence in virtual reality. *ACM Transactions on Computer-Human Interaction (TOCHI)* 2, 3 (1995), 201–219.

[20] Hyungki Son, Hyunjae Gil, Sangkyu Byeon, Sang-Youn Kim, and Jin Ryong Kim. 2018. RealWalk: Feeling Ground Surfaces While Walking in Virtual Reality. In *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems (CHI EA '18)*. ACM, New York, NY, USA, Article D400, 4 pages. https://doi.org/10.1145/3170427.3186474

[21] Misha Sra and Chris Schmandt. 2015. MetaSpace II: Object and full-body tracking for interaction and navigation in social VR. *arXiv preprint arXiv:1512.02922* (2015).

[22] Ana Tajadura-Jiménez, Maria Basia, Ophelia Deroy, Merle Fairhurst, Nicolai Marquardt, and Nadia Bianchi-Berthouze. 2015. As Light As Your Footsteps: Altering Walking Sounds to Change Perceived Body Weight, Emotional State and Gait. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*. ACM, New York, NY, USA, 2943–2952. https://doi.org/10.1145/2702123.2702374

[23] Luca Turchet, Stefania Serafin, Smilen Dimitrov, and Rolf Nordahl. 2010. Physically based sound synthesis and control of footsteps sounds. In *Proceedings of digital audio effects conference*, Vol. 11.

[24] Graham Wilson, Mark McGill, Matthew Jamieson, Julie R. Williamson, and Stephen A. Brewster. 2018. Object Manipulation in Virtual Reality Under Increasing Levels of Translational Gain. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. ACM, New York, NY, USA, Article 99, 13 pages. https://doi.org/10.1145/3173574.3173673

[25] Bob G. Witmer, Christian J. Jerome, and Michael J. Singer. 2005. The Factor Structure of the Presence Questionnaire. *Presence: Teleoperators and Virtual Environments* 14, 3 (June 2005), 298–312. https://doi.org/10.1162/105474605323384654

[26] Bob G. Witmer and Michael J. Singer. 1998. Measuring Presence in Virtual Environments: A Presence Questionnaire. *Presence: Teleoperators and Virtual Environments* 7, 3 (June 1998), 225–240. https://doi.org/10.1162/105474698565686

[27] Jacob O. Wobbrock, Leah Findlater, Darren Gergle, and James J. Higgins. 2011. The Aligned Rank Transform for Nonparametric Factorial Analyses Using Only Anova Procedures. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '11)*. ACM, New York, NY, USA, 143–146. https://doi.org/10.1145/1978942.1978963

[28] Ting Zhang, George D Fulk, Wenlong Tang, and Edward S Sazonov. 2013. Using decision trees to measure activities in people with stroke. In *Engineering in Medicine and Biology Society (EMBC), 2013 35th Annual International Conference of the IEEE*. IEEE, 6337–6340.