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Gait Differences in the Real World and Virtual Reality: The Effect of Prior Virtual Reality Experience

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Abstract

Walking through immersive virtual environments is one of the important parts of Virtual Reality (VR) applications. Prior research has established that users' gait in virtual and real environments differs; however, little research has evaluated how users' gait differs as users gain more experience with VR. We conducted experiments measuring novice and experienced subjects' gait parameters in VR and real environments. Results showed that subjects' performance in VR and Real World was more similar in the last trials than in the first trials; their walking dissimilarity in the start trials diminished by walking more trials. We found trial as a significant variable affecting the walking speed, step length, and trunk angle for both groups of users. While the main effect of expertise was not observed, an interaction effect between expertise and the trial number was shown. Trunk angle increased over time for novices but decreased for experts.

Index Terms: Human-centered computing—Human computer interaction (HCI)—HCI design and evaluation methods—User studies

1 Introduction

Researchers have broadly studied various kinds of walking in Virtual Reality (VR) as it can contribute to lowering sickness, improving the sense of presence, and enhancing the general user experience in Virtual Reality. VR applications in various fields such as health care, education, communications, and entertainment often allow users to move within Virtual Environments (VEs) via real walking for different purposes. For instance, using a treadmill for rehabilitation purposes in VEs [15], moving around in VR games to enhance user involvement and immersion [20], and physical locomotion to enrich performance in VR spatial orientation tasks [22].

Prior studies were conducted to understand users' gait behaviors in VE compared to the real environment (RE). Several experiments were completed in two real and virtual world states when participants were asked to walk in both arrangements. Hollman et al. demonstrated considerable differences in gait parameters such as stride length, stride velocity, and step width when users walked in VE compared to RE. Subjects walked in the VR environment with reduced stride lengths, increased step widths, and increased variability in stride velocity [10]. Likewise, Mohler et al. ran experiments where participants wore a Head-Mounted Display (HMD) and a backpack. They had a shorter stride length, slower walking velocity, and a lower head-trunk angle in VE than when walking in the real world [17]. Janeh et al. indicated significant distinctions in biomechanical gait parameters such as step length and walking velocity in virtual and real environments for younger and older adults. The results showed that, unlike younger adults, the older adults walked at a comparable speed in real and virtual environments. Also, older adults had similar step lengths in the VE and real world, whereas younger adults had a significantly shorter step length in the VE than in the real world [12]. Unlike the work represented above, Canessa et al. found no significant differences between gait in VE and RE, including total distance, stride length, and step length. However, they observed differences in other gait parameters, such as peak swing velocity, step count, and cadence, which they also explained by wearing cabled HMD for the virtual conditions [6].

Unlike well-established gait-related studies, no work has considered gait changes over time as users gain more experience in virtual environments. Due to the limited access to an HMD outside the VR labs, participants in earlier gait studies were likely novice VR users. Although HMDs are more available today, recent studies have not attempted to quantify participants' prior experience and incorporated it into their analysis. This paper presents our study to analyze how gait parameters may change in VR as users become more accustomed to walking in VR.

We hypothesize that gait differences in VEs and REs will shrink for more experienced users (experience with any type of VR). To test this hypothesis, we designed an experiment to examine natural walking in virtual and real rooms to see VE and RE's gait differences. We recruited two groups of participants: participants with little to no experience in VR (referred to as novices) and participants with substantial prior experience in VR (referred to as experts). Participants walked controlled in real and corresponding virtual conditions to record their gait proportions. Each participant's difference in gait parameters was computed and analyzed to determine whether walking in VE and RE varied between novice and expert users.

Knowledge of real walking in virtual environments is influential for immersive experiences, allowing users to move through Immersive Virtual Environments (IVEs) naturally. Our paper highlights the need to consider users' experience in VEs when designing walking assets and analyzing their effectiveness. Most of the experimental studies available in the literature on locomotion aids do not distinguish between experienced and inexperienced users. However, locomotion assets that are appropriate for experienced users may not provide a practical level of support for inexperienced users. Also, the assessment of user experience in locomotion applications would be more accurate by considering the effect of users' background in VR. Our results will benefit the design or update of VR applications based on the users' background, capabilities, and needs. It can help with the naturalness of users' walking in IVEs and improve user interactions in VR. So, the main contributions in this paper are:

- Evaluating the differences between walking in the real world and IVEs.
- Examining the effect of prior experience to moderate the gait differences in real and VR environments.

The next sections are structured as follows: Section 2 provides an overview of the previous research on locomotion and the impacts of prior experience in IVEs, and section 3 outlines our applied method. Then, sections 4 and 5 present the quantitative and qualitative results. Finally, section 6 discusses the challenges and limitations.

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2 Related Works

Walking is one of the most common actions for humans moving from one place to another and is performed by a stable dynamic movement. Natural walking is based on multi-sensory cues like vestibular, proprioceptive, and visual data that generate an intrinsic perception of self-motion acceleration, velocity, and direction. Bowman et al. described that walking could be broken down into three sub-tasks: direction or target selection (specification of where to move), velocity/acceleration selection (specification of movement speed), and conditions for input (specification of how travel is initiated, continued, and completed) [4]. The body parts act together throughout locomotion, controlling forces, and torques to become a smooth and unconscious physical activity.

Efficient VR applications need intuitive interfaces managed in a way that matches real-world experiences [30]. Prior work has shown that people walk differently in VR and the real world [10, 12, 17]. Researchers assessed the differentiation of walking parameters between real and virtual spaces and noticed various effective elements like VR devices' weight and deficiencies. In studies like [10] that healthy participants walked on an instrumented treadmill in a VR environment and a non-VR environment, results showed gait instability in VR. Lower stability of walking in VEs may be explained by factors such as the weight of the HMD and the smaller vertical field of view [13, 17]. In addition, Kelly et al. showed that technological deficiencies led to the smaller stability of vision in VR. Probable candidates include the reduced field of view relative to real-world viewing and graphics latency, and display quantization associated with VR [14].

There are several locomotion methods in virtual environments, such as game controller/joystick locomotion, physically walking, walking in place, teleportation, redirected walking, and arm swinging. Some locomotion methods enable users to walk in IVEs like walking in real spaces, and some provide users with routines and devices to relocate in the IVEs. However, none of these methods can provide the same sense that users obtain from naturally walking in IVEs [3].

Perception and cognition research has demonstrated the advantages of traveling within IVE through natural walking in comparison with other locomotion techniques like walking-in-place [18]. Specifically, natural walking has considerable benefits in terms of the user's sense of presence [27, 31], navigational tasks [22], cognitive map building [23], spatial knowledge [19], general learning [36], spatial recall and object placement [29], and cognitive demands [5]. However, natural locomotion is challenging to achieve in VEs. There is a problem with developing a locomotion interface that allows users to walk in virtual spaces larger than the real space embedding the VE model [33]. Hence, natural walking is becoming increasingly important to improve VR systems.

Few studies have examined how a user's prior experience with VR systems affects their behavioral and perceptual acknowledgments of VR. For instance, Bailenson et al. conducted longitudinal research, tracking users over 45-minute sessions when interacting with each other in VR; evaluating results showed that the feeling of presence did not change over time [1]. In another research, researchers compared subjects who routinely play first-person shooter computer games with those who do not implicitly involve travel proficiency as a factor in the study design [28]. Likewise, [20] did a longitudinal study investigating how users played Minecraft on the desktop and in VR, including three 45-minute sessions on each setup, although no effects were perceived within this time frame. Moreover, participants adapted to the VE and visual perturbations over time based on the results indicating increasing stride length and reducing stride width and time [16]. Although, there is yet a significant lack of research on the expected time users need to become proficient at traveling in the VR world.

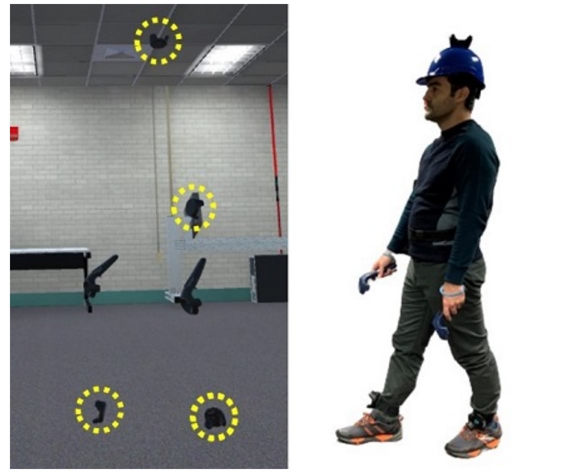

Figure 1: A user wearing four HTC Vive trackers to track his body movements during walking

3 Methods

This section describes our experiment of measuring the gait parameters of novice and expert VR users. We ran a mixed study with two factors: walking environment (real vs. virtual worlds: within-subjects) and prior VR experience (expert vs. novice: between-subjects). We designed two different conditions for running the experiments

- Virtual Space: walking with HMD for 40 trials in a virtual room.
- Real World: walking without HMD for 40 trials in a real room similar to the one inside the VE.

Participants performed the experiment in both conditions with counterbalanced order. Each phase has 40 trials of walking a 6 m path between two targets on the ground. Positional data from participants' bodies were collected for further analysis. Using the collected data, we calculated the following parameters: 1) Walking speed, 2) Step Length, and 3) Trunk angle when walking.

3.1 Virtual Environment and Equipment

Experiments took place in a fully tracked space, 10 m × 6 m in size, with a 6 m path to walk between two designated targets. This physical space has been precisely replicated in VR by using Unity (see Figure 2). The participants were asked to wear an HTC Vive HMD, which provides a resolution of 1080×1200 pixels per eye with an approximately 110 ° diagonal field of view and a refresh rate of 90 Hz. Four lighthouse tracking systems did positional tracking with the HTC Vive. Two HTC Vive trackers were used to track the user's feet and fastened right above the ankles. Also, subjects in the real-world phase wore one HTC Vive tracker on the hip and a hard hat with a fixed HTC-Vive tracker to track their head movements; the hard hat was chosen to make a similar condition to wearing an HMD and walking comfortable and stable. In addition to detecting and tracking their hands' position, they carried an HTC-Vive controller in their hands. Participants walked back and forth along the 6-meter path between two targets for 80 trials. These experiments have been done in VR and real-world conditions, wearing the HMD for walking in the virtual room and the hard hat to walk in the real-room condition.

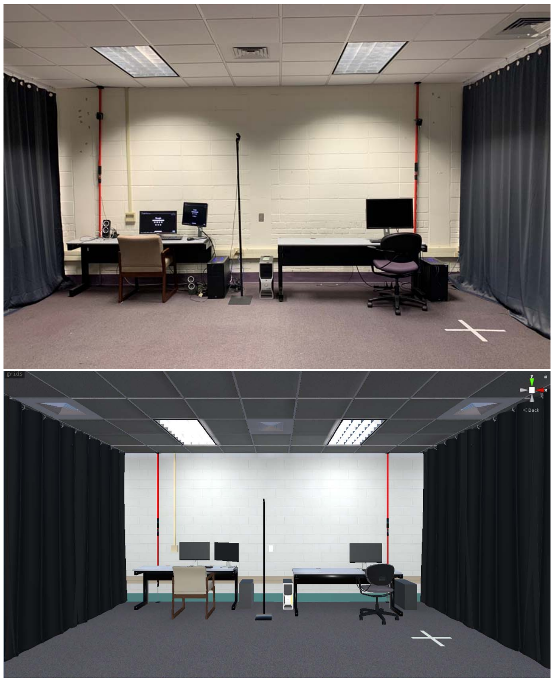

Figure 2: Top: Real room (Lab area), Bottom: Virtual room

3.2 Participants

We have recruited 30 participants, 17 novices (9 men, 8 women) who had less than 5 hours of experience with VR applications, and 13 expert VR users (10 men, 3 women) with more than 20 hours of VR experience. Participants who participated in the experiment were students at Clemson University. Nineteen were men, and 11 were women, with an average age of 24 (18-38 years). All had normal or corrected-to-normal sight with contact lenses. Our participants reported no vision or equilibrium disorders. Moreover, all of them were naive to the experimental conditions they experienced and wore their everyday clothes. Four participants had never worn a VR headset before this experiment; the rest of the participants had used HTC Vive and Oculus Rift HMDs before. The participants' study time, including pre-questionnaires, instructions, setting up the trackers, running the experiment, post-questionnaires, and interviewing was about 30 minutes.

3.3 Procedure

Participants were recruited primarily from computer science and psychology departments; they received a $10 US gift card or credit for their course. Upon arrival, participants were told the experiment's procedure and signed a consent form. Then, all participants filled out a pre-questionnaire about their demographic information and backgrounds in VR. Afterward, feet and hip trackers were affixed to their ankles and back. They were asked to wear HMD or hard hat and grab controllers based on the first condition, either VR or real-world.

After calibrating the trackers by the experimenter, participants started walking back and forth between two targets marked on the ground. Participants were asked to walk at a comfortable pace between the target zones. Once they reached the target zone, participants had to turn around and walk back to their starting point. At the end of each trial, a recorded audio instruction let the participants know that one trial had been done and they could walk in the other direction. After completing the first 40 trials in an experiment condition, the experiment was switched to another condition. The experimenter provided the participants with the hard hat or HMD and asked them to stand at the start point to proceed with the experiment. So, subjects walked another 40 trials in the opposite condition for the second part of the experiment.

Immediately after finishing the experiment session, participants filled out the post-test presence questionnaire. The questionnaire consisted of 13 questions with 7-point Likert scales. Mean I-Group Presence Questionnaire (IPQ) score [25] for the feeling present in the VE was M= 4.9, indicating a relatively good sense of presence in VR. After completing the questionnaires, the experimenter interviewed participants asking questions about their perception and understanding during the experiment. In the end, participants were invited to give feedback regarding the experiment.

4 Quantitative Results

We assumed the following hypotheses:

- H1: Participants' gait parameters in VR and the real world are not the same.
- H2: Participants with prior VR experience (experience with any types of VR) walk differently than novice VR users.

Linear-mixed models (LMMs) were used to analyze the experiment results and verify the hypotheses. So, models were created in R [21] first using the 'buildmer' [32] and 'lme4' [2] R packages. Buildmer automatically tests different possible models based on a set of independent variables and uses the model's likelihood-ratio test and the minimum Bayesian information criterion to select the model that best matches the observed data [26]. Once the final model was specified, it got fitted to the data using the lmer command provided by lme4. The lmerTest package [2] was used to estimate p-values using the Satterthwaite degrees of freedom method [24] for the models generated by lmer. Then figures were generated using ggplot2 [34]. Equivalence tests were performed using the TOSTER package in R.

4.1 Dependent and Independent Variables

We consider three independent variables in this study: 1) walking speed, 2) step length, and 3) trunk angle. These gait parameters got evaluated based on the subjects' expertise and the trial numbers. Our primary interest was how the difference in gait between the real world and VR gets moderated by prior experience using VR. We first computed the delta between participants' gait in the real world and VR for each metric and then used this value in our analysis. According to this convention, a positive delta value indicates that the metric was greater in the real world (e.g., a positive delta speed indicates that participants walked more quickly in the real world).

4.2 Average Speed m/s

Standardized parameters were obtained by fitting the model on a standardized version of the data set. 95% Confidence Intervals (CIs) and p-values were computed using the Wald approximation. We fitted a linear mixed model to predict Delta Velocity with Trial Number and Expertise. The model included Participant Identification Number (PID) as a random effect. The model's total explanatory power is substantial (conditional $R^2 = 0.56$), and the part related to the fixed effects alone (marginal R^2) is 0.07. The model's intercept is at 0.16 (95% CI [0.12, 0.20]). Within this model:

The effect of Trial is statistically significant and negative (β = -2.52e-03, 95% CI [-3.00e-03, -2.04e-03], t(1094) = -10.28, $p < 0.001$, Std. β = -0.30). Moreover, effect of Expertise(Novice) is trending towards significance and negative (β = -0.05, 95% CI [-0.11, 1.90e-03], t(1094) = -1.89, p = 0.059, Std. β = -0.29). Also, interaction effect of Expertise on Trial is statistically significant and positive (β = 1.18e-03, 95% CI [5.04e-04, 1.86e-03], t(1094)

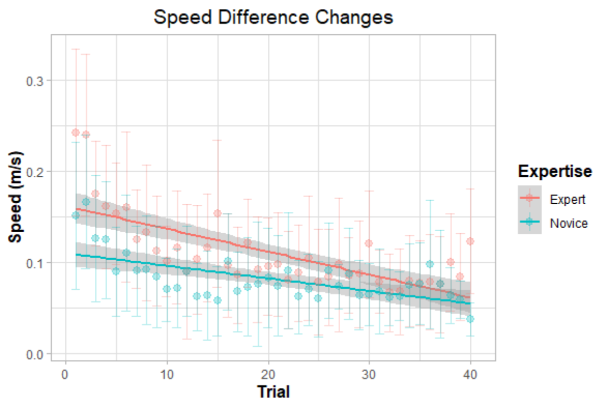

Figure 3: Difference between experts and novices average speed in VR and Real-World. The average speed for walking in the IVE was 0.954 m/s, and for walking in the real room was 1.009 m/s

= 3.42, $p < 0.001$, Std. β = 0.14). This interaction effect significantly affected the subject's walking, as observed in the experiment location and graphs. We performed an equivalence test on the effect of expertise and found that the changes in speed between experts and novices were equivalent to each other within a range of ± 0.04 meters/second.

Novices and experts walked at different speeds in VR and the real room setups; both were faster in the Real World than in the VE. Figure 3 shows the graph of speed changes during the experiment. The red line displays the experts' velocity shifts over time, as depicted in the graph. The graph shows that experts' performance in the last trials was more similar than in the first trials. Likewise, the same pattern is observed for novices' walking velocity; the blue line depicts how their performance dissimilarity in the start trials diminishes over time by walking more trials. For both groups, the more trials were completed, the more distinctions turned into similarities.

4.3 Step Length

Step length was defined as the distance between two consecutive placements of the same foot on the ground. Points of contact were located based on tracking data from the HTC Vive tracker on participants' feet. We have used the suggested method in [37] for step detection. The average step length was then computed by taking the average length of each step taken in one trial.

Standardized parameters were obtained by fitting the model on a standardized dataset version. 95% CIs and p-values were computed using the Wald approximation. We fitted a linear mixed model to predict Delta Step Length with Trial. The model included PID as a random effect. The model's total explanatory power is substantial (conditional R^2 = 0.36), and the part related to the fixed effects alone (marginal R^2) is 3.03e-03. The model's intercept is at 0.36 (95% CI [0.24, 0.48]). Within this model, the effect of Trial is statistically significant and negative (β = -2.26e-03, 95% CI [-4.30e-03, -2.15e-04], t(992) = -2.17, $p < 0.05$, Std. β = -0.06). We performed an equivalence test on the effect of expertise and found that the changes in step length between experts and novices were equivalent to each other within a range of ± 0.13 meters. The above statistics have indicated trial as a significant variable affecting the step length. Likewise, the graph illustrates the average step length distinctions over trials (see Figure 4).

4.4 Trunk Angle

A trunk angle is between the trunk segment and a vertical axis in the longitudinal plane. This angle is represented in Figure 5 as θ_2; it

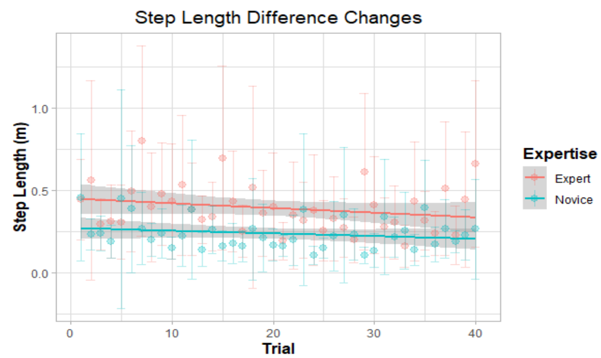

Figure 4: Step Length changes over time of experiment; when an expert's step held an average length of 1.4 m, the average step length for a novice was 1.2 m

would be positive if one leans back against the vertical line [35]. So, if a user stands in a position like Figure 5, his/her trunk angle would be negative.

We fitted a linear mixed model (estimated using REML and nloptwrap optimizer) to predict Delta Trunk-Angle (DeltaTA) by changes of Expertise and Trial, including PID as a random effect. The model's total explanatory power is substantial (conditional R^2 = 0.83), and the part related to the fixed effects alone (marginal R^2) is 0.07. The model's intercept, corresponding to Expertise = Expert and Trial = 0, is at 0.75 (95% CI [0.46, 1.04], t(710) = 5.04, $p < 0.001$). Within this model, the effect of Expertise is statistically non-significant however, the effect of Trial is statistically significant and negative (β = -2.59e-03, 95% CI [-4.46e-03, -7.29e-04], t(701) = -2.73, $p < 0.01$; Std. β = -0.05, 95% CI [-0.09, -0.01]). Moreover, there is an interaction effect of Trial on Expertise that is statistically significant and positive (β = 4.17e-03, 95% CI [2.16e-04, 8.13e-03], t(701) = 2.07, $p < 0.05$; Std. β = 0.08, 95% CI [4.17e-03, 0.16]). We performed an equivalence test on the effect of expertise and found that the changes in trunk angle between experts and novices were equivalent to each other within a range of ± 0.3 degrees.

Experienced subjects walked more upright in the IVE than in the real environment, and novices walked in VR while leaning forward. As statistics revealed, the trial was a significant variable, so the subjects' poses changed over trials. While a main effect of expertise was not observed, an interaction effect between expertise and the trial number was present, such that the difference in trunk angle increased over time for novices but decreased over time with experts (see Figure 6).

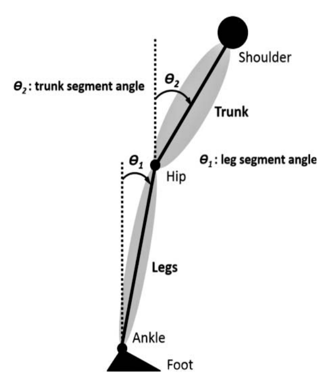

Figure 5: Trunk angle [11]

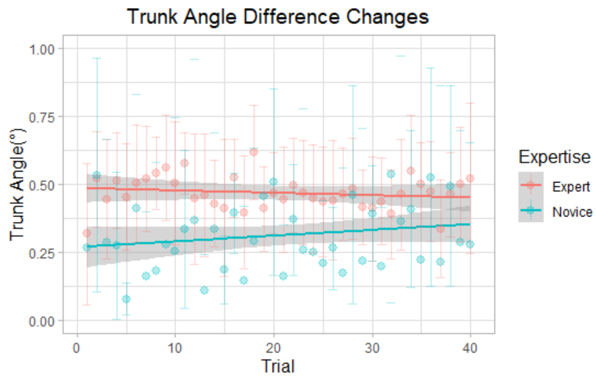

Figure 6: Difference of participants' Trunk Angle in the IVE and Real World over the 40 trials

4.5 Qualitative Results

VR consumers have matured in both their attitudes and their expectations regarding IVEs. So, implementing a qualitative approach can enhance the results conclusion and better understand subjects' perceptions. We collected data about participants' perceptions by observing and interviewing them. We analyzed all the interviews, observation notes, and recorded videos to determine how prior experience affects perception of the virtual environment. We were guided by the Grounded Theory approach when interviewing participants and analyzing their responses [7].

4.5.1 Coding and analysis process

The steps of the coding process are shown as follows:

- Step 1: Read observational notes and interview transcripts.
- Step 2: Divide the text into segments of information.
- Step 3: Code segments.
- Step 4: Refine codes.
- Step 5: Define themes based on the codes

The primary focus was to find differences in walking in virtual and real rooms affected by prior VR experience. Novice users were in two groups: no VR experience (0-1 hour) and little VR experience (1-5 hours). 46% of novices had almost zero experience in VR environments. They mostly talked about their new experiment and how VR looked exciting to them. As they did not experience a VR space before, they could not compare the experiment with similar ones. However, they could notice some interesting points like differences in distance perception in VR and RW; as one of the participants asked, “Does distance in VR seem different from the actual distance?”

On the other side, we experienced VR users who shifted from merely VR consumers to inventors and analyzers of VR hardware and software. They were actively assessing the VR setting and providing feedback on it. They addressed experiment design details such as walking path, “why did you choose to make participants walk a straight path back and forth rather than having different pathways with designated walking directions?” Also, some experienced users mentioned that they were careful at the beginning of trials and took steps a bit slow as they were concerned about hitting obstacles. Based on their expressions, they expected obstacles or challenges during walking, as seen in previous experiences. However, walking for several trials convinced them that no obstacle was coming, so they got faster in taking steps.

5 Discussion

Walking is one of the most fundamental tasks for moving in VR applications such as training, health care, and education. The principal purpose of this study was to examine if and to what extent novice and experienced VR users walk differently in immersive virtual environments. We collected valuable results to find gait differences between novice and expert subjects.

Results showed that walking time for both groups of participants was significantly higher in VR, and it was reduced by completing more trails. However, experienced VR users needed less time for both phases; they traveled the path faster than novices in VR and Real-World conditions. One possible explanation for the difference between novice and experienced VR users is that expert users may have enhanced perception-action coordination from prior VR experience. This prior VR experience may have enabled them to perceive the optic flow in VR simulations better and execute motor effort to maintain a comfortable speed of travel, support for this explanation can be found in driving and bicycling simulator research [8, 9].

Furthermore, novices had a lower speed than experts $p < 0.001$. As a part of the experiment procedure, subjects were asked to wear trackers on their feet and hip. Also, they wore a VR headset (in VR) and a hard hat (in the real session). Carrying all the equipment might be a factor that made novices slower than experts. When they started walking in the real world, they only wore trackers and a hard hat. Whereas when they walked into VR, they had both VR hardware to carry, and they stepped into a relatively new environment.

In addition, the difference between the average length of steps in VR and the real world is higher for expert users. So, the results matched our assumption that VR users' prior experience leads to differences in their behavior. They took relatively larger steps in a VR setting than in the real room.

Furthermore, novice participants inclined forward to take steps while experts were more upright when walking on the path. We may explain it by expert users' curiosity to look around and explore the virtual space. In comparison, novices were mainly focused on walking and reaching the targets on the ground.

In future research, we would like to explore the question, what if experts had more experience using alternative interfaces but not walking? It would lead to some potential follow-up studies to further research. Future work will also include the analysis of gait behaviors of experienced and novice VR users in other tasks such as collision avoidance and gap crossing.

6 Conclusion

This paper aimed to compare gait parameters in VR and the real world. The parameters include speed, step length, and trunk angle. So, the gait characteristics for two conditions and two classes of users were analyzed to assess the effect of the prior VR experience. For each participant, we compared the differences between velocity, step length, and body angle in VR versus the Real world. The more people experience VR, their walking parameters differ in VR and the real room. Our findings illustrate that the VR experience may make users self-calibrate and distinguish actions in the two conditions.

7 Acknowledgement

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References

[1] J. N. Bailenson and N. Yee. A longitudinal study of task performance, head movements, subjective report, simulator sickness, and transformed social interaction in collaborative virtual environments. *Presence: Teleoperators and Virtual Environments*, 15(6):699–716, 2006.

[2] D. Bates, M. Mächler, B. Bolker, and S. Walker. Fitting linear mixed-effects models using lme4. *Journal of Statistical Software*, 67(1):1–48, 2015. doi: 10.18637/jss.v067.i01
[3] C. Boletsis and J. E. Cedergren. Vr locomotion in the new era of virtual reality: an empirical comparison of prevalent techniques. *Advances in Human-Computer Interaction*, 2019, 2019.
[4] D. A. Bowman, D. Koller, and L. F. Hodges. Travel in immersive virtual environments: An evaluation of viewpoint motion control techniques. In *Proceedings of IEEE 1997 Annual International Symposium on Virtual Reality*, pp. 45–52. IEEE, 1997.
[5] G. Bruder, P. Lubos, and F. Steinicke. Cognitive resource demands of redirected walking. *IEEE transactions on visualization and computer graphics*, 21(4):539–544, 2015.
[6] A. Canessa, P. Casu, F. Solari, and M. Chessa. Comparing real walking in immersive virtual reality and in physical world using gait analysis. In *VISIGRAPP (2: HUCAPP)*, pp. 121–128, 2019.
[7] K. Charmaz. *Constructing grounded theory*. sage, 2014.
[8] B. Chihak, H. Pick Jr, J. Plumert, C. Ziemer, S. Babu, J. Cremer, and J. Kearney. Optic flow and physical effort as cues for the perception of the rate of self-produced motion in ve. In *Proceedings of the 6th Symposium on Applied Perception in Graphics and Visualization*, pp. 132–132, 2009.
[9] B. J. Chihak, J. M. Plumert, C. J. Ziemer, S. Babu, T. Grechkin, J. F. Cremer, and J. K. Kearney. Synchronizing self and object movement: how child and adult cyclists intercept moving gaps in a virtual environment. *Journal of experimental psychology: human perception and performance*, 36(6):1535, 2010.
[10] J. H. Hollman, R. H. Brey, R. A. Robb, T. J. Bang, and K. R. Kaufman. Spatiotemporal gait deviations in a virtual reality environment. *Gait & posture*, 23(4):441–444, 2006.
[11] S. Hwang, P. Agada, S. Grill, T. Kiemel, and J. J. Jeka. A central processing sensory deficit with parkinson's disease. *Experimental brain research*, 234(8):2369–2379, 2016.
[12] O. Janeh, G. Bruder, F. Steinicke, A. Gulberti, and M. Poetter-Nerger. Analyses of gait parameters of younger and older adults during (non-) isometric virtual walking. *IEEE transactions on visualization and computer graphics*, 24(10):2663–2674, 2017.
[13] O. Janeh, E. Langbehn, F. Steinicke, G. Bruder, A. Gulberti, and M. Poetter-Nerger. Walking in virtual reality: Effects of manipulated visual self-motion on walking biomechanics. *ACM Transactions on Applied Perception*, 14(2):1–15, 2017. doi: 10.1145/3022731
[14] J. W. Kelly, B. Riecke, J. M. Loomis, and A. C. Beall. Visual control of posture in real and virtual environments. *Perception & psychophysics*, 70(1):158–165, 2008.
[15] A. Kim, N. Darakjian, and J. M. Finley. Walking in fully immersive virtual environments: an evaluation of potential adverse effects in older adults and individuals with parkinson's disease. *Journal of neuroengineering and rehabilitation*, 14(1):1–12, 2017.
[16] D. Martelli, B. Xia, A. Prado, and S. K. Agrawal. Gait adaptations during overground walking and multidirectional oscillations of the visual field in a virtual reality headset. *Gait & posture*, 67:251–256, 2019.
[17] B. Mohler, J. Campos, M. Weyel, and H. H. Bülthoff. Gait parameters while walking in a head-mounted display virtual environment and the real world. In *13th Eurographics Symposium on Virtual Environments and 10th Immersive Projection Technology Workshop (IPT-EGVE 2007)*, pp. 85–88. Eurographics Association, 2007.
[18] N. C. Nilsson, S. Serafin, and R. Nordahl. Walking in place through virtual worlds. In *International Conference on Human-Computer Interaction*, pp. 37–48. Springer, 2016.
[19] T. C. Peck, H. Fuchs, and M. C. Whitton. An evaluation of navigational ability comparing redirected free exploration with distractors to walking-in-place and joystick locomotio interfaces. In *2011 IEEE Virtual Reality Conference*, pp. 55–62. IEEE, 2011.
[20] J. Porter III, M. Boyer, and A. Robb. Guidelines on successfully porting non-immersive games to virtual reality: a case study in minecraft. In *Proceedings of the 2018 Annual Symposium on Computer-Human Interaction in Play*, pp. 405–415, 2018.
[21] R Core Team. *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria, 2017.
[22] R. A. Ruddle and S. Lessels. The benefits of using a walking interface to navigate virtual environments. *ACM Transactions on Computer-Human Interaction (TOCHI)*, 16(1):1–18, 2009.
[23] R. A. Ruddle, E. Volkova, and H. H. Bülthoff. Walking improves your cognitive map in environments that are large-scale and large in extent. *ACM Transactions on Computer-Human Interaction (TOCHI)*, 18(2):1–20, 2011.
[24] F. E. Satterthwaite. An approximate distribution of estimates of variance components. *Biometrics bulletin*, 2(6):110–114, 1946.
[25] T. Schubert, F. Friedmann, and H. Regenbrecht. The experience of presence: Factor analytic insights. *Presence: Teleoperators & Virtual Environments*, 10(3):266–281, 2001.
[26] G. Schwarz. Estimating the dimension of a model. *The annals of statistics*, pp. 461–464, 1978.
[27] M. Slater, M. Usoh, and A. Steed. Taking steps: the influence of a walking technique on presence in virtual reality. *ACM Transactions on Computer-Human Interaction (TOCHI)*, 2(3):201–219, 1995.
[28] S. P. Smith and S. Du'Mont. Measuring the effect of gaming experience on virtual environment navigation tasks. In *2009 IEEE symposium on 3D user interfaces*, pp. 3–10. IEEE, 2009.
[29] E. Suma, S. Finkelstein, M. Reid, S. Babu, A. Ulinski, and L. F. Hodges. Evaluation of the cognitive effects of travel technique in complex real and virtual environments. *IEEE Transactions on Visualization and Computer Graphics*, 16(4):690–702, 2009.
[30] L. Turchet. Designing presence for real locomotion in immersive virtual environments: an affordance-based experiential approach. *Virtual Reality*, 19(3):277–290, 2015.
[31] M. Usoh, K. Arthur, M. C. Whitton, R. Bastos, A. Steed, M. Slater, and F. P. Brooks Jr. Walking¿ walking-in-place¿ flying, in virtual environments. In *Proceedings of the 26th annual conference on Computer graphics and interactive techniques*, pp. 359–364, 1999.
[32] C. C. Voeten. Using 'buildmer'to automatically find & compare maximal (mixed) models, 2020.
[33] M. C. Whitton, J. V. Cohn, J. Feasel, P. Zimmons, S. Razzaque, S. J. Poulton, B. McLeod, and F. P. Brooks. Comparing ve locomotion interfaces. In *IEEE Proceedings. VR 2005. Virtual Reality, 2005.*, pp. 123–130. IEEE, 2005.
[34] H. Wickham. *ggplot2: Elegant Graphics for Data Analysis*. Springer-Verlag New York, 2009.
[35] F. Yang and G. A. King. Dynamic gait stability of treadmill versus overground walking in young adults. *Journal of Electromyography and Kinesiology*, 31:81–87, 2016.
[36] C. A. Zanbaka, B. C. Lok, S. V. Babu, A. C. Ulinski, and L. F. Hodges. Comparison of path visualizations and cognitive measures relative to travel technique in a virtual environment. *IEEE Transactions on Visualization and Computer Graphics*, 11(6):694–705, 2005.
[37] Y. Zhang, Z. Zhu, and S. Wang. Method Based on the Characteristics of Gait. *2018 Ubiquitous Positioning, Indoor Navigation and Location-Based Services (UPINLBS)*, pp. 1–5, 2018.