Implicit Visual Feedback Distortions in Gait Rehabilitation Using Virtual Reality

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Visual Feedback Distortion from Virtual Reality Avatars Does not Result in Effects on Gait Asymmetry

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***Abstract*—Stroke survivors often struggle with gait asymmetry post-therapy. Researchers are exploring Virtual Reality (VR) to address this problem with the help of visual feedback and virtual avatars. VR also makes repetitive tasks more enjoyable, improving patient compliance and outcomes. Motor adaptation, essential in rehabilitation, involves adjusting movements to new conditions. Studies have used forms of motor adaptation with visual feedback to distort participants' gait symmetry, making people walk asymmetrically. This approach is called implicit Visual Feedback Distortion (VFD), where visual feedback is manipulated without the user's awareness. This thesis explores using implicit VFD with avatars in immersive VR to address gait asymmetry. An experiment with 11 healthy participants tested implicit VFD by gradually increasing the step length of the avatar's right leg. Contrary to previous screen-based VFD studies, results showed no significant effect on gait symmetry. Additionally, no correlations were found between step symmetry and psychological states (presence, embodiment, motivation). We hypothesize that the high distortion level on the right foot, suboptimal virtual environment design, and reported neck pain contributed to these findings. Future research should explore different VFD designs, or look at multiple groups to see what conditions lead to more gait asymmetry during adaptation.**

Keywords: Implicit learning, visual feedback distortion, virtual reality, and gait rehabilitation

I. Introduction

A. Stroke rehabilitation

The numbers do not lie: It is estimated that 1 in 4 people will suffer a stroke in their lifetime [1]. If a person survives, their life will change after the stroke. It is said that up to 25 % of patients post-stroke are unable to walk without full assistance [2]. It is also found that post-stroke survivors rate walking as their highest priority [3]. Despite the critical importance of gait rehabilitation, approximately 80% of stroke survivors [3] continue to face persistent challenges, particularly with gait asymmetry. Even after the rehabilitation, stroke patients still struggle with gait asymmetry. Gait asymmetry does not reduce or disappear in patients throughout rehabilitation periods, possibly due to the lack of specificity of the gait interventions on gait asymmetry in rehabilitation settings [4]. One proposed solution to improve this impairment is the use of biological cues to provide feedback [5]. Unlike verbal explanations or numerical graphs, biological cues provide clearer and more immediate information about patients' movements, potentially enhancing the effectiveness of gait training. Integrating biofeedback into rehabilitation practices could enhance the effectiveness of gait training. Currently, gait rehabilitation therapy often employs treadmill training with therapists or robotic devices. The underlying hypothesis is that intensive, repetitive movements, simulating the movements of healthy gait cycles might strengthen central pattern generators, which are neural circuits that generate rhythmic patterns of motor activity and improve the ability to gait control [6]. However, the repetitive nature of such exercises can demotivate patients, resulting in poorer performance during rehabilitation. Previous research states that motivation has a positive effect on motor learning [7] and should therefore be strengthened in gait rehabilitation.

B. Implicit learning and motor adaptation

For years, researchers have relied on Fitts and Posner's three-stage model of motor learning, which emphasizes the importance of explicit instructions during the initial stages of learning [8], [9]. However, the effectiveness of explicit instructions for neurorehabilitation patients, particularly for lower body rehabilitation, has been questioned [10] because explicit knowledge has been said to disrupt relatively automatic control processes [11]. An alternative approach is implicit learning, which involves the unconscious acquisition of knowledge [11]. Studies utilizing implicit learning techniques in rehabilitation have shown promise in inducing motor adaptation processes, which are inherently implicit [12].

Motor adaptation, defined as the modification of movement from trial to trial based on error feedback, is crucial for effective rehabilitation [13] and can enhance rehabilitation outcomes. Key characteristics of motor adaptation include its specificity to actions such as walking or reaching, the requirement for repetition, and its short-term nature, typically occurring within minutes [14, 13]. Importantly, motor adaptation involves after-effects: Persistent changes in the movement that remain even after the perturbation used for adaptation is removed. This process is not only about canceling out perturbations but also involves calibrating the brain's predictions of body movements while considering associated costs such as energy demands, forces, fatigue, and movement accuracy [13]. Therefore, understanding and utilizing motor adaptation and implicit learning can significantly improve rehabilitation strategies for neurorehabilitation patients.

C. *Implicit visual feedback distortions*

Implicit Visual Feedback Distortion (VFD) is a method used to create motor adaptation exercises by manipulating visual feedback, such as distorting the lengths of bar graphs representing the gait cycle, to induce asymmetric gait patterns in participants [15]. The distortion induced during the visuals triggers a motor adaptation that causes a sensory prediction error, which is the difference between the brain's predicted outcome of the movement and the observed outcome. Sensory prediction errors can be used to calibrate the internal representations of body dynamics and the environment and re-calibrate for changes in either [13]. While VFDs can effectively aid adaptation, they can be ineffective if not applied correctly. Previous work with visual feedback distortions in VR is seen in the work of Willeart et al, to investigate the effects of modulating an embodied self-avatar's stride length on the gait of healthy participants walking on a treadmill. They found no significant differences between any of the modulations on the stride lengths, possibly due to the lack of gradual integration of distortions [16].

Additionally, researchers can add a distraction task with the imposed paradigm, called a dual paradigm. The implicitly induced dual paradigm retained aftereffects [6]. This concludes that implicit processes in the dual paradigm group may improve retention.

We are particularly interested in utilizing these elements in VR because of the extrinsic feedback it provides. Extrinsic feedback refers to information provided to the user about their performance from an external source, which can be visual, auditory, or haptic. VR environments can deliver immediate and detailed extrinsic feedback, which is crucial for motor learning and adaptation. This real-time information helps users correct errors and improve their motor skills more efficiently by providing continuous updates about their movements and progress. By leveraging such feedback, VR-based rehabilitation can enhance the effectiveness of training sessions, helping patients to correct errors and improve their motor skills more efficiently. In tests comparing different motor adaptation paradigms VFD and split-belts (an approach, where two belts move at different speeds to create gait asymmetry), the implicit VFD paradigm demonstrated the longest noticeable aftereffect magnitude compared to the split-belt results, suggesting that motor adaptation behavior was more prominently stored in the visual distortion basis. This finding advocates using implicit VFD for error signals regarding visual information to re-calibrate the internal model for walking [17].

D. *Virtual reality in stroke rehabilitation*

Recent advancements in virtual reality (VR) technology have introduced the use of avatars as an effective method for gait rehabilitation. A recent study has shown that the visual feedback given with the avatar helps improve post-stroke gait asymmetry [5]. Previous work has also looked at the effectiveness of VFD in 2D environments both with implicit and explicit instructions on a television screen [15]. To date, there has not been a study that utilizes the Visual Feedback Distortion (VFD) paradigm in combination with immersive virtual reality (VR) using head-mounted displays (HMDs) to create a motor adaptation exercise aimed at improving gait asymmetry in stroke patients. We propose a novel approach to explore the use of VFD in the form of avatars in immersive virtual reality (IVR), focusing on achieving gait asymmetry in healthy participants by targeting the distortion on the length of the right foot.

E. *Psychological states*

In addition to the physical aspects associated with gait training, psychological states play a significant role in influencing neurorehabilitation outcomes. Among these, **Motivation** is crucial for enhancing neurorehabilitation. High levels of motivation lead to increased engagement and adherence to therapy, which are critical for achieving optimal rehabilitation outcomes. VR makes repetitive tasks more enjoyable with gaming techniques thereby improving patient compliance and outcomes [18]. To foster motivation in participants who need to perform numerous movement repetitions, rehabilitation centers are increasingly using immersive virtual reality (VR) games. These VR games create engaging virtual environments where meaningful, goal-directed movements can be practiced [18] [19]. Moreover, researchers are enhancing patient motivation through the use of serious games—games designed with objectives beyond mere entertainment—which further promote engagement and adherence to rehabilitation protocols.

Other psychological components, such as presence and embodiment, are more tightly related to VR but can influence outcomes of neurorehabilitation. **Presence** refers to the subjective feeling of being in the Virtual Environment (VE), with users experiencing the computer-generated environment rather than the actual physical location of the user [20]. **Embodiment** happens when the VE starts to behave and act like your body and is defined as the cognition that a body and its parts belong to oneself [21]. A high level of embodiment over an avatar in VR has been linked to better motor performance [22].

Despite these advancements, it is still necessary to better understand how psychological states such as motivation, presence, and embodiment affect the outcomes of practicing in VR environments. Furthermore, the technical level of immersion provided by VR setups also plays a critical role in these outcomes [23]. By exploring these factors, we can develop more effective neurorehabilitation protocols that leverage the full potential of VR technology in rehabilitation.

F. Main question and hypotheses

The goal of this thesis is to explore the use of IVR with VFD to induce gait asymmetry in healthy participants. To find out whether our proposed research is a promising method, we need to answer the following research question:

- Is there an effect on the asymmetry in step length when a person walks in immersive VR with an avatar experiencing a visual feedback distortion on the right step length?

If there is an effect found during the experiments on gait asymmetry: What is the retention rate of a person embodying an avatar in an immersive virtual environment? how is this implicit visual feedback distortion (asymmetry during adaptation and retention) then correlated to the psychological states?

To test this effect on healthy participants, a VR experiment with questionnaires is needed where we will collect data from walking and on participants' embodiment, presence, and motivation. In addition, collecting the data from the adaptation and retention period is crucial to prove whether this experimental setup is a viable method for implicit motor adaptation exercises.

Our hypotheses are as follows:

- Based on previously conducted experiments with VFD, there shall be asymmetry in people's gait cycle measurable due to the implicit VFD in this experimental setup. Namely: the imposed distortion activated on the right foot will decrease the step length of the right compared to the left foot.
- In this experimental setup, there will be an after-effect, namely the asymmetry of people's gait cycle will decrease in participants, which the implicit VFD causes during the retention period.
- A correlation will be shown between the participant's psychological states and the asymmetry. In other words, there will be a positive correlation between the gait asymmetry and the participant's presence, embodiment, and motivation on a person.
- The dual paradigm is another factor in measuring participants' performance on their distraction tasks. Their score for the distraction game will also correlate with their gait asymmetry. Namely, the higher the score from the distraction task of the participant, the higher the measured gait asymmetry.

II. Methods

A. Experimental setup

Participants walked on a treadmill (C-Mill, Forcelink B.V., Culemborg, The Netherlands) designed for rehabilitation, featuring an extra-wide surface and a front bar for support. This treadmill is suitable for Virtual Reality (VR) studies, providing ample lateral space to mitigate falling risk as people walk with the Head-Mounted Displays. An emergency button is attached to the bar (Figure 1 A) to stop the treadmill if needed. A rope connecting the user to the treadmill controller stops the treadmill if pulled off, e.g., during a fall (Figure 1 C). To further ensure safety, a ceiling-mounted rail system with a secure rope and safety harness was used to prevent falls. A TU Delft employee operated the emergency button, as participants could not see it while wearing the Head-Mounted Display (HMD). For additional safety, participants held the treadmill bar via the Vive controllers while walking. Vive controller holders were 3D printed and secured to the bar (Figure 1 B). The VR system included an HTC Vive Pro Eye with two SteamVR™ Base Station 2.0 units. Participants used two HTC Vive Pro controllers 2.0 for their hands, two HTC Vive trackers (3.0) on their feet, and a third tracker at the waist (Figure 1 C). Trackers were placed at the bridge of the feet to accurately represent foot movement in VR, and a hip tracker ensured correct body positioning of the waist. The VR computer featured an AMD Ryzen 9 5900X 12-Core processor (AMD Ryzen, USA), an NVIDIA GeForce RTX 3080 GPU (NVIDIA Corporation, USA), 32 GB of RAM, and ran on Windows 10 Enterprise (Microsoft Corporation, USA).

B. Virtual Reality

1) Virtual Environment: To develop the VR world and logic, the Unity version 2021.3.2f1 was used and programs were written in C# language. The VE consists of

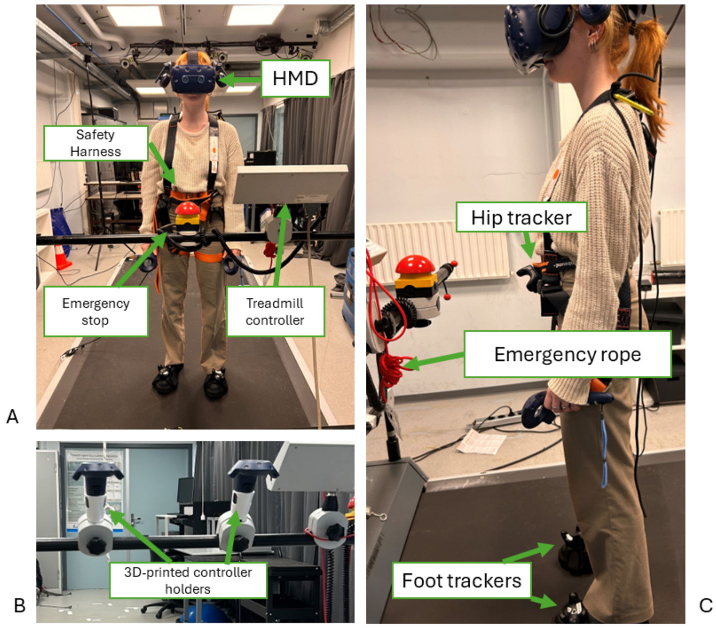

Fig. 1: Experimental setup. A. the HTC Vive Pro Eye, the safety harness, the emergency stop (detached and held by a second experimenter during the experiments), and the treadmill controller board. B. 3D printed controller holders attached to the treadmill bar. C. Side view of the set-up showing the positioning of the HTC Vive trackers (3.0) on the hip and feet and the emergency rope.

Virtual renderings and libraries that were used to make a calm, natural environment that was completely different from the laboratory environment (see also Figure 2 B & C for the virtual environment background). The VE consists of a virtual path in nature, an avatar (from the ready player me package), and a light game (Figure 2 D & E). The virtual world and avatar were developed previously by our group. The SteamVR plugin v2.2 and the Vive Input Utility toolkit were used to interface the HTC Vive Pro and the HTC Vive trackers. The avatar's appearance was based on the participant's gender: there was a male and female avatar (Figure 2 B & C), and they were downloaded from Ready Player Me. The avatar's body was animated using the position and orientation of the HMD, controllers, and trackers on the body using the VRIK full-body solver. Participants were immersed in the VE from the avatar's first-person perspective, seen in Figure 2 A, meaning they saw the vision of the avatar as if it were their vision directly (no out-of-body experience).

2) Distortion: During the VFD, or adaptation trial, we distorted the length of the right step in 2 % increments from 100% to 130%. To perform this distortion in Unity, we wrote an algorithm. The algorithm modifies the avatar's right foot position based on a timer and an initial distortion setting. When the distortion algorithm is activated, a timer starts. If the timer passes 60 seconds, the algorithm increases the distortion by adjusting the foot's z-position or longitudinal position by 2%. This continues until the maximum number of increments (15) is reached, then the timer stops. The distortion amount is determined by the participant's average step length.

3) Distraction task: Participants were asked to look at their feet during the experiment. To help them succeed in that task, a distraction game with lights draws participants' attention on their feet. This distraction task is not only a tool to force participants to keep an eye on their feet, but it also functions as a dual paradigm by distracting them from the main task (walking with the distortion).

The details of this light game are as follows: a yellow point light, built-in standard in Unity, was chosen for its brightness and constant visibility. To avoid creating a bias on the right foot, the light also appeared on the left foot. Both lights could be on at the same time. The lights went off every 10 to 15 seconds, which we found during pilot testing will keep everyone attentive enough to look at their feet for the duration of the trial. The participant was instructed to turn the light off by pressing the trigger on the back of the controller, as fast as possible. The light must be turned off with the controller on the same side, so if the left foot is lit, the participant must press the left trigger. If he/she fails to do so, no points are granted, and they must wait for the next interval. Participants did not

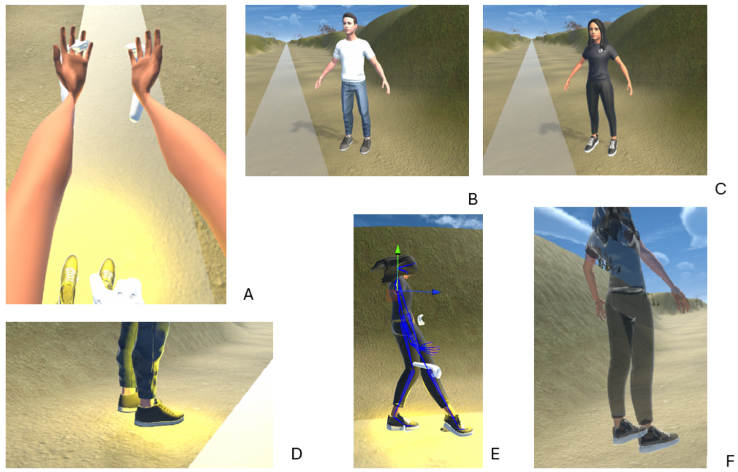

Fig. 2: Screenshots taken from the virtual environment. A. First-person perspective with hands in front of the person and light game. B. & C. the male and female avatars, respectively. D. & E. Close-up of the foot and full body frame with the light game. F. Fading avatar mid-fade.

see their points during the game because we believed that this will be too distracting. The light was visible for 10 seconds and then automatically turned off. Participants' reaction times and the number of mistakes were tracked to measure attentiveness.

C. *Participants*

Twelve participants, six females and six males aged from 20 to 29 years (24.96 ± 2.50) with a healthy gait cycle, were selected and provided written informed consent to participate in the study. The recruitment of participants was performed within the TU Delft via advertisement on social media and word-of-mouth. The study was approved by the TU Delft Ethics Committee (TU Delft reference number: 3617).

D. *Experimental procedure*

After participants signed the informed consent form, the gear was put on (HMD, trackers, etc). Once the gear was properly set up, participants received detailed instructions about the experiment, written in Appendix A. The initial instruction provided an overall explanation of the experiment, describing what they would see in the HMD and outlining the calibration process. The second instruction is told right before the baseline walk at the relaxed phase of the treadmill. The third and final instruction was given before the adaptation phase, without any notion of distortion. Relevant details about the distraction task and duration of each trial were also communicated.

The participants walked on a treadmill at a set speed of two km/h wearing the VR HMD in two trials: one short familiarization trial (two minutes) and a longer trial (20 minutes). The short familiarization trial served two purposes: it allowed the participant to get used to the virtual environment and to calculate the step length of the participant without VFD. After the first trial, the participant took a short break (five minutes) while the researcher quickly analyzed the baseline data to check for a "steady state" of the gait. Steady state was defined as consistent walking in place without any significant lateral or longitudinal movements. In that case, a short period was selected with at least four heel strike and toe-off marks and processed to determine the participant's mean step length. For the experiment, an overall average step length was used the left and right step length, because we assumed that participants had symmetrical gait. The 20-minute trial consisted of participants walking in the same VE with distraction tasks and distortion. No further instructions were given once the second trial began. Just before the end of the adaptation period, the light game stopped and the avatar disappeared, and the last five minutes were designated as the retention period. Participants then removed the gear and filled out the questionnaire to collect quantitative data about their psychological states.

E. *Data processing*

1) Calculating step length and step-alternating foot-steps: The mean step length is calculated after the baseline trial in Matlab R2023b. In Matlab, we used the signaling processing box to find the peaks and minimum values of the coordinate of each foot in the forward position, representing the heel strike and toe-off, respectively.

After finding those forward coordinate points, they are stored in a table and the timestamp when they happen. The step length from the heel strike is calculated by subtracting one heel strike from the other foot, minus the distance the treadmill has traveled between those timestamps. See also Algorithm 2 in Appendix C for an explanation of the calculations.

The step lengths (SL_r & SL_l) and time differences (Δt_r & Δt_l) were calculated using the following equations:

$$\Delta t_r = \mathrm{t}_l - \mathrm{t}_r \tag{1}$$

$$\Delta t_l = \mathrm{t}_r - \mathrm{t}_l \tag{2}$$

$$SL_r = (\mathrm{HS}_r - \mathrm{HS}_l) - v\Delta t_r \tag{3}$$

$$SL_l = (\mathrm{HS}_l - \mathrm{HS}_r) - v\Delta t_l \tag{4}$$

where:

- t_l is the timestamp of the heel strike on the left foot.
- t_r is the timestamp of the heel strike on the right foot.
- HS_r is the heel strike coordinate of the right foot at timestamp t_r.
- HS_l is the heel strike coordinate of the left foot at timestamp t_l.
- v is the treadmill speed.
- Δt_r is the time interval between successive heel strikes of the right foot.

We employed the step length ratio as a measure of gait symmetry. The ratio (%) between the left step length and the right step length was calculated for each stride to create the step symmetry ratio [15]. The formula is:

$$\text{Step Symmetry Ratio} = \frac{\text{Left Step Length}}{\text{Right Step Length}}$$

Thus, a step length ratio greater than one means that the right step is shorter than the left step and visa versa for values smaller than one.

2) Analyzing the step length data from participants: After calculating all the step lengths from the left and right feet and put them in separate tables, we proceeded to filter the data, removing the outliers or incorrect data points caused by miscommunication with the Vive Base 2.0. We use the 1D median filter from the Python library Scipy to smooth the data. The 1D median filter is commonly employed for noise removal in signals. The 1D median filter will filter the earlier calculated step lengths, to make sure no faulty step lengths are measured. To preserve as much of the original data as possible, we opted for a kernel size of 5 to avoid smoothing out important features.

3) Questionnaires: After the walking trials, participants were asked to fill in questionnaires using Qualtrics. For each questionnaire, the question's scores were reversed if necessary and averaged into a single value per sub-scale. The questionnaires that deviated from the published questions are shown in Appendix B.

To assess their motivation, participants answered 17 questions selected from the well-established Intrinsic Motivation Inventory (IMI) [24] using a seven-point Likert scale, where 1 indicated "not at all true" and 7 indicated "very true." Three IMI sub-scales were selected for their relevance in this study: Interest/Enjoyment, Tension, and Competence.

To assess participants' sense of presence, they responded to 11 questions selected from the well-established Igroup Presence questionnaire (IPQ) [25] using a seven-point Likert scale from 0 to 6. The questions were selected for their relevance to the experiment. This questionnaire consists of three sub-scales: Spatial Presence, Involvement, and Experienced Realism.

To assess their subjective feeling of embodiment, participants responded to nine questions selected and adapted from the well-established questionnaire frequently used in rubber hand illusion studies [21] and adjusted for this application. Participants also responded on a seven-point Likert scale: -3 indicating "strongly disagree" and 3 indicating "strongly agree". The word "rubber hand" was replaced with "virtual body" to fit the context. The sub-scales were: Ownership, Location, and Agency.

F. Statistical analysis

To see whether the data is normally distributed we used the Shapiro-Wilk test for all the following acquired results. The first hypothesis suggests that the distortion will lead to an increase in the step length ratio, indicating a measurable asymmetry in people's gait cycle. To test this hypothesis, we utilized a one-tailed paired t-test. This statistical test is appropriate because it allows us to compare the mean step length ratio of participants after the adaptation phase (at t = 15 minutes) to the mean ratio at the beginning (at t = 0 minutes) when no distortion was present. The one-tailed test is chosen as we anticipate a directional change – an increase in the step length ratio due to the distortion.

To test the second hypothesis, we performed a one-tailed paired t-test between the mean step length ratio at the beginning of the retention period and the end of that period to find out if the step length ratio will decrease over time. Previous work has shown that the step length ratio decreased during the retention period[17].

The third hypothesis examines the relationship between participants' psychological states and gait asymmetry. Specifically, we hypothesized a positive correlation between gait asymmetry and psychological factors (presence, embodiment, and motivation). To test this hypothesis, we used the Pearson correlation coefficient. This statistical test is appropriate for determining the strength and direction of the linear relationship between two continuous variables. In this case, the variables of interest are the difference in step length ratio and the psychological state scores from the participants.

The fourth hypothesis explores the impact of the dual-task paradigm on participants' gait asymmetry, specifically examining how their scores on a distraction task correlate with their gait asymmetry. The performance score for this task is defined by the participant's mean reaction time, with shorter reaction times hypothesized to be correlated with higher gait asymmetry. To test this hypothesis, we used the Pearson correlation coefficient. By incorporating the reaction times into the Pearson test, we aim to determine if the distraction task has a statistically significant impact on the change in step length symmetry. All statistical analyses were performed in Python 3.7 with the packages Matplotlib (3.5.3), Pandas (1.3.5), and SciPy (1.7.3).

III. RESULTS

Right after the baseline period, the step length of every participant was calculated and used for the adaptation experiment. Across all participants, the step lengths are 0.43 (left) and 0.44 meters (right). The median step lengths during the short trial are presented in Table II (Appendix D). We noticed that there was a difference in the median left and right step length across all participants (0.011 meters). This indicates that, on average, the right leg's median step length is slightly longer than the left median step length. In Figure 6, we plot all mean step length ratios during the adaptation period with the mean step length ratio of all participants and the error bar (std $\pm$ 1) (Appendix E). The retention period, after the adaptation period, is highlighted in Figure 3 in green. The results of the questionnaire and mean reaction times from the distraction task are presented in Table I together with the difference in mean step length of the right foot during the adaptation period, so from when the distortion is 30 % minus when distortion was 0%.

A. Step length asymmetry due to VFD in adaptation period

The adaptation period lasted from t = 0 to t = 15 minutes. In this section, we will discuss the results of that period, as seen in Figure 3. After we tested the data for normality (at t = 0, p = 0.925 & at t = 15, p = 0.826) we tested whether the distortion caused an increase in step length ratio for all participants. We performed a one-tailed paired t-test across the adaptation period and found no statistically significant increase in step length ratio between the adaptation period (t-statistic = 1.033, p-value = 0.163). However, when looking at a shorter adaptation period between the t = 0 to t = 6 minutes, we found that the difference in step length ratio was approaching statistical significance (t-statistic = 1.677, p-value = 0.062).

B. Step length asymmetry during the retention period

The retention period lasted from t = 15 to t = 19 minutes. In this section, we will discuss the results of that period. After we tested for normality for the step length ratios (at t = 16, p = 0.304 & at t = 19, p = 0.725), we tested whether the retention period caused any effect on the step length ratio for all participants. The gait symmetry ratio for the retention period is shown in Figure 3 to show what happened after the avatar disappeared and the participant continued to walk for 4 more minutes. The step length ratio of every participant appears to decrease after the avatar disappears. The mean step length ratio decreases during the retention period (t-statistic = -2.842, p-value = 0.009).

C. Correlation between psychological states, distraction task, and gait asymmetry

The scores of all participants for embodiment, motivation, and presence can be found in Table I, as well as the difference in step length ratio during the adaptation period and the mean reaction times of the distraction task. We tested for normality for the psychological states (see Appendix D) in Table III, the table shows that all data was normally distributed (p ¿ 0.05).

We found no statistically significant correlations between the independent variables (motivation, embodiment, presence, and mean reaction time) and the difference in step length ratio during the adaptation period. See also Appendix D for the correlation coefficients and p-values in Table IV. We looked more into the data of motivation: we compared the sub-scales of motivation (competence, enjoyment, and tension) to the gait symmetry ratio during adaptation and those results are presented in Table VI. We also compared the difference of the gait symmetry ratio of the retention period to the psychological states, see also Appendix D Table V. This also resulted in no significant correlations. Lastly, we compared the sub-scales of embodiment (ownership, location, and agency) to the difference in step length symmetry ratio during the retention period, the results are shown in Table VII.

IV. DISCUSSION

A. No significant asymmetry observed in participants' gait cycle during adaptation

We hypothesized that there would be an increase in the gait asymmetry.

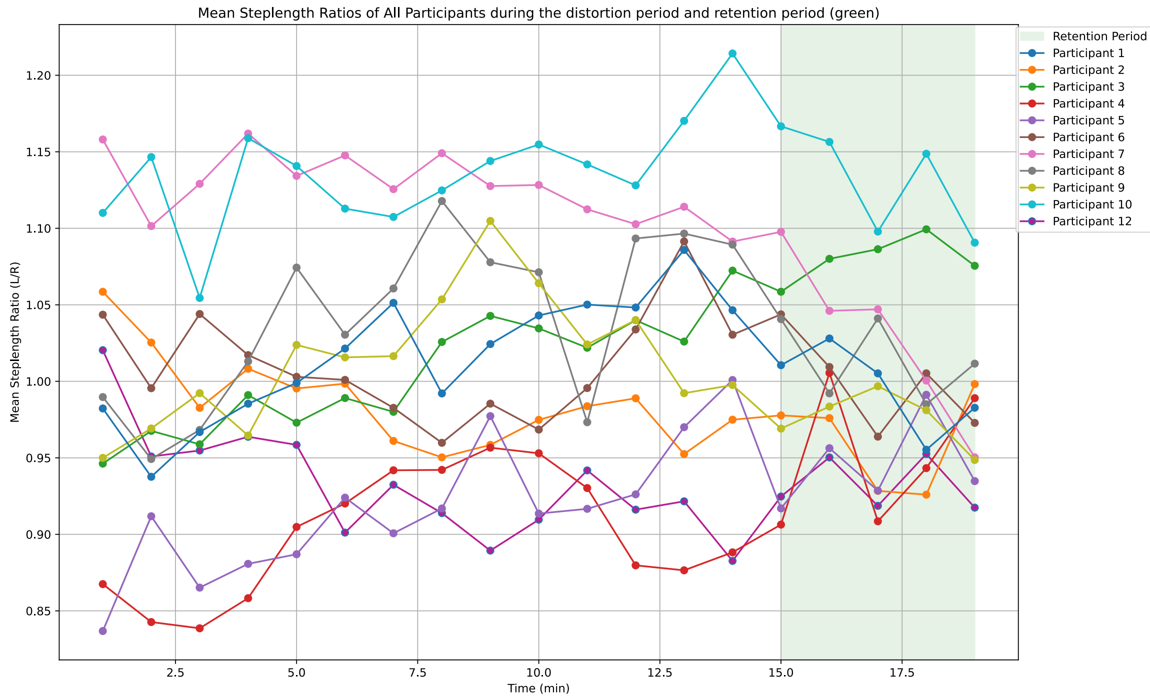

Fig. 3: Mean step length ratios of all participants in one figure from the adaptation period and the retention period when the avatar disappeared (highlighted in green). The mean was calculated over every minute of data.

The VFD was present in the avatar's gait because the mean right step length across all participant's avatars increases during the adaptation phase, see also Figure 7 (Appendix E). This confirms that the VFD was present during experiments, but participants did not appear to adapt to the distortion. The results did not replicate the more promising findings on implicit VFD from earlier studies [17, 15, 6]. This study has shown that using IVR together with VFD is not yet suitable for motor adaptation exercises in gait rehabilitation in its current form. One reason for this might be that the virtual environment was not designed to induce gait asymmetry in the right foot, resulting in no observable change. Other similar studies use the third-person perspective from the paretic side [5] or mirrors in VR to observe the avatar [16]. Implementing these design elements in our virtual environment could potentially address the issue observed in our study.

The high amount of distortion acting on the right foot may have also influenced the results. As seen in the data, between t = 0 and t = 6 minutes, the mean step length ratio approaches almost significant differences ($p = 0.062$). The amount of distortion at t = 6 minutes is 12 %, which is similar to the distortion found in earlier studies [17]. Therefore, it may be beneficial to implement a lower maximum distortion level, ideally within a range of 10% to 14%.

Another possible reason for this result is the neck pain experienced by participants during the adaptation phase. All participants reported neck pain from looking down at their feet while wearing the HMD. During the long trial, they were instructed to keep looking at their feet for the distraction task, which may have negatively impacted the results. It is possible that the neck pain interfered with the adaptation task during the experiment. One study has shown that pain can negatively influence motor learning and motor adaptation for walking tasks [26]. Therefore, neck pain may have affected the results of our study.

Finally, the absence of a control group or a second group with a different condition limits the strength of our conclusions. Inter-subject variability makes it hard to see results on a group level. Other studies have used within-subject experiments where participants tested two or more conditions [15, 17]. This could potentially strengthen the conclusions found within the group.

TABLE I: Participants' averaged scores of motivation, embodiment, and presence with the difference in step length ratio during the adaptation phase (a) and retention period (r). The last column is the mean reaction time from the distraction task from all participants in seconds.

Participant	Embodiment	Motivation	Presence	Diff Ratio (a)	Diff Ratio (r)	reaction time (sec)
1	1.00	3.06	4.09	-0.04	-0.06	0.74
2	1.00	3.24	3.45	-0.08	0.02	0.85
3	-0.22	4.88	3.82	0.11	-0.00	0.81
4	-0.22	3.29	3.82	0.04	-0.02	1.12
5	0.33	3.94	3.45	0.08	-0.02	0.82
6	1.89	3.71	4.18	0.00	-0.04	0.74
7	0.33	4.18	3.27	-0.06	-0.10	0.78
8	0.67	4.12	2.45	0.05	0.02	0.98
9	1.89	3.71	4.55	0.02	-0.03	0.69
10	2.00	3.59	3.82	0.06	-0.07	0.95
12	1.78	2.76	4.27	0.03	-0.05	0.81

B. Psychological states were not correlated with the measured asymmetry during adaptation

We hypothesized that there would be a correlation between the psychological states chosen in this study and gait asymmetry. To test this, we performed a Pearson test on the difference in step length symmetry during the adaptation phase and the scores of the psychological states (motivation, presence, and embodiment). However, we did not find any statistically significant correlations between these predictors and the difference in gait ratio. This indicates that the experimental setup did not effectively optimize the psychological states during the experiments. Future studies could investigate the impact of psychological states on gait symmetry by altering these variables in different groups. For instance, one group could have their sense of presence and embodiment enhanced or reduced by removing the avatar [27] to observe the effects on gait symmetry when VFD is applied This could provide new insight into whether these psychological factors influence the outcomes observed with VFD.

C. Tension sub-score and its potential relationship with gait asymmetry during adaptation

When looking at the correlation scores in Table IV, the motivation score was close to being significant (p = 0.17). We investigated the correlation between motivation and step symmetry, focusing on whether a stronger correlation existed between the sub-scales of motivation and gait symmetry during the adaptation phase. The results from this Pearson test are in Table VI.

None of the sub-scales (competence, enjoyment, and tension) had a statistically significant effect on the gait asymmetry during the adaptation phase. However, we see that the tension sub-scale approaches statistical significance (p = 0.077), suggesting that tension may have a stronger relationship with this VFD experiment than the competence or enjoyment of participants. Future research could investigate this potential relationship further by examining whether increased tension during a task leads to greater gait asymmetry in this VR exercise. This could mean that for example negative points are given for making mistakes or ranking participants at the end of their trial to increase tension.

D. Location sub-score and its potential relationship with after-effects of gait asymmetry

We examined the relationship between the gait symmetry ratio during the retention period and psychological states, as detailed in Appendix D, Table V. Specifically, we looked for correlations between the sub-scales of embodiment to identify any significant relationships. Given our expectation that making the avatar disappear would influence the level of embodiment, we focused on potential correlations between these sub-scales and gait symmetry during the retention phase. The results of the Pearson test are presented in Table VII.

While the sub-scales of embodiment did not show significant correlations with gait symmetry during the retention period, the location sub-scale approached statistical significance (p = 0.052). This suggests that location might have a more substantial relationship with the VFD experiment than either ownership or agency. Location is defined as the sense that the virtual body and one's own body occupy the same space and the perception of causation between seen and felt touches [21]. Notably, this sense of location was distorted during our experiment by the VFD in the adaptation phase and again in the retention phase by removing the avatar from the VE. Future research could further investigate this potential relationship by manipulating the sense of location after the adaptation phase in various experimental setups. This could help determine if embodiment, specifically the sense of location, is a psychological state that influences the mechanism through which we intend to affect gait asymmetry.

E. Mean reaction time during the adaptation period

The reaction times from the participants were high compared to a similar study on reaction times with lights while walking [28]. Participants reported that the treadmill speed was low (2km/h), and it has been proven that when people walk at a slower pace than their preferred pace, their reaction time increases [29]. Lower reaction times could indicate that participants are more attentive to the distraction task, but more research is needed to determine the optimal parameters for individual participants and the optimal reaction time for the distraction task.

F. Future work

Future research may be conducted to see if these design changes could change the gait symmetry in participants using IVR. First of all, future studies should reduce the amount of distortion during the adaptation phase to the values used in earlier studies [6, 15, 17]. Additionally, incorporating mirror feedback could mitigate the neck pain experienced by participants. Placing mirrors at an angle that allows participants to see their feet at eye level could prevent neck pain. Furthermore, explicit instructions were not used during this experiment, since studies seem to lean towards using implicit processes for gait adaptation [12]. As we have discussed in the introduction, Fitts and Posner's model underlines the role of explicit instructions at the beginning of the learning process [9]. We did not test with another group of people during this experiment to achieve our goal during the adaptation phase with explicit instructions. IVR is a relatively new research field for gait adaptation, and maybe a study is needed to answer whether implicit or explicit instructions are more beneficial in showing effects (and after-effects). And lastly, more research needs to focus on the analysis of gait before the adaptation. As seen in the results at the beginning of the adaptation phase: young, healthy participants tended to have asymmetric gait cycles before we applied the distortion, which is expected [30]. However, this may influence the results of the gait adaptation in this study.

V. Conclusion

This study described an experiment using implicit VFD combined with a dual paradigm in Immersive Virtual Reality to alter gait. The main question was whether there is an effect (asymmetry in step length) measured when a person walks in virtual reality with an avatar experiencing a VFD on the step length. We have found no significant change in step length symmetry when gradually increasing the Visual Feedback Distortion. There was, however, an after-effect measured when the distortion was taken out of the experiment. Furthermore, we found no correlation between the step length ratio and the psychological states of motivation, embodiment, and presence during the adaptation phase. However, the results when looking for correlations in sub-scales of motivation and embodiment approached significance. Even though we did not find any statistically significant results, there is still a chance that this method could be suitable to induce gait (a)symmetry in future work because of the results found in previous work. Perhaps implementing new design elements in the VE and applying a lower maximum distortion during the adaptation phase could change the outcome of the results and make this a viable method. Future work should be done to determine if IVR or implicit processes are a suitable method to induce implicit VFD.

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Appendix

Appendix A: Speech VR experiment

Introduction before the first trial:
"You are going to experiment with the VR headset while walking on a treadmill, the total time you will be here is about 45 minutes to an hour. In the virtual world, we are going to calibrate your body to an avatar, who is going to follow your movements in VR. The steps are as follows: you first calibrate while standing on the treadmill, then we turn on the treadmill when you are ready, and then I let the environment move at the same speed as the treadmill. There will be a light game on your feet, where you are asked to turn off the light as quickly as possible. At the end, you take a questionnaire and tell us about the experience."

Instructions for the first trial:
"Walk as you normally would at the relaxed pace set by the treadmill. Try to get used to the Virtual Environment, there is no light game in this short trial."

Instructions for the second trial:
"Walk as you normally would at the relaxed pace set by the treadmill. In this trial, you will see the lights turn on at one or both feet. Please press the trigger of the controller on the same side as the light that is on to turn off the light as fast as possible. If both lights have turned on at some point, press first the trigger of the first ignited light and then the other trigger. Please keep looking at your feet as much as possible. After 15 minutes, the avatar will fade away. You can continue walking, this is the last part of the experiment and this will take 5 minutes."

Appendix B: Questionnaire questions

Motivation (IMI): IMI is split into six subcategories, and we have chosen a shortened version of a 22-item version using interest/enjoyment, perceived competence, and pressure/tension (perceived choice seemed irrelevant for our experiment, there were no "choices" during the task). Interest and enjoyment is the self-report measure of intrinsic motivation. Questions with an underscore are Inverse questions (7- response). We asked the following questions from subcategories:

Interest/Enjoyment

- While I was working on the task I was thinking about how much I enjoyed it.
- I found the task very interesting.
- Doing the task was fun.
- I enjoyed doing the task very much.
- I thought the task was very boring.
- I thought the task was very interesting.
- I would describe the task as very enjoyable.

Competence

- I think I am pretty good at this task.
- I think I did pretty well at this activity, compared to other students.
- I am satisfied with my performance at this task.
- I felt pretty skilled at this task.
- After working at this task for a while, I felt pretty competent.

Tension

- I did not feel at all nervous about doing the task.
- I felt tense while doing the task.
- I felt relaxed while doing the task.
- I was anxious while doing the task.
- I felt pressured while doing the task.

Presence (IPQ): Questions with an underline are inverse questions. Inverse the question by doing 6 - question_response and take the mean of each sub-scale. The main questionnaire was Q5 with 9 questions divided over 3 sub-scales.

Spatial Presence - the sense of being physically present in the VE

- Somehow I felt that the virtual world surrounded me.
- I felt like I was just perceiving pictures.
- I did not feel present in the virtual space.
- I had a sense of acting in the virtual space, rather than operating something from outside.
- I felt present in the virtual space.

Involvement - measuring the attention devoted to the VE and the involvement experienced

- I was not aware of my real environment.
- I still paid attention to the real environment.
- How aware were you of the real world surrounding while navigating in the virtual world? (i.e. sounds, room temperature, other people, etc.)?

Experienced Realism - measuring the subjective experience of realism in the VE

- The virtual world seemed more realistic than the real world.
- How real did the virtual world seem to you?
- How much did your experience in the virtual environment seem consistent with your real world experience?

Embodiment (rubber hand): The paper "What is embodiment? A psychometric approach" investigates the structure of bodily self-consciousness using structured introspective reports of the rubber hand illusion. It employs principal components analysis (PCA) to analyze the subjective experiences of participants who observed a rubber hand stroked either synchronously or asynchronously with their own hand. For this experiment, the rubber hand needs to be replaced with a virtual body.

Ownership - assessing the degree to which participants feel that the virtual body are part of their own body

- . . .it seemed like I was looking directly at myself, rather than at a simulation.
- . . .it seemed like the virtual body began to resemble my real body.
- . . .it seemed like the virtual body belonged to me.
- . . .it seemed like the virtual body was my body.
- . . .it seemed like the virtual body was part of my body.

Location - focusing on the perceived location of the virtual body or objects in relation to the participant's physical body

- . . .it seemed like my body was in the location where the virtual body was.
- . . .it seemed like walking in VR was caused by the Avatar in the virtual body.

Agency - gauging how much control participants feel they have over movements or actions within the virtual environment

- . . .it seemed like I could have moved the virtual body if I had wanted.
- . . .it seemed like I was in control of the virtual body.

Appendix C: Algorithms

Algorithm 1 Distortion logic

```
function UPDATE
    if foot.activeSelf is true and not disable then
        timer ← timer + Time.deltaTime
        if timer > delay then
            if MaxIncrement ≥ 0 and keeptime then
                INCREASEDISTORTION
                Print parentTransform.position.z
                MaxIncrement ← MaxIncrement - 1
                timer ← 0.0
        if MaxIncrement == 0 then
            SETOFFSETTIME
            STOPTIMER
        if not disable then
            time ← time + Time.deltaTime
function INCREASEDISTORTION
    increaseDistortionValue ← AverageSwingSize * 0.02
    newPosition ← parentTransform.position
    newPosition.z ← newPosition.z + increaseDistortionValue
    parentTransform.position ← newPosition
```

Algorithm 2 Calculate step lengths from heelstrike timestamps

```
for i ← 1 to num_steps do
    if merged_timestamps[i, 2] == 1 then
        if index_l > length(heelstrike_z_l) then
            break
        if merged_timestamps[i+1, 2] == 2 then
            if index_r > length(heelstrike_z_r) then
                break
            delta_t_sl ← merged_timestamps[i+1, 1] − merged_timestamps[i, 1]
            SL ← (heelstrike_z_l[index_l] − heelstrike_z_r[index_r])
            SL ← SL − (−v × delta_t_sl)
            left_steplength ← append(left_steplength, SL)
            left_timestamps ← append(left_timestamps, merged_timestamps[i, 1])
            print "Left Step: i = i, index_l = index_l, index_r = index_r, SL = SL"
            index_l ← index_l + 1
    else if merged_timestamps[i, 2] == 2 then    ▷ Right heel strike
        if index_r > length(heelstrike_z_r) then
            break
        if merged_timestamps[i+1, 2] == 1 then    ▷ Next is a left heel strike
            if index_l > length(heelstrike_z_l) then
                break
            delta_t_sl ← merged_timestamps[i+1, 1] − merged_timestamps[i, 1]
            SL ← (heelstrike_z_r[index_r] − heelstrike_z_l[index_l])
            SL ← SL − (−v × delta_t_sl)
            right_steplength ← append(right_steplength, SL)
            right_timestamps ← append(right_timestamps, merged_timestamps[i, 1])
            print "Right Step: i = i, index_l = index_l, index_r = index_r, SL = SL"
            index_r ← index_r + 1
```

A. Appendix D: Tables

Participant	Median_StepLength_Left (m)	Median_StepLength_Right (m)
1	0.46	0.48
2	0.44	0.43
3	0.43	0.41
4	0.39	0.44
5	0.44	0.45
6	0.42	0.46
7	0.48	0.46
8	0.34	0.33
9	0.47	0.53
10	0.48	0.44
12	0.40	0.44

TABLE II: The median step length during the baseline period (where no distortion was present) for each participant.

	Shapiro-Wilk T	**Shapiro-Wil p-value**
Presence	0.936	0.475
Embodiment	0.893	0.150
Motivation	0.977	0.946
Reaction time	0.905	0.215

TABLE III: Shapiro-Wilk Test Results

	Motivation	Presence	Embodiment	Reaction time
Corr. Coefficient	0.445	-0.006	-0.202	0.293
P-Value	0.170	0.987	0.551	0.382

TABLE IV: Results from the Pearson test between the difference in mean step length ratio (adaptation) and the independent variables (motivation, presence, embodiment, and reaction time.

	Motivation	Presence	Embodiment
Corr. Coefficient	0.180	-0.345	-0.287
P-Value	0.596	0.298	0.393

TABLE V: Results from the Pearson test between the difference in mean step length ratio (retention) and the independent variables (motivation, presence, embodiment, and reaction time.

	Competence	Enjoyment	Tension
Corr. Coefficient	0.078	0.304	0.554
P-Value	0.821	0.363	0.077

TABLE VI: Results from the Pearson test between the difference in mean step length ratio (adaptation) and the independent variables of sub-scales in motivation (competence, enjoyment, and tension)

	Ownership	Location	Agency
Corr. Coefficient	-0.464	-0.597	0.343
P-Value	0.151	0.052	0.302

TABLE VII: Results from the Pearson test between the difference in mean step length ratio (retention) and the independent variables of sub-scales in embodiment (ownership, location, and agency).

Appendix E: Figures

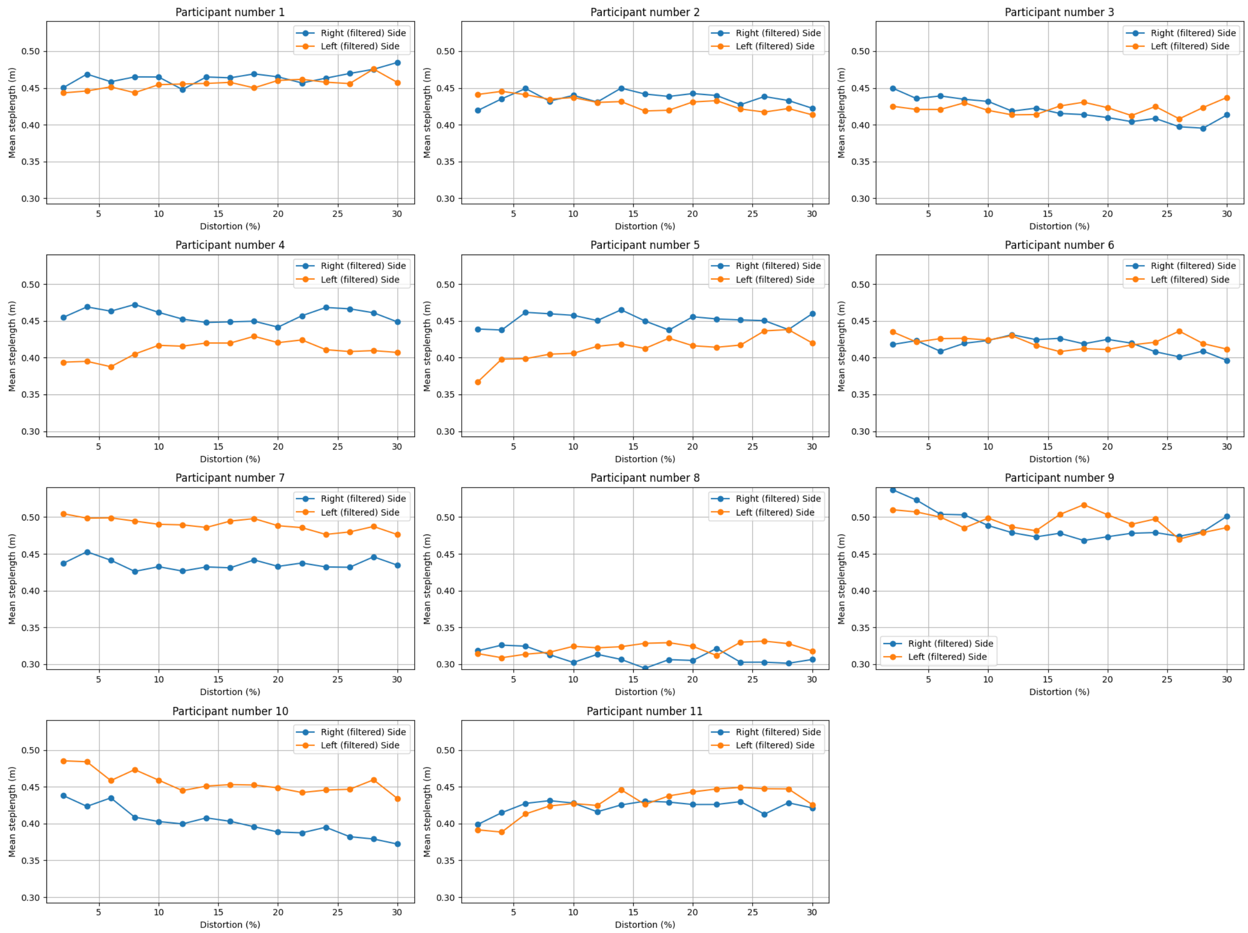

Fig. 4: Right and left step length averages per minute of all participants over distortion levels

Fig. 5: The Step symmetry ratio (%) between the left and right step length over the amount of distortion during the adaptation phase for all participants

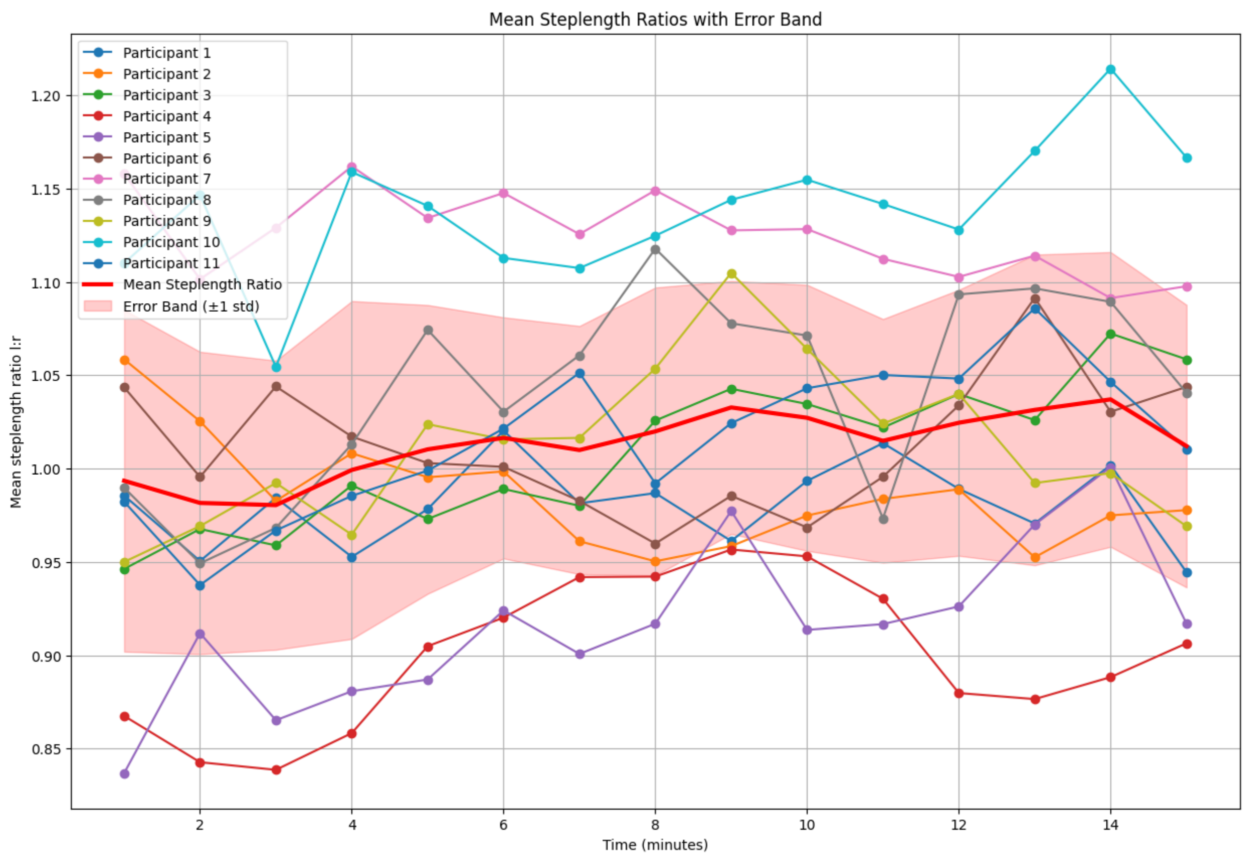

Fig. 6: Mean step length ratios of all participants in one figure: including error bar and the average ratio of all participants (red)

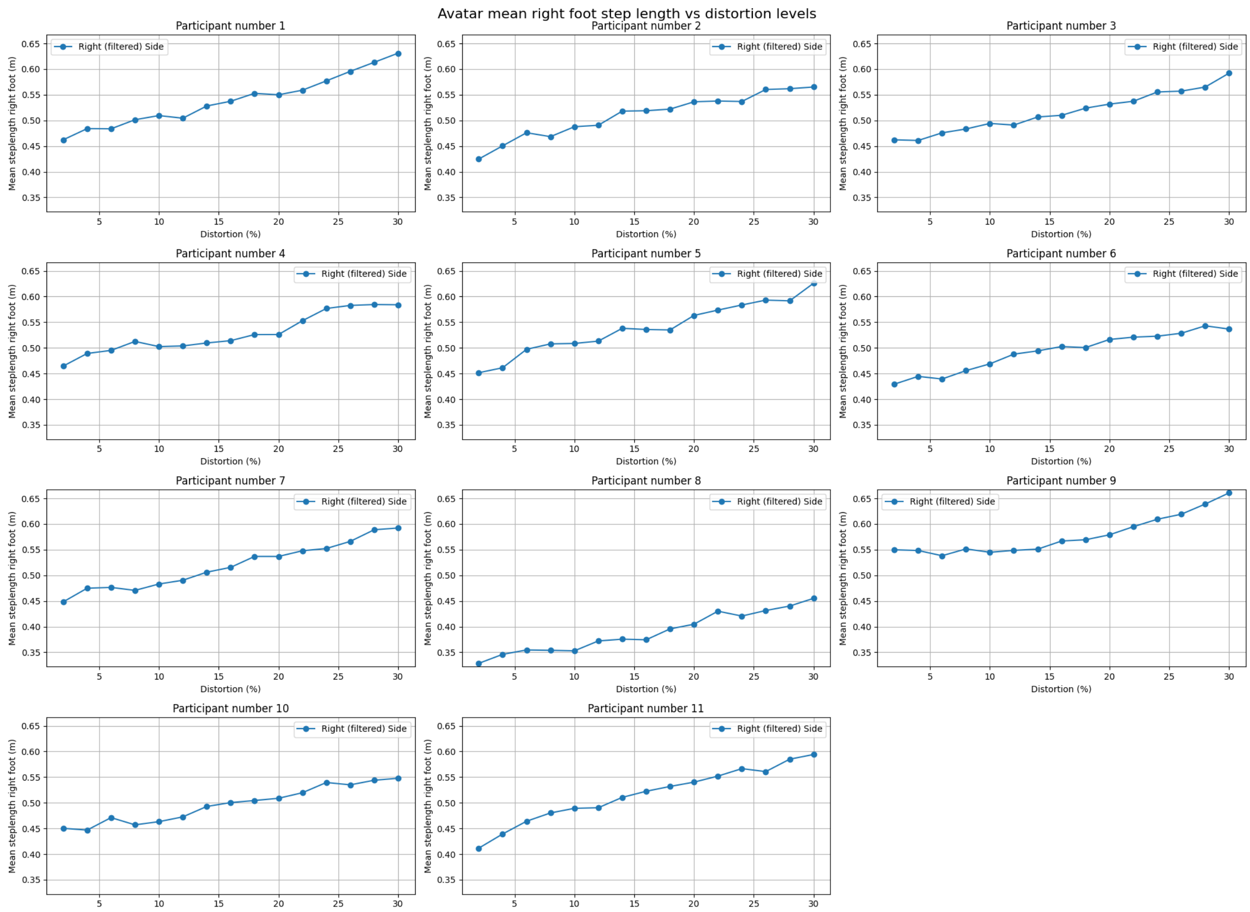

Fig. 7: The mean step length of the right foot, measured from the position of the VR avatar's foot, vs the level of distortion over time.

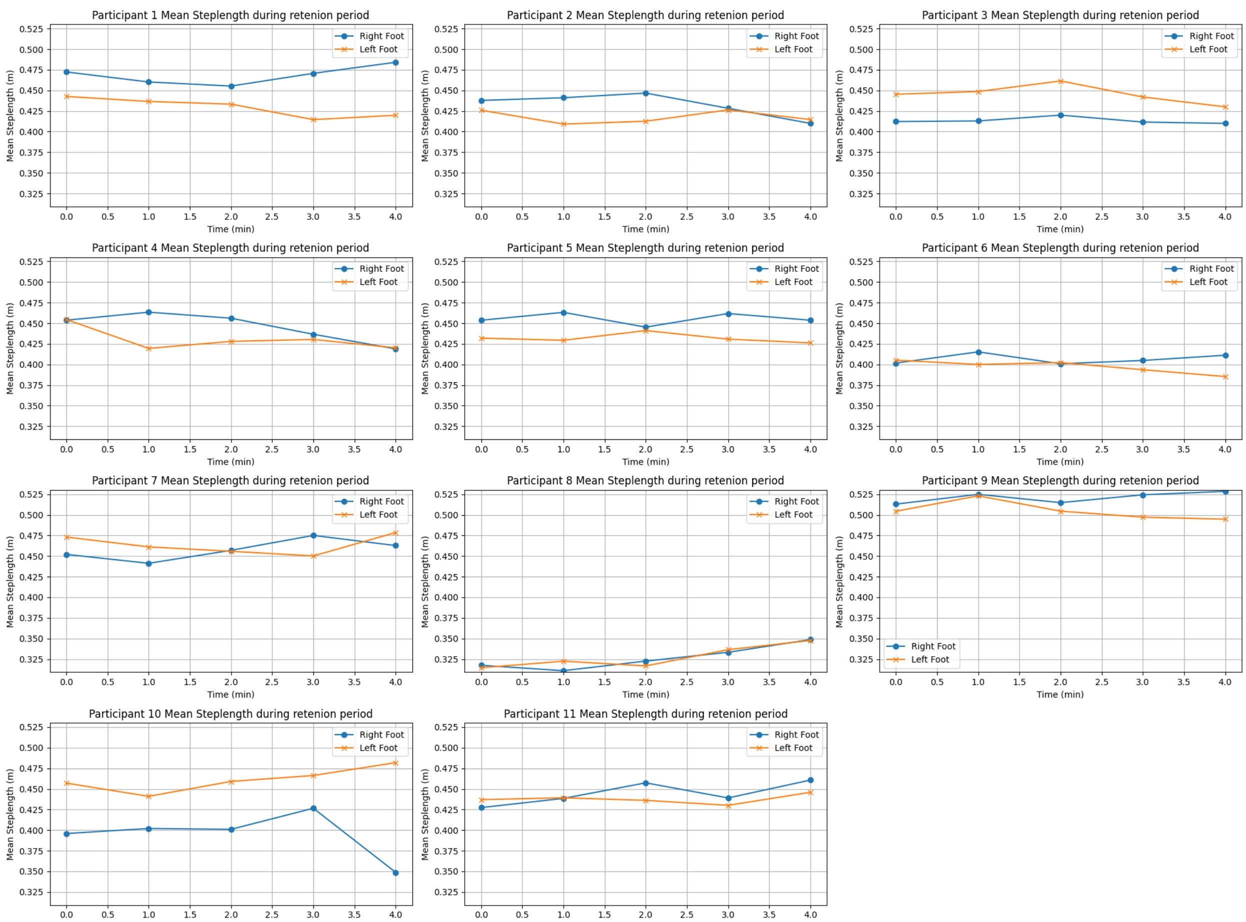

Fig. 8: The mean step length of the right foot and left foot, after the avatar disappeared in the retention period