Visual Disturbances to Avatar Foot Position Increase Step-width Variability in Immersive VR Treadmill Walking

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Visual Disturbances to Avatar Foot Position Increase Step-Width Variability in Immersive VR Treadmill Walking

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***Abstract*— Gait variability, the subtle fluctuations in walking patterns, is crucial for adaptation and motor learning. While existing methods to increase gait variability often rely on force-based perturbations, these can reduce motivation. This study explored if a subtle visual feedback distortion (VFD), applied to a first-person avatar's foot position in an immersive virtual reality environment, could increase gait variability without such a drawback. Twenty healthy adults walked on a treadmill wearing a head-mounted display and motion trackers, performing a stepping task under two conditions: with and without VFD. The VFD introduced a continuously changing, noise-like offset to the displayed foot positions, designed to be minimally noticeable. We quantified gait variability through the standard deviation of step width and step length and collected self-report measures on embodiment, motivation, and simulator sickness. We found that VFD significantly increased step width variability by about 15%, indicating enhanced lateral adaptability. In contrast, step length variability remained unchanged. Participants adjusted their foot placement in the opposite direction of the visual distortion, supporting the idea that proprioceptive recalibration underpinned the observed changes. Notably, this increase in variability occurred without any significant effects on embodiment, motivation, or simulator sickness. These findings suggest that subtle VFD can enhance gait variability—potentially facilitating motor learning and adaptability—while preserving user experience and motivation. Future research should determine whether such VFD-based interventions yield lasting functional improvements and investigate their applicability in rehabilitation contexts, potentially offering a noninvasive, user-friendly approach to promoting healthy gait dynamics.**

***Index Terms*— Visual feedback disturbance, gait, variability, proprioceptive recalibration, virtual reality.**

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I. Introduction

Although healthy gait appears constant, rhythmic, and predictable, it actually comprises subtle, inherent variations known as gait variability [1]. Repeated movements, such as foot placements during walking, are never executed in exactly the same way, exhibiting both temporal and spatial variability [2]. This variability is not merely system noise but a critical feature rooted in neurophysiological processes, enabling us to develop and sustain a broad range of movement strategies [3]. For example, recent evidence suggests that gait variability plays a key role in improving efficiency and robustness in motion control, particularly when adapting to different constraints and environments [4], [5], [6].

While gait variability is important for the flexibility and adaptability of healthy movement, it may also signal challenges within the physiological control system [3], [7]. For instance, gait variability increases with added secondary tasks or environmental constraints [8], [9], [10] and with aging [11] and is often amplified in individuals with certain pathologies [12], [13]. A high level of gait variability could be problematic, as it has been consistently associated with fall risk [14], [15], [16], [17], [18]. Indeed, both excessive and insufficient step width variability have been linked to increased fall risk [19].

In rehabilitation contexts, it is important to realize appropriate mechanisms for influencing gait variability [3], [20]. One way of manipulating variability during gait training is by incorporating disturbances. Several studies have demonstrated that adding force disturbances can increase variability in locomotor tasks, thereby enhancing motor learning and adaptability [21], [22], [23]. For example, pulse-like, random magnitude force disturbances significantly improved motor learning in a simple lower-limb task, outperforming the error amplification method [21]. However, introducing disturbances might decrease participants' motivation if the task becomes too challenging [24], which can limit the effectiveness of motor learning strategies [25]. Moreover, force disturbances may reduce the sense of agency—the feeling of control over one's actions—which might influence skill learning [26], [27]. Finally, force perturbations can induce increased muscle co-contractions [28], which may adversely affect motor performance [29].

An alternative way to introduce variability during training is through Visual Feedback Disturbance (VFD), which could increase variability without the potential drawbacks of force perturbations. For example, disturbances to visual flow—the visually induced illusion of movement representing the relative motion between the user and the virtual environment—within a Virtual Reality (VR) environment have been shown to increase variability in step width, step length, and postural sway [30], [31]. However, disturbances to visual flow may also introduce potential side effects such as simulator sickness-induced nausea and disorientation [32], [33], [34], potentially limiting the feasibility of this approach in training environments [35].

An alternative approach is to manipulate the avatar's movements within VR, i.e., the visual representation of the user's body motions. With affordable off-the-shelf Head-Mounted Displays (HMDs), immersive VR allows users to embody avatars seen from a first-person perspective, where the avatar's limbs are processed as one's own [36], [37]. This embodiment has been shown to be correlated with better motor performance [38] and can be used to influence movement planning and execution [39], [40]. For example, the "self-avatar follower effect" occurs when users unconsciously mimic their avatar's movements when there is a mismatch between their real movements and the avatar's [41], [42], [43]. Critically, this effect may be weakened or broken when there is a persistent offset between the real and virtual bodies that cannot be compensated for by user movement [42]. This effect appears to be modulated by the level of embodiment over the avatar [41], which may be reduced by the VFD itself [42], [44]. Regardless, embodiment often remains robust despite limb position disturbances [45], provided the disturbance does not cause the avatar to reach the joint limits inaccurately [46].

Conversely, VFD can also prompt users to move in the opposite direction of the disturbance, as seen in a study with Parkinson's disease patients who improved their gait symmetry after the virtual foot of their shorter step was visually shifted backward during stepping over targets [47]. Notably, applying the same offset to the target locations failed to induce similar gait changes. Evidence from upper-limb studies suggests that this movement adjustment may arise partly from a rapid, reflex-like visuomotor response to mismatched visual and proprioceptive cues [48], [49]. This sensory mismatch can also lead to proprioceptive recalibration, a slower process whereby the brain updates its internal estimate of limb position [50]. However, these adaptive processes may diminish if a user's sense of embodiment is compromised [51], highlighting the importance of designing VFDs that minimally disrupt embodiment. By leveraging these effects through manipulations of the avatar's movements, we might promote gait variability.

In the current study, we aimed to evaluate the potential of using VFD applied to the participant's virtual feet to increase movement variability during treadmill walking. The VFD introduced a subtle visual offset in the horizontal plane of the foot position relative to the tracked real foot position. This offset followed a noise-like function that updates during the swing phase but is held constant during the stance phase. A key aspect of our VFD design is that the disturbance is intended to be minimally noticeable. We aimed for this because an overtly noticeable disturbance may reduce embodiment and diminish the potential effect on variability [41], [51]. To leverage the body's natural mechanisms for adapting to sensory discrepancies, we implemented a target stepping task in which targets appeared every 10 s to 15 s, providing a clear indicator of the error between the planned and observed foot placement.

Our primary research question is: Can we increase gait variability using VFD during treadmill walking without negatively impacting participants' motivation, embodiment, and simulator sickness? We hypothesize that introducing the VFD will increase gait variability (H1). Additionally, we expect that the effect of the VFD on gait variability will be modulated by the level of embodiment, as measured by the Virtual Embodiment Questionnaire (VEQ) [52]; specifically, we anticipate a greater increase in gait variability with higher VEQ scores (H2). We also hypothesize that the VFD will potentially reduce the level of embodiment (VEQ) and motivation (measured through the Intrinsic Motivation Inventory [IMI] [53]), and increase scores in the Simulator Sickness Questionnaire (SSQ) [32] scores (H3). Finally, we hypothesize that participants will respond to the visual distortion by adjusting their foot placement in the opposite direction (H4) as a compensatory movement adjustment to the mismatched visual feedback [47].

II. Methods

A. Participants

Twenty healthy participants participated in this study (5 female, 15 male), with a mean age of 24.80 years ($SD = 2.82$). Five more participants were initially recruited but later excluded because their data were found to show frequent tracker disconnections. This resulted in unreliable step detection and may have negatively impacted the overall user experience. The study was approved by the Human Research Ethics Committee of the Delft University of Technology (TU Delft, approval number: 4203) and conducted in compliance with the Declaration of Helsinki.

B. Setup

Participants walked on a treadmill while immersed in a virtual environment displayed by an HTC Vive Pro Eye (HTC Corporation, Taiwan). Limb movements were recorded by five motion trackers (HTC Vive 3.0 trackers, HTC Corporation, Taiwan): one on the front of the waist (at the iliac crest level), two on the midfoot of each foot, and two on the back of each hand (see Fig. 1a).

Participants also wore a safety harness (see Fig. 1a). The safety harness is part of a bodyweight support system and was used to mitigate the risk of falls without actively bearing

Fig. 1. (a) Participant wearing the experimental setup, including: 1) three treadmill trackers; 2) foot trackers; 3) pelvis tracker; 4) hand trackers; 5) head-mounted display; and 6) safety harness. (b) Male avatar in the virtual environment showing: I) stepping target example; II) score popup; III) treadmill surface; and IV) virtual environment coordinate system (not visible to participant). (c) Illustration of steps relative to the step onto the target that we removed from the analysis, as well as Unity's reference frame's x (right), y (up), and z (forward) directions.

any weight. The treadmill and safety harness are part of a modified Lokomat® (Hocoma AG, Switzerland). To align the virtual environment (shown in Fig. 1b) with the treadmill, we mounted three HTC Vive 3.0 trackers onto the treadmill. We positioned four lighthouses around the treadmill. The experiment was conducted on a Windows 10 (Microsoft, USA) machine equipped with an NVIDIA GeForce RTX 2080 Ti GPU, 32 GB of DIMM DDR4 memory, and an Intel Core I7 4.20 GHz 4-core processor (Intel, USA).

We built the virtual environment in the Unity Game Engine (version 2021.3.15f1, Unity Technologies, USA), which we designed to resemble a long and straight natural valley for participants to walk through. We configured the environment to run at a minimum frame rate of 90 Hz, matching the HMD's refresh rate to ensure smooth visuals by minimizing lag or stuttering in the movements in the virtual environment. We collected all data within Unity using the Unity Experimental Framework [54]. Position and orientation data of the trackers were recorded at a frame rate fixed at 90 Hz. Custom loggers were used to record target stepping results and timestamps (Section II-C). Questionnaire data were collected using the VR Questionnaire Toolkit [55].

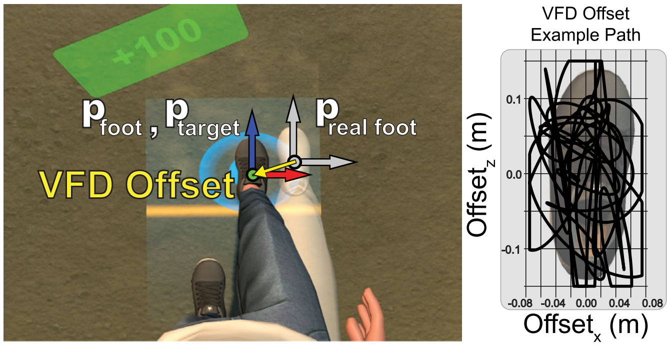
In the virtual environment, a blue, semitransparent rectangle represented the treadmill surface, matching the treadmill's size and position, as seen in Fig. 1b. This representation helped participants orient themselves and reduce the risk of stepping off the treadmill accidentally. A User Datagram Protocol (UDP) connection continuously synchronized the participant's forward movement in the virtual environment with the constant speed of the treadmill belt. The coordinate frame is shown in Fig. 1b, indicating the origin of the virtual environment and direction of forward movement (z-axis), sideways movement (x-axis), and upward movement (y-axis) as defined in Unity.

To represent the virtual body, we obtained male and female avatars via Ready Player Me (https://readyplayer.me/, 2023). To calibrate the avatar, we matched the avatar's gender, height, and limb length to the participant's. The avatar's height was automatically estimated by matching the height of the avatar's eyes to the position of the HMD. We manually scaled the limbs by asking the participant to stretch their arms and legs fully, during which we scaled the virtual limbs until they could reach the tracked positions without the virtual limbs bending. The avatar's limbs moved according to positional and orientation data from the HMD and the waist, feet, and hands trackers. We automatically estimated the offsets between the trackers and the avatar's tracked positions using the package FinalIK (version 2.3, Rootmotion, U.S.). After this, we manually fine-tuned them in the Unity editor to ensure the avatar's pose accurately reflected the participant's. FinalIK was also responsible for estimating the positions of the untracked body parts using inverse kinematics. Due to tracking inaccuracies and body measurement mismatches, the avatar did not always perfectly align with the participant's body. To minimize the impact on the task and embodiment, we prioritized foot positions for precise tracking of the virtual feet and legs and assigned medium priority to the hips. We set a lower priority to other body parts that were less visible and less critical for the task (arms, shoulders, chest, and head). The virtual environment and avatar are shown in Fig. 1b.

C. The Stepping Task

We introduced a stepping task that required participants to precisely place their feet on visual targets. Mirroring previous work [47], we used visual targets in the stepping task that conveyed the error between the planned and observed foot placement, which we expected would facilitate proprioceptive recalibration. Additionally, this encouraged participants to pay attention to the position of their virtual feet. Participants were instructed to walk on the treadmill as they normally would while maintaining focus on the position of their virtual feet. As they walked, blue, circular targets (radius of 0.2 m) would appear pseudo-randomly ahead of them on the ground of the virtual environment. Participants were asked to step onto these targets, aiming to place the center of their foot as close to the center of each target as possible.

Targets appeared pseudo-randomly every 10 s to 15 s and between 1.0 m to 1.5 m ahead along the positive z-axis, based on pilot testing to ensure participants would notice targets without overly disrupting their gait patterns. This positioning balanced three factors: reducing disruption to gait by showing targets late enough to trigger only brief preparatory adjustments, allowing sufficient time to react, and encouraging participants to look near their feet. Because steps on and around targets were excluded from the variability analysis, we also set this target frequency to preserve enough untargeted steps. The target position did not depend on treadmill speed or participant height. In addition, targets were placed randomly within 0.3 m to the left or right of the treadmill's center (x-axis). This lateral variation provided enough offset to challenge participants without requiring overly large gait adjustments and without risking them stepping off the treadmill, even under maximum visual disturbance. We added these randomized aspects to make the task more unpredictable, keeping participants focused on the task.



(a) (b)

Fig. 2. (a) First-person perspective of the participant during the experiment with added annotations to illustrate the visual feedback disturbance (VFD). The white, semitransparent avatar leg and shoe represent the real foot position, and the colored versions represent the displayed avatar position. During the experiment, only the colored avatar was shown. The disturbance was applied only in the x, z-plane. Here, $\mathbf{p}_{\text{real foot}}$ represents the center of the real foot, $\mathbf{p}_{\text{foot}}$ represents the center of the virtual foot after being displaced by the VFD with the **VFD Offset**, and $\mathbf{p}_{\text{target}}$ represents the target position (here, coinciding with $\mathbf{p}_{\text{foot}}$). (b) An example trajectory of the VFD offset for one three-minute walk test.

A 'target step,' defined as a step registered as being taken onto a target, was detected when the distance between the center of the foot and the center of the target was less than 0.2 m for at least 0.1 s. We added this time threshold to ensure participants completed their foot placement, preventing premature step detection. Participants received feedback on their stepping accuracy immediately after a target step was detected through a score pop-up (illustrated in Fig. 2a). The score was displayed in a window next to each target and was calculated using the following equation:

$$\text{Score} = 10 + 90 \cdot \left(1 - \frac{\|\mathbf{p}_{\text{target}} - \mathbf{p}_{\text{foot}}\|}{0.2}\right), \quad (1)$$

where $\mathbf{p}_{\text{target}}$ and $\mathbf{p}_{\text{foot}}$ denote the horizontal positions (in the x, z-plane) of the target's center and the avatar's foot's center (as shown in Fig. 2a), respectively. The constant 0.2 represents the radius of the target, allowing the score to vary between 10 points to 100 points on step accuracy. To motivate participants to continue performing the task, we set a minimum score of 10 points, awarded when the distance between the foot and the target equals the target's radius. After the score appeared, a 0.1 s animation was played to confirm that the step was registered, i.e., the target gradually moved upward in the y-direction by 0.1 m while fading to full transparency.

D. Visual Feedback Disturbance

We implemented the visual feedback disturbance as a noise-like, unpredictable offset on the avatar's foot position in the horizontal plane (x, z-plane), as illustrated in Fig. 2. The visual disturbance was designed to be minimally noticeable to reduce any impact on participants' sense of embodiment and motivation. To achieve this, the offset changed only when the foot was at least 2 cm above the floor. Below this level, the offset remained constant to avoid the unnatural appearance of the feet 'sliding' while on the ground. The threshold was chosen to exceed tracking noise while allowing enough range for the offset to change once the foot was lifted.

Each foot's disturbance offset was based on a multi-sine signal, which allowed for a continuous signal with controlled characteristics. The multi-sine signal comprised 100 sinusoids with frequencies evenly distributed between 0.01 Hz to 0.3 Hz, chosen to ensure that the offset could vary subtly within a single step and shift by a larger distance over several steps. This frequency range was determined through iterative pilot testing to balance subtle variability and minimal perceptibility. The multi-sine signal $m(t)$ is defined as:

$$m(t) = \sum_{i=1}^{100} A_i \sin(2\pi f_i t + \varphi_i), \quad (2)$$

where $A_i \in [0.5, 1.0]$ is the amplitude, $f_i \in [0.01, 0.3]$ Hz the frequency, and $\varphi_i \in [0, 2\pi)$ rad the phase of the i-th sinusoid, randomly assigned by the UnityEngine.Random class. Upon initializing the virtual environment, this class was assigned a unique seed based on the system time to ensure the signal differed for every participant.

The sum of randomly generated sinusoids could result in unpredictable, large, extreme values, potentially making the disturbance more noticeable. To mitigate this, we took additional steps to guarantee that the multi-sine signal maintained a consistent and predictable range of values. We first calculated the variance σ^2 by summing the squared amplitudes of its components and dividing by two:

$$\sigma^2 = \frac{1}{2} \sum_{i=1}^{100} A_i^2. \quad (3)$$

We then divided the signal by twice this variance and clamped it between 0 and 1 to ensure that the amplitude of the visual disturbance remained bounded.

The resulting scaled and clamped multi-sine signal was further scaled to the desired maximum magnitude of the offset distance between the real and virtual feet, namely, 0.15 m in the z-direction and 0.075 m in the x-direction. We carefully selected the maximum magnitude through pilot tests to determine the largest offset that was still hardly noticeable to users and did not result in the avatar reaching its joint limits during natural gait, which could compromise the sense of embodiment [46]. Note that the maximum magnitude in the x-direction was smaller than that in the z-direction to mitigate the chance of participants accidentally stepping off the treadmill belt. The supplementary materials include the code for generating and applying the multi-sine signal in Unity.

E. Experimental Protocol

The experimental protocol is summarized in Fig. 3. We first obtained the participants' informed consent and then collected basic demographic information (age, VR experience, level of education, and whether they were sensitive to motion sickness; see Section III-A). Next, we briefed them on the overall objective of the experiment and the task of walking naturally on the treadmill through a virtual environment. After this briefing, five trackers were attached to the participant (see

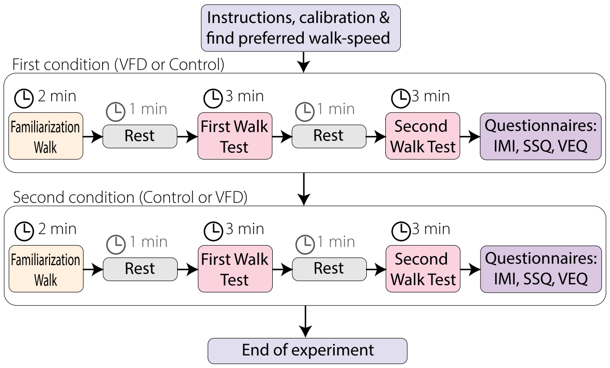


Fig. 3. Overview of the experimental protocol, which consists of two conditions: Visual Feedback Distortion (VFD) and Control. Each condition includes a familiarization walk, rest periods, two walk tests, and questionnaire assessments. The questionnaires used are the Intrinsic Motivation Inventory [53], the Virtual Embodiment Questionnaire [52], and the Simulator Sickness Questionnaire [32].

Fig. 1a), and they put on the safety harness and head-mounted display. When the participant was prepared and able to view the virtual environment, the experimenter performed a brief, one-time calibration procedure to adjust the avatar as well as the position and orientation of the virtual environment (further described in Section II-B). After calibration, we used the height of the foot trackers while standing still to define the floor height.

Once the calibration was completed, we turned on the treadmill at an initial speed of $1.0\,\mathrm{km\,h^{-1}}$. Participants were instructed to ask the experimenter to increase or decrease the treadmill speed until they found a walking speed that allowed them to walk naturally and comfortably through the virtual environment. Letting participants choose their comfortable walking speed is important because self-selected speed minimizes natural gait variability, making it easier to detect any changes in the movement variability introduced by the visual feedback distortion [56]. The selected speed was then used for the rest of the experiment.

Participants were then briefed about the objective of the stepping task (described in Section II-C) and were informed they would complete two blocks of walking tasks sequentially. The exact instructions we gave the participants can be found in the supplementary material. To reduce the initial stabilization period of gait variability, each block started with a two-minute familiarization period, during which participants practiced walking in the virtual environment and performing the target stepping task without visual disturbances. After the familiarization period, participants performed two consecutive three-minute walk tests under the same condition, either with visual feedback disturbances (VFD) or without (Control). Half of the participants performed the first experimental block with the VFD condition, while the other half started with the control condition. Before each walking test, the treadmill accelerated at a rate of $0.25\,\mathrm{m\,s^{-2}}$, and the three-minute task began only after the treadmill reached the participant's self-selected target speed. This transition time was not included in the analysis.

Between the familiarization period and walk tests, participants took a one-minute standing break, during which they were instructed to stretch their necks to reduce strain. After the second walk test, participants removed the HMD and answered three questionnaires on motivation, embodiment, and simulator sickness (see Section II-G). Participants then put the HMD back on and performed a second block with the same sequence (familiarization and two walk tests) with the alternate condition, ending again with the three questionnaires. The whole experiment, including the setup and questionnaires, had an approximate duration of 60 minutes.

F. Data Processing

We detected steps in the virtual environment using a coordinate-based algorithm validated for treadmill walking [57]. We began by determining each foot's position relative to the hip tracker along the z-axis. We then processed this relative position through a zero-phase 4th-order low-pass Butterworth filter with a cutoff frequency of 5 Hz to reduce artifacts caused by noise or brief tracker loss, which could otherwise result in incorrect step detection. Once filtered, we identified the local maxima of the relative position signal, corresponding to the timestamps of heel strikes. These heel strike timestamps were further refined by identifying the first frame in which the velocity of the foot in the x, y-plane fell below $0.1\,\mathrm{m\,s^{-1}}$. Because our goal was to evaluate variability arising from the VFD, we excluded the steps that were likely influenced by stepping onto the targets, i.e., the two heel strikes immediately preceding a target, the step onto the target, and the subsequent three steps (see Fig. 1c for an illustration).

Because our step detection relied solely on tracker position data, brief tracking losses or noise in the data sometimes led to incorrect detections or missed steps. To address this, we applied manual outlier detection and filtering using an interactive graphical user interface built into our analysis interface (explained in more detail in the supplementary materials). This tool allowed for the selection of erroneous heel strikes based on the x and corrected z-positions (z_{corr}), calculated as:

$$z_{\text{corr}} = z + (\text{time elapsed in test} \cdot \text{treadmill speed}). \quad (4)$$

Using this method, we identified and removed 382 erroneously detected steps, enhancing the accuracy of our dataset for further analysis. On average, participants took 256.34 steps ($SD = 23.56$) during each three-minute walk test. Of these, we removed 81.97 steps ($SD = 2.87$) as target-related steps and 4.78 steps ($SD = 3.56$) as manually selected outliers, leaving an average of 169.65 steps ($SD = 24.38$) per walk test for our analysis.

G. Outcome Metrics

Gait variability was assessed through foot placement measurements, specifically focusing on two key variables: step width and step length. Step width was calculated as the absolute distance between the consecutive heel strike positions in the x direction. Step length was calculated as the difference between the corrected z-positions (z_{corr}) of the consecutive heel strikes. The variability of each metric for each walk test and each foot was calculated by determining the standard deviation of all steps included after filtering. Since each condition block included two walk tests, and each leg was analyzed separately, this resulted in four values per participant per condition. The variability of the left and right heel strikes was separated to prevent gait asymmetry from inflating overall variability, as each side might have low variability individually but appear highly variable when combined [58].

Embodiment was evaluated using the Virtual Embodiment Questionnaire (VEQ) [52]. For this study, we used the complete questionnaire, comprising three categories: body ownership, agency, and sensation of change in the body. Body ownership refers to how much participants felt the avatar's body was theirs. Agency reflects how much they felt like they were controlling the virtual body. The sensation of change assesses whether participants felt their bodies had changed during the virtual experience. Each question was rated on a 7-point Likert scale (1: strongly disagree, 7: strongly agree).

Motivation was assessed using the Intrinsic Motivation Inventory (IMI) [53]. We selected four questions from three categories of the IMI: interest/enjoyment, perceived competence, and effort. Interest/enjoyment is the primary self-report measure of intrinsic motivation, indicating participants' interest in and enjoyment in performing the task. Perceived competence reflects participants' self-evaluation of their performance. Finally, effort assesses how much effort participants felt they invested in the task. Like the VEQ, responses were rated on a 7-point Likert scale. The questions we selected from the IMI can be found in the supplementary material.

Finally, *simulator sickness* was measured using the Simulator Sickness Questionnaire (SSQ) [32], a widely used 16-item survey assessing symptoms like nausea, dizziness, headache, and eye strain on a 4-point scale (0: none, 3: severe). Final SSQ scores were calculated according to the formula detailed in the original publication [32].

For completeness, we examined participants' performance on the target stepping task. In particular, we evaluated the stepping accuracy, defined as the mean distance from the virtual foot's center to the target's center for each step taken onto the targets. Statistical analysis and results on participants' performance can be found in the supplementary material.

H. Statistical Analysis

We used linear mixed models (LMMs) to analyze the effects of the VFD on gait variability (hypotheses H1 and H2), with step length and step width variability as dependent variables. Final models were obtained through a stepwise comparison between models of different complexity that included potential fixed effects (e.g., treadmill speed) using the Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) to prevent overfitting and ensure stability. The final model included the fixed effects: (i) *Condition* (VFD vs. Control); (ii) the *Starting Condition* (whether participants experienced the VFD or control condition first) to account for any order effects; (iii) the *Test Number Within Condition*, coded as an ordered factor (first or second walk test in a block), to examine potential changes over time within each condition; and (iv) the *Virtual Embodiment Questionnaire (VEQ) score*. To improve model interpretability and reduce potential multicollinearity, we standardized the VEQ scores by subtracting the mean and dividing by the standard deviation.

We included interactions between *Condition* and *Starting Condition*, and between *Condition* and the standardized *VEQ score*, to assess whether the effect of the VFD on gait variability depended on the starting condition or the level of embodiment (H2), respectively. Participant ID was specified as a random effect to account for individual differences in baseline variability. Categorical and ordinal variables were handled using treatment coding, with the control condition serving as the reference level for the *Condition* variable and the first condition and first walk test as the reference level for the *Starting Condition* and *Test Number Within Condition* variables, respectively.

The model we used for the analysis of step length and step width variability was:

$$\begin{aligned}&\text{Variability}\\&\quad\sim \text{Condition} \times (\text{Starting Condition} + \text{VEQ}_{\text{standardized}})\\&\qquad + \text{Test Nr. Within Condition} + (1|\text{Participant}). \end{aligned} \tag{5}$$

To rule out the potential effect that the relatively short duration of the walk tests might have on the stabilization of the variability, we performed additional LMM analysis. Specifically, we segmented each three-minute test into six intervals of 30 seconds each to confirm that step-width and step-length variability did not change over these intervals. The detailed statistical analysis and results can be found in the supplemental materials.

To test H3, i.e., if VFD reduces the level of embodiment (VEQ) and motivation (IMI) and increases scores in the Simulator Sickness Questionnaire (SSQ), we employed an LMM with fixed effects *Condition* (VFD vs. Control), *Starting Condition*, and their interaction. The participant ID was included as a random effect.

The model we used for the questionnaire data was:

$$\begin{aligned}&\text{Questionnaire Score}\\&\quad\sim \text{Condition} \times \text{Starting Condition} + (1|\text{Participant}). \end{aligned} \tag{6}$$

To test our hypothesis that participants would adjust their foot placement in the opposite direction of the visual distortion due to proprioceptive recalibration (H4), we employed an LMM with centered heel strike location in the x- and z-directions as the dependent variables (Centered Heel strike$_{x,z}$). The data were centered by subtracting the mean heel strike position of all steps for each foot for each walk test of each participant. We included as fixed effects the visual offsets in both directions at heel strike (Offset$_x$ and Offset$_z$) and their interaction (Offset$_x$ × Offset$_z$). Including both Offset$_x$ and Offset$_z$ as fixed effects allowed us to examine whether visual distortions in one axis influence foot placement in that specific direction. By adding the interaction term (Offset$_x$ × Offset$_z$), we aimed to investigate potential cross-axis effects. We also included the *Starting Condition* and *Test Number Within Condition* as fixed effects. The participant ID was included as a random effect.

Only steps from the VFD condition were included in the analysis for H4, as this was the only condition relevant for addressing the hypothesis. Additionally, data from one participant were excluded from this analysis due to a recording error with the offset magnitude during their session.

The model we used for the analysis of heel strike location in both x- and z-directions was:

$$\text{Centered Heel strike}_{x,z} \sim \text{Offset}_x \times \text{Offset}_z + \text{Starting Condition} + \text{Test Nr. Within Condition} + (1|\text{Participant}). \quad (7)$$

We checked for the normality of residuals through visual inspection of the QQ plots and assessed homoscedasticity and linearity by visual inspection of the residuals against the fitted values. Collinearity among fixed effects was assessed using Variance Inflation Factors (VIF), with all values falling below the commonly accepted threshold of 5, indicating no significant multicollinearity. We applied the Bonferroni correction for multiple comparisons and reported effect sizes using Cohen's d. Where significant interactions were found, post-hoc pairwise comparisons were conducted to explore the nature of the effects further. The significance level was set at $\alpha = 0.05$.

All statistical analyses were performed using R (version 4.4.0). We utilized the `lme4` package (version 1.1.35.3) for the linear mixed models and `ggplot2` (version 3.5.1) for data visualization. Detailed information on the data analysis, including the dataset, the complete analysis code, and the instructions, is provided in the supplementary materials.

III. Results

A. Participants

Participants selected a comfortable treadmill walking speed, with a mean speed of $0.71\,\text{m}\,\text{s}^{-1}$ ($SD = 0.13\,\text{m}\,\text{s}^{-1}$). They had varying levels of experience with VR headsets: nine participants reported approximately 10 h of use, three participants reported around 100 h, one participant reported more than 100 h, and seven participants had no prior experience. Regarding educational background, eight participants reported secondary education as their highest level, whereas 12 participants had higher levels of education. Additionally, six participants reported sensitivity to motion sickness.

B. Influence of VFD on Gait Variability

For step width variability, we found significant main effects of condition ($\beta = 0.0042$, SE = 0.0008, $t(144.76) = 5.28$, $p < 0.001$, $d = 1.33$) and VEQ total score ($\beta = 0.0024$, $SE = 0.0008$, $t(156.46) = 3.25$, $p = 0.010$, $d = 0.77$); see Fig. 4 and Table. I. Specifically, participants exhibited significantly higher step width variability when walking with VFD than without it. Higher VEQ scores were also associated with increased step width variability across conditions.

We also found a significant interaction between condition and starting condition ($\beta = -0.0031$, $SE = 0.0011$, $t(141.89) = -2.89$, $p = 0.032$, $d = -0.98$), indicating that the effect of visual distortion on step width variability depended on whether participants started with the control or the VFD condition. Post-hoc pairwise comparisons revealed that significant effects were observed only for participants who transitioned from Control to VFD conditions ($\beta = -0.0042$, $SE = 0.0008$, $t(150.02) = -5.1709$, $p < 0.001$).

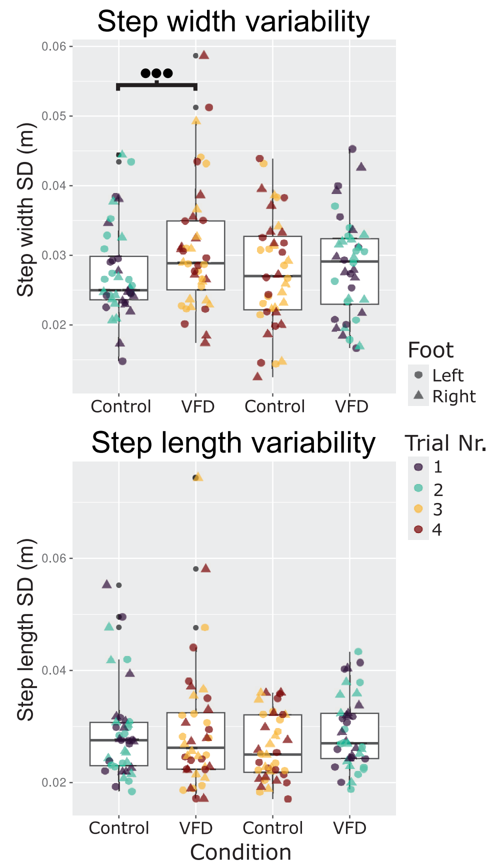


Fig. 4. Comparison of step variability by starting condition and condition. The top plot shows step width variability, the bottom shows step length variability. The significant differences in step width variability ($p < 0.001$) are marked by ···. Black dots next to individual data points denote values exceeding 1.5 times the interquartile range.

In contrast, no significant main or interaction effects were observed for step length variability, as shown in Fig. 4. Detailed statistical results for the post-hoc analysis of the step width variability and the LMM analysis of the step length variability are provided in the supplementary material.

C. Effect of VFD on Questionnaire Scores

The total scores of the three questionnaires (see Section II-G) are shown in Fig. 5. Statistical analysis revealed no significant effects of VFD on any of the questionnaire scores, nor any significant effects of the starting condition or interaction effects between condition and starting condition. We provided detailed statistical results in the supplementary material.

D. Effect of VFD on Heel Strike Location

To test our hypothesis that participants would adjust their foot placement in the opposite direction of the visual distortion (H4), we conducted LMM with both the centered mediolateral (x) and centered anteroposterior (z) components of the heel strike position as dependent variables. The visualization of this analysis can be found in the supplemental materials.

For the centered heel strike x-position, the offset magnitude in the x-direction had a significant negative effect ($\beta = -0.1561$, $t(9845.00) = -19.18$, $p < 0.0001$, $d = -5.31$),

TABLE I

RESULTS FROM THE LINEAR MIXED MODEL ON STEP WIDTH VARIABILITY. SE = STANDARD ERROR, DF = DEGREES OF FREEDOM, EFFECT SIZE IS DETERMINED BY COHEN'S d, p-VALUES ARE BONFERRONI CORRECTED. p-VALUES IN BOLD INDICATE STATISTICAL SIGNIFICANCE (I.E., $p < 0.05$). VEQ VALUES WERE CENTERED AND SCALED BEFORE INCLUDING THEM IN THE LMM

Effect	Estimate	SE	df	t-value	Effect size	p
(Intercept)	0.0272	0.0023	20.97	12.02	8.587	**0.000**
Condition	0.0042	0.0008	144.76	5.28	1.328	**0.000**
Starting condition	-0.0001	0.0032	20.98	-0.03	-0.030	1.000
$\text{VEQ}_{\text{standardized}}$	0.0024	0.0008	156.46	3.25	0.773	**0.010**
Test number within condition	0.0008	0.0004	139.92	2.17	0.243	0.223
Condition : Starting condition	-0.0031	0.0011	141.89	-2.89	-0.977	**0.032**
Condition : $\text{VEQ}_{\text{standardized}}$	-0.0017	0.0006	143.14	-2.69	-0.534	0.056

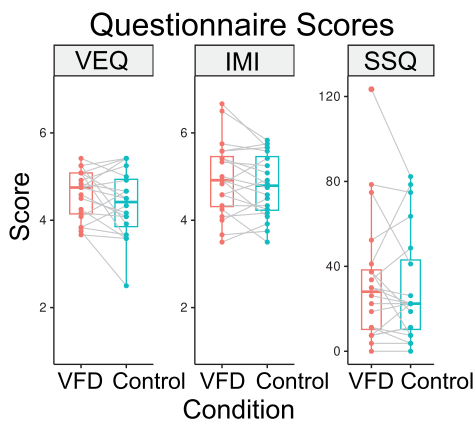


Fig. 5. Questionnaire scores for both conditions. VEQ: Virtual Embodiment Questionnaire, SSQ: Simulator Sickness Questionnaire, IMI: Intrinsic Motivation Inventory. Error bars show 95% confidence intervals. Each point represents a participant's score, with lines connecting data from the same participant.

indicating that as the visual distortion increased in one direction, participants adjusted their foot placement in the opposite direction along the x-axis, in line with our hypothesis. None of the other factors, including the offset in the z-direction, the test number within condition, or the interaction between offsets, significantly affected the centered x-position.

For the centered heel strike z-position, the offset magnitude in the z-direction had a significant negative effect ($\beta = -0.0493$, $t(9845.00) = -5.25$, $p < 0.0001$, $d = -0.72$), indicating that participants also adjusted their foot placement opposite to the visual offset in this direction (albeit with a much smaller effect size). None of the other factors, including the offset in the x-direction, the test number within condition, or the interaction between offsets, showed significant effects on the centered z-position. Detailed statistical results and visualizations can be found in the supplementary material.

IV. DISCUSSION

A. VFD Applied on Avatar's Feet Increases Step-Width Variability

Our results support our first hypothesis (H1), showing that introducing a subtle visual feedback disturbance (VFD) on the avatar's feet significantly increased step width variability. Specifically, we observe about a 15% increase, calculated by dividing the condition-related fixed-effect estimate from our LMM ($\beta = 0.0042$) by the model intercept ($\beta = 0.0272$). Across all 20 participants, 14 (70%) showed an increase in step width variability under VFD, with an overall mean increase of 2.10 mm (SD = 3.81 mm). This effect is similar to previously reported increases in step width variability for small (20 cm to 35 cm) visual flow disturbances [30] and for force disturbances in the anteroposterior direction [31], [59]. However, larger visual flow perturbations (50 cm) and mediolateral disturbances achieved larger increases in step width variability in these works. The substantial effect size ($d = 1.33$) and the fact that the VFD did not influence embodiment, motivation, and simulator sickness underscores the practical significance of this finding.

Our analysis also revealed a significant order effect, with increased step width variability observed only in participants who began with the control condition and subsequently experienced the VFD. One possible explanation is that participants attributed greater relevance to deviations after adapting to the unperturbed avatar, which may have been inhibited when participants started with the VFD condition. The nervous system adapts more strongly to errors when judged as more relevant and consequently may lead to a greater adaptation [60]. A second explanation may be that the VFD conditions led to a lasting increase in motor variability that carried over to the subsequent control condition, diminishing the observed differences. Previous work has shown that practicing a task can reshape movement variability to improve adaptation [61]. This suggests that the initial VFD condition may have primed an exploratory mechanism leading to slightly increased variability that persisted during the control condition.

Whereas the VFD significantly increased step width variability, it did not affect step length variability. This contrasts previous findings, where visually manipulating the avatar's foot position influenced the step length and improved step length symmetry in Parkinson's patients [47]. However, previous work also shows that step length variability is more difficult to influence than step width variability [30], [31], [59]. Step width variability is thought to reflect the amount of active control required for lateral stabilization [62]. When sensory feedback becomes less reliable, this active control can introduce substantial variability in lateral movements [63]. As a result, step width variability is more easily perturbed, whereas step length variability remains comparatively stable even under challenging conditions [63], [64], [65]. In other words, it may be that the VFD was impactful enough to influence lateral stability control but insufficiently impactful to significantly alter the more robust patterns governing step length variability. Another potential explanation for this discrepancy is that, at maximum amplitude (see Section II-D), the VFD in the lateral direction accounted for about 50% of the average step width. In contrast, our maximum forward VFD amplitude was only about 30% of the average step length, which may have been insufficient to disrupt the more robust step length control.

B. High Embodiment Is Associated With High Variability

We unexpectedly found that a higher VEQ score led to a higher variability, regardless of the condition. We expected that this would only be the case for the VFD condition, as previous research has demonstrated that higher levels of embodiment can enhance motor responses and adaptations [51]. However, the fact that the interaction between the VEQ scores and the condition is insignificant contradicts this hypothesis (H2). Moreover, even if we would still consider interaction for this interpretation (since the interaction is close to significance, $p = 0.056$), this would lead to the conclusion that the increase in step width variability associated with higher VEQ scores was diminished during the VFD condition, which is precisely the opposite of what we hypothesized. In other words, participants with a higher level of embodiment exhibited larger step width variability, especially in the control condition.

One possible explanation may be that walking with the VR avatar by itself already increases the variability. This aligns with the finding that walking in VR significantly increases gait variability compared to real-world walking [66]. It may be that embodiment modulates this effect, leading to the main effect of VEQ scores on step width variability that we observed. However, to confirm this, a future experiment must be designed to investigate this specifically.

C. The VFD Does Not Affect Embodiment, Motivation, or Simulator Sickness

Contrary to our hypothesis (H3), the VFD did not significantly change questionnaire scores. This outcome contrasts with previous findings in upper limb tasks, where positional disturbances typically reduced embodiment [42], [44], [67]. Using a subtle, hard-to-notice VFD may have limited its impact on embodiment, aligning with evidence that gradually introduced disturbances mitigate—though not fully prevent—decreases in embodiment [42], [45], [68].

The lack of motivational changes also differs from results in more demanding tasks, where disturbances were shown to decrease motivation [24]. The absence of a motivational impact in our study may potentially be attributed to the simplicity of the task. Specifically, the disturbance may not have been sufficient to render the task overly difficult, thus not diminishing motivation. Similarly, we observed no increase in simulator sickness, which contrasts with scenarios where disruptions in optic flow may induce discomfort [33], [34]. As we expected, a VFD applied to avatar foot positioning likely does not create the same sensory conflicts, as it did not lead to any simulator sickness. This may be a critical advantage for therapeutic applications.

D. Adjustment of Foot Placement in Response to VFD

Our fourth hypothesis (H4) was that the participants would adjust their foot placement in the opposite direction of the visual distortion. Our results support this hypothesis.

In both the mediolateral (x) and anteroposterior (z) directions, we observed significant negative effects of the offset magnitudes on heel strike positions. Specifically, as the visual distortion increased in one direction, participants adjusted their foot placement in the opposite direction. This behavior indicates proprioceptive recalibration, where the sensory discrepancy between visual and proprioceptive inputs results in the brain updating the estimated limb position. The significant adjustment in foot placement suggests that participants relied on visual feedback to guide their locomotion and actively corrected for the discrepancies introduced by the VFD. This finding aligns with previous studies demonstrating similar visual perturbations can lead to compensatory adjustments in gait patterns [47].

The effect sizes further highlight the impact of the VFD on foot placement. In the x-direction, the large effect size ($d = -5.31$) indicates a strong and consistent adjustment across participants. In the z-direction, the effect size is smaller ($d = -0.72$) but still results in a significant difference. As described in Section IV-A, this did not lead to a significant difference in step length variability compared to walking without the VFD.

Considering that the maximum visual disturbance applied was 7.5 cm in the x-direction and 15 cm in the z-direction, the regression coefficients suggest that participants adjusted their foot placement by up to approximately 1 cm in the x-direction and about 0.65 cm in the z-direction at the maximum offset. The adaptation is not one-to-one, likely because foot placement is influenced by additional factors such as maintaining balance and staying centered on the treadmill.

E. Limitations

Although our study provides valuable insights into using subtle VFD to increase gait variability, several limitations should be acknowledged. First, we only analyzed data from 20 young, unimpaired, and mostly male participants (15 male, 5 female), and each walk test lasted only three minutes—much shorter than often seen in, for example, split-belt treadmill studies [69], [70]. Because we expected that the effects of the VFD would manifest quickly, we chose this shorter walk time to mitigate boredom and neck strain from looking downward. Yet, this short test duration might raise concerns about the stabilization of the variability. As reported in the supplementary materials, we did not find significant differences in the variability within test walks. However, because such brief sessions may not reveal longer-term changes, future work should validate these findings with larger, more diverse participant groups and with longer training durations.

Second, although one motivation for avoiding force-based perturbations was to minimize muscle co-contraction, we did not measure muscle activity here. Future work should include electromyography (EMG) analysis to confirm that VFD does not result in stiffening strategies seen with force-based disturbances [28]. Furthermore, although we aimed for a subtle VFD, we did not measure its noticeability or how that might influence our outcomes. Future work should systematically vary offset magnitudes relative to each user's just-noticeable difference to see if detectability modulates gait variability, embodiment, or motivation.

Finally, our stepping task required participants to focus on stepping onto targets while walking, directly influencing their stepping parameters. To mitigate this task's effects on our gait variability analysis, we excluded the steps associated with target stepping from the variability calculations. However, this removed a substantial portion of the data, potentially reducing statistical power. Further, it remains unclear how the stepping task influenced the gait kinematics of the remaining steps. Note that because all walk tests, including familiarization, involved focusing on the feet, we did not record participants' "natural" walking, which could have served as a baseline measurement. Future studies should consider tasks that minimally affect typical gait and include an unperturbed, eyes-forward condition to better contextualize how any VFD-induced changes compare to everyday walking.

F. Implications and Future Directions

Our findings demonstrate that – in short treadmill sessions – a subtle, minimally noticeable visual feedback disturbance applied to the virtual avatar's feet can acutely increase gait variability without adversely affecting embodiment, motivation, or simulator sickness. This result is relevant to gait rehabilitation scenarios, where enhancing gait variability is thought to support the exploration of movement strategies and promote motor learning [3], [20]. However, it remains unclear whether simply increasing gait variability leads to improved functional outcomes or long-term benefits. Some evidence suggests that restoring healthy levels of gait variability could improve adaptability to changing conditions, yet robust clinical confirmation is still lacking [1]. Moreover, introducing variability does not always enhance performance retention or skill transfer and can, in some cases, negatively affect learning [71]. Future research should, therefore, examine whether repeated exposure to the VFD leads to lasting improvements in gait stability and adaptability, including retention and transfer tests. Such studies should ideally involve patient populations, such as individuals recovering from stroke or living with Parkinson's disease, to determine whether subtle visual disturbances can effectively improve rehabilitative outcomes in real-world clinical settings.

However, to evaluate this, refining and optimizing the VFD design to enhance the possible impact on variability would be beneficial. In this study, we selected the disturbance signal and its parameters based on limited pilot testing. Although the introduced variability was meaningful, the magnitude of the effect was smaller than what can be achieved through other forms of perturbation, such as altering visual flow [30], [31] or applying mechanical force disturbances [23]. The disturbance pattern may be systematically explored and adapted to maximize the effects on variability. For instance, leveraging patterns with multifractal features could more closely align with the natural complexity of human gait and potentially enhance adaptability [6]. Similarly, adaptive algorithms could adjust the disturbance amplitude or frequency in real time, tailoring the challenge level to a user's current gait state. Nevertheless, achieving a higher impact on variability may not be necessary, as maintaining variability within "normal" bounds may already be optimal for motor adaptation [3].

The minimal impact on participants' subjective experience suggests that VFD could be integrated seamlessly into home-based training programs. Since participants did not report decreased embodiment, motivation, or increased simulator sickness, therapists may introduce VFD without worrying about negative experiences or reduced motivation. Future research should aim to simplify the setup. For example, using only the virtual feet rather than a full avatar may still produce similar effects on gait variability [47] without impacting motor control in terms of foot placement accuracy [38]. Additionally, it would be worth investigating whether similar adaptations occur without a stepping task, perhaps by encouraging participants to pay attention to their feet for other reasons. These simplified approaches could reduce costs, improve accessibility, and streamline the integration of VFD into routine clinical practice.

Finally, our finding that increased gait variability emerged only when participants were first exposed to a baseline (control) condition suggests that sequencing and familiarity play important roles in adaptation. Extending the duration of this undisturbed exposure before introducing the VFD or exploring alternative protocols may further amplify the effects. Also, it may be fruitful to enhance embodiment through additional techniques. For example, incorporating visuo-tactile stimuli aligned with virtual feedback may boost embodiment despite distortions [45], [68].

In short, this work contributes to our understanding of how visually induced variability can be leveraged for motor learning and adaptability in gait. By demonstrating that subtle VFD can increase gait variability without diminishing embodiment, motivation, or comfort, we pave the way for more accessible and user-friendly interventions. Future studies should examine the long-term impact and clinical effectiveness of integrating subtle VFD into existing walking interventions, such as instrumented treadmill adaptability training [72]. By superimposing subtle VFD on the virtual foot, clinicians could further increase the level of challenge, induce additional gait variability, and potentially enhance motor learning. With iterative refinement and validation among patient groups, subtle VFD has the potential to emerge as a widely applicable and customizable tool, fostering adaptive motor responses and improving gait patterns in a range of rehabilitation contexts.

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Data Availability

The datasets, code used in this study, and instructions for reproducing our analyses are publicly available on Zenodo (https://zenodo.org/records/14754914). This paper has supplementary downloadable material available at https://doi.org/10.1109/TNSRE.2025.3570241, provided by the authors, comprising a detailed pdf document that provides additional methodological details and statistical results to improve the transparency and reproducibility of our results.

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