Visual Cues for a Steadier You: Visual Feedback Methods Improved Standing Balance in Virtual Reality for People With Balance Impairments

M. Rasel Mahmud*
Computer Science
The University of Texas at San Antonio

Alberto Cordova†
Kinesiology
The University of Texas at San Antonio

John Quarles‡
Computer Science
The University of Texas at San Antonio

Abstract— Users of head-mounted displays (HMDs) for virtual reality (VR) sometimes have balance issues since HMDs impede their view of the outside world. This has a greater impact on people with balance impairments since many rely more heavily on their visual cues to keep their balance. This is a significant obstacle to the universal usability and accessibility of VR. Although previous studies have verified the imbalance issue, not much work has been done to diminish it. In this study, we investigated how to increase VR balance by utilizing additional visual cues. To examine how different visual approaches (static, rhythmic, spatial, and center of pressure (CoP) based feedback) affect balance in VR, we recruited 100 people (50 with balance impairments due to multiple sclerosis and 50 without balance impairments) across two different geographic locations (United States and Bangladesh). All people completed both standing visual exploration as well as standing reach and grasp tasks. Results demonstrated that static, rhythmic, and CoP visual feedback approaches enhanced balance significantly ($p < .05$) in VR for people with balance impairments. The methods described in this study could be applied to design more accessible virtual environments for people with balance impairments.

Index Terms—Virtual Reality, visual feedback, balance, VR accessibility, Head-Mounted Display, VR usability, postural stability

1 Introduction

Balance is defined as the maintenance of the body's center of mass over its base of support within the limits of stability [20]. Virtual reality (VR) which is a computer-generated interactive experience that is engineered to feel real to the user, is not accessible to many persons with disabilities due to balance impairments (BI) [1, 15, 16, 19, 48]. Unfortunately, these groups are seldom taken into account while developing VR technology, which may lead to experiences that are exclusive and inaccessible. In VR experiences, for instance, those with BI may not be able to stand comfortably because their balance is disrupted by VR Head Mounted Displays (HMDs), as HMDs block the entire visual periphery. However, there has not been much research to mitigate the imbalance issues of VR.

Very few prior studies have investigated balance with assistive feedback (e.g., audio, vibration, visual) in VR. For example, Mahmud et al. [32] investigated the effects of several auditory approaches on balance in immersive VR, where the auditory feedback improved balance significantly in VR for both people with and without BI. Another popular assistive feedback is vibrotactile, which is a type of haptic feedback that specifically uses vibration as the mode of sensory feedback. Mahmud et al. found vibrotactile feedback in VR improved balance significantly for people with and without BI [33]. However, they did not investigate the effects of visual feedback in their studies. Auditory feedback might not be effective for people with hearing issues. Vibrotactile feedback was also reported to lack immersion, and interaction [11]. Moreover, different feedback modalities (audio, visual, and haptic) provided different results in VR [59]. Therefore, visual feedback could be helpful in many scenarios. Ferdous et al. [50] investigated the impact of a static rest frame ('+' sign surrounded by four 'L' shaped boundaries) on postural stability in VR and augmented reality (AR). They observed that static rest frames significantly improved postural stability for participants with MS in VR and AR. However, they only investigated static visual feedback.

Many HMD-based approaches require participants to stand in a fixed position. Hence, increasing the accessibility of VR in the context of standing balance is the primary objective of this study (i.e., improving short-term balance while the users are in VR). In our research, we performed empirical studies where participants (people with and without BI) sought to maintain balance while standing in virtual environments (VEs) with several types of visual feedback (e.g., spatial, static, rhythmic, and Center of Pressure (CoP)). Future VR developers may learn from the findings how visual feedback can be used to increase accessibility in VR. In the future, research will be done on long-term balance improvement (also known as balance rehabilitation), which we did not investigate in our current research. Our major contributions include the following:

- Three novel visual feedback (spatial, rhythmic, and CoP) techniques had been implemented for balance improvement in VR. We also implemented an existing static condition to compare with other conditions. A few studies investigated only one kind of visual feedback with a single group of people. To our knowledge, no study analyzed and compared four different visual techniques in an immersive virtual setting.
- We carried out research to find out how our VR visual feedback methods affected standing balance. We conducted the study in two different countries (United States and Bangladesh) to increase the generalizability of our results.
- We included people with Multiple Sclerosis (MS) with balance issues, rarely considered in VR, and people without balance impairments. We had 100 people in our study (50 with BI due to MS and 50 without BI).

2 Background and Related Work

2.1 Imbalance in VR

Previous research reported that VEs cause balance impairments for users. According to research published in the early 2000s, VEs led to unsteadiness and motion sickness [55]. In comparison to the actual world, participants had less control over balance in the VE [25]. Head-mounted displays (HMDs) also offered less balance stability in VE compared to the real world [24]. Participants using HMDs may become unbalanced due to end-to-end latency and the deceptive impression

*e-mail: m.raselmahmud1@gmail.com, mrasel.mahmud@my.utsa.edu
†e-mail: Alberto.Cordova@utsa.edu
‡e-mail: John.Quarles@utsa.edu

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of body movement induced by VEs as HMDs obstruct visual input from the real world [34, 52]. Additionally, postural instability was brought on by prolonged immersion in VEs [40]. The consequences of imbalance on gait (walking patterns) have also been examined in other research [31, 53]. Therefore, in HMD-based VR, balance problems are a well-known concern for consumers. Although to mitigate the imbalance issues in VR, there have not been many prior efforts. This motivated us to explore ways to enhance balance in VR.

2.2 Assistive Feedback Technology for Balance Improvement in a Virtual Environment

Very few prior studies attempted to improve balance in VR using assistive feedback. Mahmud et al. [32] was one of the very few who studied the effects of several auditory approaches (static, rhythmic, spatial, and CoP) on immersive VR balance. They reported that each auditory technique improved balance significantly in VR for both people with and without BI. Spatial and CoP auditory feedback conditions outperformed other conditions significantly in their study. According to research by Gandemer et al. [17], spatial audio in an immersive virtual world increased postural stability for blindfolded individuals. Most of the time, spatial audio was favored for usage in VR since it offered a deeper sense of immersion. However, auditory feedback is not applicable to people with hearing issues.

Mahmud et al. [33] investigated the impact of several vibrotactile feedback modalities on VR balance. In their study, balance in VR was significantly enhanced under vibrotactile feedback conditions for all participants. Spatial and CoP vibrotactile feedback performed significantly better for both groups of participants. Nevertheless, vibrotactile feedback was reported to lack immersion and interaction in many cases [11].

2.3 Visual Feedback to Improve Balance in the Real World

Hasegawa et al. [21] explored the learning effects of visual and auditory biofeedback (BF) training on dynamic postural control. They assigned healthy young adults randomly into two groups (visual BF and auditory BF). A monitor displayed a circle that increased in size to represent an increased forward or backward deviation of the CoP. In contrast to auditory BF, which demonstrated a substantial improvement ($p < 0.01$) in their investigation, visual BF did not significantly enhance postural stability ($p > 0.05$). Their CoP visual feedback condition was limited to providing less feedback in forward/backward directions and not in any other directions.

Wang et al. recruited female healthy college students to investigate the effect of CoP-based visual feedback on balance [60]. They randomly divided the participants into three groups (visual feedback, non-visual feedback, and control). Participants stood on a force plate. For the visual feedback group, they displayed the dynamic points of CoP on an iPad screen based on the participants' positions. They instructed the participants to keep the dynamic points inside a center circle on the screen. The non-visual feedback group tried to maintain an open-eye balance without real-time visual feedback. The control group did not practice balance training. The four-week balance training program consisted of three 30-minute sessions each week with 1-2 day intervals. Their findings showed that CoP-based real-time visual feedback training improved balance significantly ($p < .05$) for the visual feedback group compared to the non-visual and control group.

VR techniques have been increasingly popular in rehabilitation to enhance balance and gait [2, 3, 8, 12, 13, 37, 41, 45]. Visual feedback is also effective in rehabilitation [5, 54, 57]. For example, visual feedback has been used to convey real-time information about posture to improve patients' sitting balance in rehabilitation [29]. However, most prior works either did not employ HMDs or were limited to sitting conditions. Rehabilitation programs commonly use visual feedback displayed via projectors or large screens, which do not provide immersive experiences. However, HMDs provide fully immersive experiences, which can improve users' presence [39]. We used HMDs in our study.

2.4 Visual Feedback to Improve Balance in VR

Ferdous et al. [50] investigated the effect of a static rest frame on postural stability in VR and augmented reality (AR). Participants stood on a Wii balance board and played a balancing game where they had to avoid a barrage of virtual tennis balls being flung at them. They used a Vive HMD for VR and HoloLens for AR experiences. Results revealed that the static rest frame significantly improved ($p < .05$) postural stability for participants with MS in VR and AR.

Mohebbi et al. [38] investigated the impact of amplitude and velocity of the visual field on the dynamic body sway of healthy adults. Subjects stood on a stance analysis apparatus. They designed and projected a three-dimensional VE to the HMD, mimicking the inside of a modern house. They changed the amplitude and velocity of the visual field to investigate the effect on postural stability. The root mean square (RMS) of the body angle was computed for each trial as a measure of overall body sway. They found that increasing visual input amplitude increased RMS hip displacement (body angle) whereas velocity had a nonlinear effect. However, the impact of visual input on balance in immersive VR has seldom ever been studied.

3 Methods

We recruited 100 participants (50 with BI due to MS and 50 without BI) to investigate the effect of different visual feedback on balance in VR. Standing visual exploration as well as standing reach and grasp were the two activities that each participant undertook. They performed the tasks in the real world and in an identical VR with four different visual feedback. The tasks and visual feedback were counterbalanced.

3.1 Study Conditions

Figure 1 shows the different visual feedback used in our study. We selected a simple texture, which is a '+' surrounded by four L-shaped boundaries, similar to [15]. Previous studies have shown that cybersickness can increase with visual complexity [35]. Thus, to minimize cybersickness, we decided to select a simple texture with few visual features over other, more complex textures.

3.1.1 Static Visual Feedback:

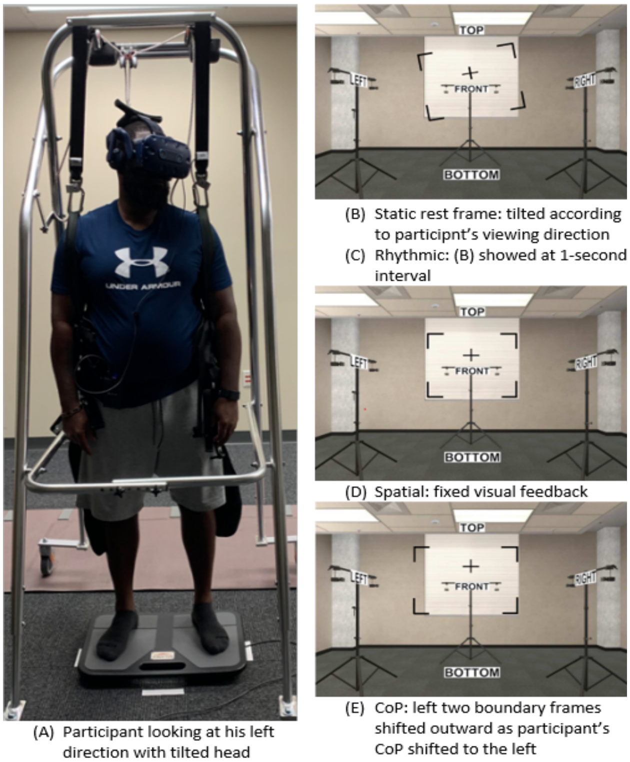
This was a virtual static frame (e.g., a '+' sign within four boundaries) on the front wall that was affixed to the users' view in VR. It was similar to a reticle in popular games and was a type of heads-up display. We implemented this based on the preliminary work by [50].

3.1.2 Rhythmic Visual Feedback:

This was similar to the previous static rest frame condition, except the virtual static frame was shown at every 1-second interval instead of continually. Thus, the static restframe was repeatedly visible for one-second and then invisible for one-second. We selected a 1-second interval for rhythmic conditions as it was found to be effective in prior auditory feedback research [32]. Previous studies in VR [32] and non-VR [18] settings reported that rhythmic auditory beats improved balance and gait significantly. This motivated us to investigate rhythmic visual feedback, which was not explored before.

3.1.3 Spatial Visual Feedback:

We used the same virtual frame texture from the static condition. The texture was in the same position and the same size. However, the texture was affixed to the wall this time and was not moving with the participant's view. The texture was big enough to remain within the participants' field of view, even if the participants were moving their heads slightly in left or right directions. The texture was placed three meters in front of the participants. We based this on a previous study [27] where they investigated the impact of the visual effect of a texture on the front wall and optic flow on the balance of the participants. However, as the feedback was a combination of spatial and optic flow in their study, it was not clear to what extent spatial feedback affected balance which motivated us to investigate the spatial condition separately. Also, our spatial feedback condition uniquely consisted of four "L" shaped boundaries which were not investigated in the prior study.



(A) Participant looking at his left direction with tilted head
(B) Static rest frame: tilted according to participnt's viewing direction
(C) Rhythmic: (B) showed at 1-second interval
(D) Spatial: fixed visual feedback
(E) CoP: left two boundary frames shifted outward as participant's CoP shifted to the left

Fig. 1. Diffferent visual feedbacks conditions used in our study

3.1.4 CoP Visual Feedback:

When participants stood in the center position on the balance board, the texture was the same as in the spatial visual feedback condition. The boundaries of the texture were shifted outward to indicate increased deviation of the Center of Pressure (CoP). For example, when participants moved away from their center position on the balance board to the left, right, front, or back, the CoP value increased, and the two boundaries on the corresponding side shifted outward based on the CoP value. Thus, participants could correct their posture by looking at the texture boundaries. Hasegawa et al. [21] explored visual feedback in the real world, where a monitor displayed a circle that was increased in size to represent an increased forward/backward deviation of the COP. However, they could only provide feedback in forward/backward directions using a circle, whereas we used a square structure and provided feedback in left, right, front, and backward directions. We also streamed the real-time CoP data to Unity using our developed Labview program to CoP feedback accurately, which was not the case for the prior study by Hasegawa et al. [21]. Additionally, as they conducted the study in the real world, the effect on balance has been untested in immersive VR, which we investigated in our study using HMDs. Moreover, they only recruited 18 healthy young adults and balance impaired people. However, we recruited 100 people with and without balance impairments.

3.1.5 No Visual Feedback:

Participants performed the two virtual tasks without any additional visual feedback. However, they were still able to see the VE the whole time. We utilized this to measure participants' balance without any visual feedback in VR.

3.2 Hypotheses

Our research looked at how balance in VR settings was affected by several visual feedback (spatial, static, rhythmic, and CoP). These approaches had never been directly compared to each other before. We investigated the following hypotheses based on prior research (see the background and related work (section 2) for details).

A few prior research confirmed that if there is no additional feedback in VR, balance will be significantly diminished [24, 34, 52]. We expected similar results in our study.

H1: Compared to the baseline (non-VR) condition, balance will deteriorate without visual feedback in the VR condition.

We chose to implement the spatial approach because in a prior study [27], spatial feedback combined with the optic flow was effective in improving balance in VR. We chose to implement CoP-based visual feedback because it improved balance in the real world for participants [21], where they provided CoP visual feedback in forward and backward directions. We developed a technique to provide CoP-based visual feedback to participants in all four directions (left, right, front, and back). Thus, we expected this technique would improve balance. We chose to implement static visual feedback because it has been shown to significantly improve balance in VR for people with MS [50].

H2: Compared to the no visual feedback in the VR condition, balance will be greatly improved in each of the VR-based visual feedback conditions (spatial, static, rhythmic, and CoP).

Although they had not been directly compared before, there had been more previous examples in the real world and in VR of static rest frames and rhythmic visual feedback having a positive impact on balance and perception in general. When there was a static rest frame in a VE, it helped people to increase their depth perception [23], presence [44], and reduced cybersickness [6, 44], which eventually contributed to balance improvement. So, we assumed static rest frames would provide more significant feedback than other conditions. Further, in our study, rhythmic visual feedback was similar to static feedback. However, it was provided to participants at every 1-second interval. Mahmud et al. found that rhythmic auditory feedback [32] and rhythmic vibrotactile feedback [33] provided at every 1 -second interval significantly enhance stability for all participants with and without BI. Based on the effect of auditory and vibrotactile feedback in VR, and the prior literature on static rest frames in VR, we hypothesized that rhythmic and static visual feedback would improve balance in VR more than other conditions.

H3: Compared to other visual feedback systems, static and rhythmic visual feedback may promote greater balance.

3.3 Participants, Selection Criteria, and Screening Process

Based on study design and correlations found in prior studies [32, 33], we conducted a power analysis with a = .05, at 80% power, and an expected medium (.5) effect, which indicated 44 participants would be needed. Thus, we recruited 50 participants from the United States to accommodate any possible dropouts. 25 people (Male: 12; Female: 13, age range: 40-50) experienced BI brought on by MS. The other 25 people (Male: 12; Female: 13, age range: 40-50) did not have BI, MS, or any other physical conditions, but they were comparable to the people with BI in terms of age, weight, and height. Participants with BI were 34.1% White, 33.4% Hispanic, and 32.5% African American. For without BI group, there here were 33.4% White, 33.3% Hispanic, and 33.3% African American. We also recruited 50 people from Bangladesh. 25 people (Male: 12; Female: 13, age range: 40-50) experienced BI due to MS. The other 25 people (Male: 12; Female: 13, age range: 40-50) did not have BI, MS, or any other physical conditions, but they were comparable to the people with BI in terms of age, weight, and height. All people in Bangladesh were Asian. Table 1 displays information for all participants with and without BI. Each individual could walk without any help. We found people from local MS support groups, rehabilitation institutions, hospitals, and local communities. The main methods for recruiting were phone calls, email lists, websites, and flyers.

We conducted the same study in the two locations because we wanted to see how our methods worked in different locations with entirely different populations to increase the generalizability of our results [42]. With this regard, the cross-cultural comparisons would allow for comparisons of posture between the two cultural groups for generalization. It is known that there is a considerable geographic variation between these groups of people who suffer from MS. Therefore, we were interested to see if there would be differences in our study. Because one of the authors was going to be visiting Bangladesh for several months, it was a convenient location to run the study.

Table 1. Gender, age, height, weight for study participants

Types of Participants	Gender		Age (years)		Height (cm)		Weight (kg)	
	Male	Female	Mean	SD	Mean	SD	Mean	SD
BI (United States)	12	13	45.3	5.0	163.97	4.32	78.19	4.99
Without BI (United States)	12	13	44.87	4.6	163.74	4.18	79.03	4.86
BI (Bangladesh)	12	13	46.1	3.9	160.11	4.26	77.58	4.19
Without BI (Bangladesh)	12	13	45.64	3.1	161.46	4.17	77.06	4.11

Screening Process: To determine if each prospective participant was eligible for this research, we first conducted a phone interview with each of them. To test their mental abilities, for instance, we asked them a few basic questions initially, such as the year and date, as well as some demographic details. Anyone who struggled to grasp the questions or lacked proficiency in the English language was not chosen. After that, they were asked why they had a balance problem. Additionally, we made sure that individuals for both groups were comparable in terms of age, height, and weight. Participants who needed help to stand or were taking medication to enhance their balance were not allowed to participate in the research.

3.4 System Description

For our research, we used the following tools:

Balance Measurement: Participants' balance was assessed in each scenario using the BTrackS Balance Plate. 25 HZ was the sample rate for the balance plate.

Safety System: To avoid unexpected falls, each participant wore a harness to support them. A weight-bearing suspension system was connected to the harness. Kaye Products Inc. supplied the suspension system and the harness.

Computers, VR Equipment, and Software: We used Unity3D to create the VEs. The HTC Vive featured a 110-degree field of view, 2160 x 1200 pixel resolution, and a 90 Hz refresh rate. In this research, the VE was rendered, and the data were recorded using a computer. The computer had a Windows 10 operating system, a 4.20 GHz Intel Core i7 processor, 32 GB of DDR3 RAM, and an NVIDIA GeForce RTX 2080 graphics card. We collected data from the BTrackS Balance Plate using the NI LabView software (version 2020), and then we streamed that data to Unity3D using sockets.

Environment: There was a sufficient user study area with around 600 sq ft. in our lab. For the duration of the study, the lab was only accessible to the participant and the experimenter. We had the same VR environments for both studies in the United States and Bangladesh, and we also tried to make the real environments similar. We placed the markers, balance board, and table in the same positions with the same sizes for both studies.

3.5 Study Procedure

The Institutional Review Board (IRB) approved the study. Before each user study, we cleaned and sterilized every piece of apparatus. The participants' body temperatures were recorded when they entered the lab, and they completed a COVID-19 screening questionnaire form. After reading the consent document, the participant signed it. In order to identify the participants' dominant and non-dominant hands, we asked them handedness questions [10]. Then, participants completed the Simulator Sickness Questionnaire (SSQ) [26] and the Activities-specific Balance Confidence (ABC) [49]. Next, the experimenter explained the whole study's methodology to the participant. The participants were then fastened to the suspension system and harness to protect them from falling. The participants stood on balance boards wearing no shoes the whole time the trial was being conducted. The whole study procedure has been shown in Fig. 2.

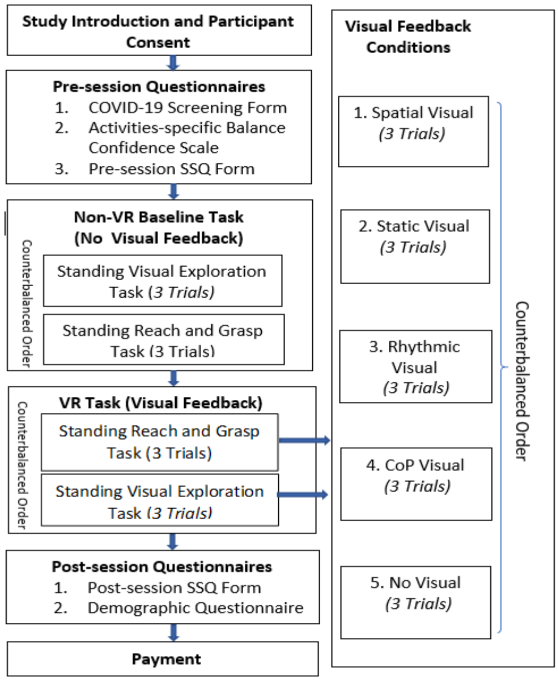


Fig. 2. Study procedure for both groups of participants.

The experiment was conducted by the same experimenter across the two locations, and the protocol was followed consistently. While the experimenter traveled to Bangladesh for the study, he carried the same equipment (Btracks balance board, wireless HTC Vive Pro Eye, and markers) used in the US with him. We collected the same make and model harness in Bangladesh. We used a desk in the study to place the objects where we were able to acquire the same height, color, shape, and size. There were some subtle differences between the two desks used in the two locations, but we expect this had minimal effects on the results. We used the same virtual scenes in both locations.

3.5.1 Tasks

Participants engaged in standing reach and grasp and standing visual exploration tasks which were carried out in both a VR environment and a non-VR setting. The VEs were exact replicas of the non-VR setting. We counterbalanced both tasks in our study.

Standing Visual Exploration: To compare participants' real lab balance with the balance in the VE lab, we opted to execute a simple motor/balance activity. A prerecorded audio file was played which instructed participants to look at markers placed in various positions ('Left,' 'Right,' 'Top,' 'Bottom,' and 'Front') across the lab. We wanted all participants to view the lab in a controlled manner so that it was uniform for everyone. The BTrackS Balance Plate was used to acquire real-time balance data. The real environment and equivalent VE are depicted in Figure 3. We followed the work described in [16] for developing this task.

Standing Reach and Grasp Task: We placed a table in front of the participants. Participants reached for and grasped four cubes, each 5.08 cm in width, and positioned them at specific places on the table. Each pair of items were separated by 12 cm. The balance board was positioned parallel to the table's center on the ground. The balance board was 12 cm away from the table. Participants removed their shoes and utilized their dominant hand to hold the items. We told the participants to pick up the four items in a random sequence, raise them to chest height, and bring them again to the same place. To implement this task, we followed the work described in [9]. This task's workspace is shown in Figure 4, along with a comparison between the real and

Fig. 3. Standing visual exploration task: the left figure shows the real environment whereas the right figure shows the virtual environment.

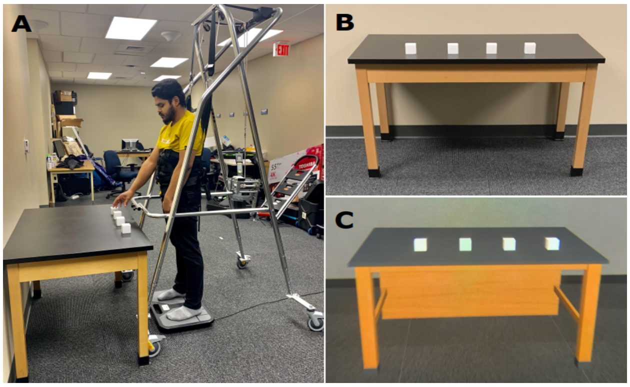


Fig. 4. The workspace for standing reach and grasp task has been shown in (A), the Real environment in (B), and the virtual environment in (C).

virtual environments. We picked this motor task because reaching is a fundamental aspect of daily life, has been used to assess balance, and is a common component of VR [4, 22, 56].

3.5.2 Baseline Measurements without VR

A harness protected the participants from falling when they stood on a BTrackS Balance Plate. Then, we assessed their balance using three trials of both tasks for all participants. Three minutes were allotted for each trial.

3.5.3 Tasks in Virtual Reality

We replicated the preceding baseline activities in VR, with the exception that they were completed in VR with different visual feedback. For both virtual activities, participants observed the VE using the HTC Vive HMD. We performed the following tasks for four VR-based visual feedback conditions and a VR condition with no additional visual feedback. We counterbalanced the visual conditions and tasks and conducted the tasks three times for each condition.

Standing Visual Exploration: We played the same recorded instructions that were used to evaluate balance in the real world to navigate the virtual environment. We positioned the virtual markers at the same location and made the markers the same size as the real world. The measurement procedure was identical to the standing visual exploration task in the real world.

Standing Reach and Grasp: All people stood in front of a virtual table where we placed the four virtual cubes. Using the Vive controllers, participants used their dominant hand to reach for and grasp virtual cubes. The cubes' color turned red as soon as the participants touched the virtual cubes with the controller. The participants brought the cubes to chest level using a controller, then released the trigger of the controller when returning the cube to its original location. The VE, table, cubes, and data collection procedure in the VE were identical to the real-world task.

3.6 Post-Session Questionnaires

Finally, participants completed an SSQ and a demographic questionnaire.

The study took around one and a half hours for all participants. Participants in the United States received 30 U.S. dollars per hour plus parking costs. Participants in Bangladesh received five U.S. dollars per hour, as most things in Bangladesh are approximately six times cheaper than in the United States.

4 Metrics

4.1 CoP Velocity

In our research, the Center of Pressure (CoP) [47] velocity was the major parameter of balance. We selected CoP velocity since it is extensively used as a reliable measurement for assessing balance [30]. We used the formula by Young et al. [61] while measuring CoP.

$$CoP(X,Y) = \frac{\sum_{i=1}^{4} Weight_i * (x_i, y_i)}{\sum_{i=1}^{4} Weight_i} \tag{1}$$

(x_i, y_i) denotes coordinates of sensor i, $Weight_i$ denotes ith sensor, and $CoP(X,Y)$ denotes the coordinates of the CoP.

Then, the CoP path was measured by applying the below formula.

$$CoP\ Path = \sum_{i=1}^{n-1} \sqrt{(CoP_{i+1}X - CoP_iX)^2 + (CoP_{i+1}Y - CoP_iY)^2} \tag{2}$$

CoP_iX denotes X coordinate of CoP at ith frame, and CoP_iy denotes Y coordinate of CoP at ith second.

In the end, CoP velocity was measured using the following formula (T).

$$CoP\ Velocity = \frac{CoP\ Path}{T} \tag{3}$$

Where T denotes all samples' data recording time.

4.2 Activities-specific Balance Confidence (ABC) Scale

This questionnaire consists of 16 questions about the ability to do some daily life activities [43]. The ABC score is determined by adding the percentages of all questions. ABC% is obtained by dividing the total by sixteen.

4.3 Simulator Sickness Questionnaire

SSQ consists of 16 questions, each of which inquires about the physiological discomfort of the individual [26]. This test is required to identify individuals susceptible to severe cybersickness and investigate the relationship with postural instability.

5 Statistical Analysis

To ensure that the data were normal, we utilized the Shapiro-Wilk test. We discovered that the data was normally distributed for participants in both tasks, with p =.386 and w = 0.76. Then, in order to determine if there was any significant variation in CoP velocities, we conducted a 2×6 mixed-model ANOVA where participants with BI and without BI were two between-subject variables and the six study conditions were within-subject factors. Post-hoc two-tailed t-tests were used to compare within and between group conditions. In order to analyze cybersickness, we also employed two-tailed t-tests to compare initial and final SSQ scores for both groups independently. To assess the differences in physical ability, we also applied t-tests for the ABC scores of the two participant groups. For all tests that involved multiple comparisons, we used the Bonferroni corrections.

6 Results

To investigate the difference between the balance data for people from the United States and Bangladesh, we conducted a 2×6 ANOVA. When we noticed a significant difference in the ANOVA test, we applied two-tailed -tests separately for people with and without BI. However, we observed no significant difference between the BI people from the United States and the BI people from Bangladesh; $F(1,123) = 2.1$, $p = .9$; and effect size, $\eta^2 = 0.002$. Also, we did not find any significant difference while comparing the people without BI from the United States and Bangladesh; $F(1,123) = 1.6$, $p = .9$; and effect size, $\eta^2 = 0.001$. As there was no significant difference between BI and without BI people from the United States and Bangladesh, we merged BI people from the United States and Bangladesh to form a combined BI group of 50 people. We also merged the without BI people from the United States and Bangladesh to form a combined without BI group of 50 people.

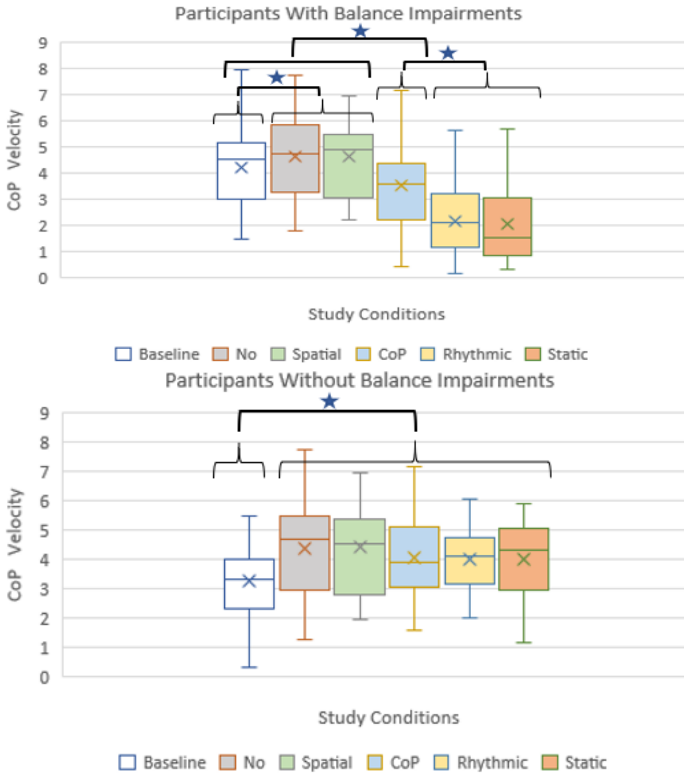


Fig. 5. CoP velocity for standing visual exploration task (within groups).

6.1 CoP Velocity Comparison (Within Group)

From the ANOVA tests, we found a significant difference for individuals with BI for standing visual exploration task, $F(1,123) = 16.8$, $p < .001$; and effect size, $\eta^2 = 0.06$ and for standing reach and grasp task, $F(1,123) = 44.1$, $p < .001$; and effect size, $\eta^2 = 0.04$. Additionally, a significant difference was found for individuals without BI for standing visual exploration task, $F(1,123) = 15.4$, $p < .001$; and effect size, $\eta^2 = 0.04$ and $F(1,123) = 38.98$, $p < .001$; and effect size, $\eta^2 = 0.03$ for standing reach and grasp task. Finally, the pairwise comparisons were performed utilizing t-tests for finding out the differences between study conditions. The results are shown in Table 2. For both groups of participants, figure 5 shows CoP velocity comparisons for different study conditions for the standing visual exploration task and results for the standing reach and grasp task has been shown in Figure 6.

A significant increase in CoP velocity in the no visual condition in VR compared to the real-world baseline conditions for all participants was also found. As balance decreases with the increase of CoP velocity, results indicated that participants had significantly less control in balance in the no visual condition in VR compared to the real-world baseline for both tasks.

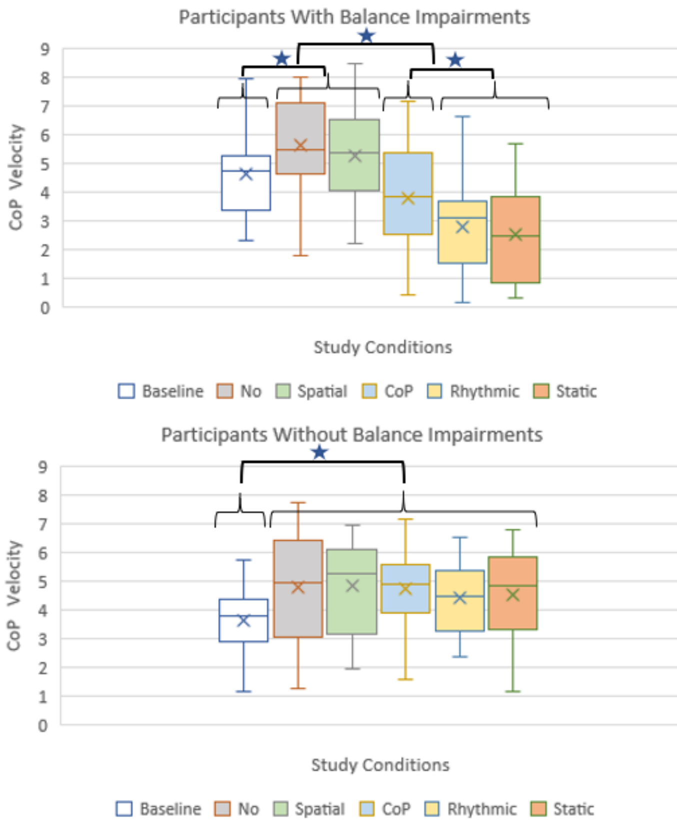


Fig. 6. CoP velocity standing reach and grasp task (within groups).

There was no significant difference between the spatial condition and no visual condition in VR for participants with BI for both tasks. We also found no significant difference between spatial and no visual conditions for participants without BI for both tasks.

For participants with BI, CoP velocity decreased significantly in CoP, rhythmic, and static visual conditions compared to the no visual condition for both tasks. We also found CoP, rhythmic, and static visual conditions outperformed spatial visual conditions significantly. Rhythmic and static conditions also outperformed CoP condition significantly. However, there was no significant difference when comparing rhythmic and static conditions. However, for participants without BI, there was no significant difference in CoP velocity in CoP, rhythmic, and static conditions compared to the no visual condition in VR for both tasks.

6.2 Between Group Comparisons on CoP Velocity

We conducted a 2×6 mixed-model ANOVA to find any significant difference between the BI and without BI groups. we found a significant difference for individuals with BI for standing visual exploration task, $F(1,123) = 18.2$, $p < .001$; and $\eta^2 = 0.08$ and for standing reach and grasp task, $F(1,123) = 46.7$, $p < .001$; and $\eta^2 = 0.06$. There was a significant difference for individuals without BI for standing visual exploration task, $F(1,123) = 18.3$, $p < .001$; and $\eta^2 = 0.07$ and for standing reach and grasp task $F(1,123) = 41.4$, $p < .001$; and $\eta^2 = 0.05$. Next, we conducted the independent sample two-tailed t-tests to identify differences between specific study conditions. The results are shown in Table 3. Figure 7 shows the CoP velocity (mean and SD) for each condition.

Experiment results revealed a significant difference between baseline conditions for all people. There was also a significant difference between no visual, spatial, CoP, rhythmic, and static conditions for all people.

Table 2. Within group pairwise comparisons (Here, t = t-statistic value, p = probability value where the * indicates significant difference, r = correlation)

Comparisons of different study conditions (based on t-tests)	Standing Visual Exploration						Standing Reach and Grasp					
	BI			Without BI			BI			Without BI		
	t	p	r	t	p	r	t	p	r	t	p	r
No Visual vs. Baseline	2.8	.01*	0.89	3.33	.002*	0.37	2.82	.009*	0.35	2.53	.02*	.008
No Visual vs. Spatial	0.08	.94	0.47	0.06	.96	0.53	0.74	.47	0.2	0.04	.97	0.34
No Visual vs. CoP	2.74	.01*	0.14	0.11	.91	0.34	4.95	.01*	0.38	10.42	.07	0.04
No Visual vs. Rhythmic	5.81	<.001*	0.07	0.86	.39	0.41	7.01	<.001*	0.21	0.84	.41	0.82
No Visual vs. Static	5.13	<.001*	0.25	0.84	.41	0.13	5.83	<.001*	0.13	0.5	.62	0.06
Spatial vs. CoP	3.48	.002*	0.77	1.02	.32	0.29	3.18	.004*	0.15	0.17	.86	0.26
Spatial vs. Rhythmic	5.56	<.001*	0.23	1.15	.26	0.06	5.7	<.001*	0.17	1.07	.29	0.17
Spatial vs. Static	5.68	<.001*	0.05	0.96	.35	0.07	6.28	<.001*	0.3	0.61	.55	0.03
CoP vs. Rhythmic	3.48	.002*	0.16	0.25	.4	0.70	3.04	.006*	0.14	1.13	.27	0.43
CoP vs. Static	4.07	<.001*	0.38	0.12	.9	0.11	2.92	.008*	0.26	0.54	.6	0.16
Rhythmic vs. Static	0.4	.7	0.31	0.08	.94	0.09	0.58	.57	0.37	0.26	.8	0.27

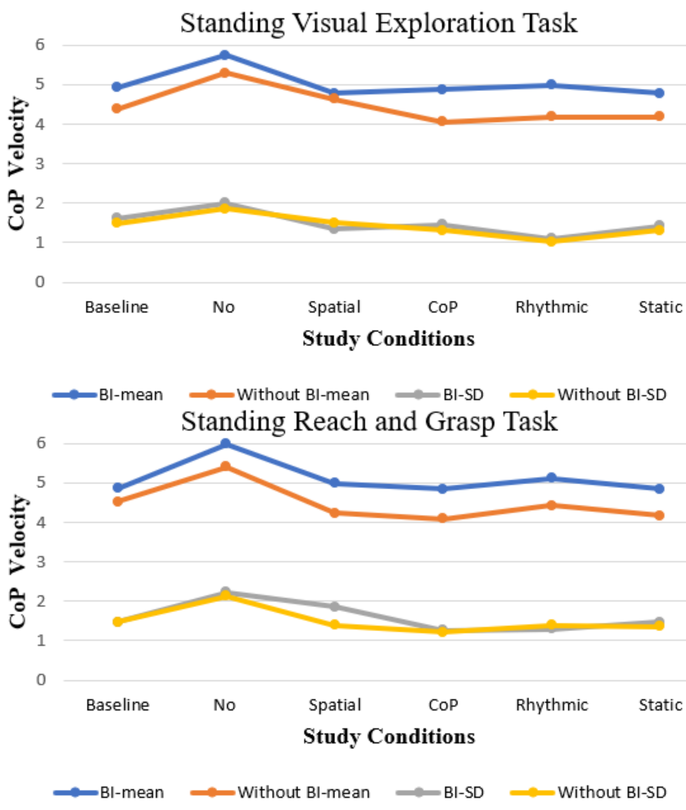


Fig. 7. Between group (BI vs. without BI) CoP velocity comparisons (mean and SD) for standing visual exploration (top), and standing reach and grasp task (bottom).

Table 3. Between group comparisons (BI vs. without BI) for different study conditions (Here, t = t-statistic value, p = probability value where the * indicates significant difference, r = correlation)

Comparisons	Standing Visual Exploration			Standing Reach and Grasp		
	t	p	r	t	p	r
Baseline	2.8	.01*	0.89	2.82	.009*	0.35
No Visual	0.08	.94	0.47	0.74	.47	0.2
Spatial	2.74	.01*	0.14	4.95	.01*	0.38
CoP	5.81	<.001*	0.07	7.01	<.001*	0.21
Rhythmic	5.13	<.001*	0.25	5.83	<.001*	0.13
Static	3.48	.002*	0.77	3.18	.004*	0.15

6.3 ABC Scale Results for Both Groups

We calculated the ABC scale for all participants with and without BI from the United States and Bangladesh, where 80% indicates the participants had a high level of physical ability; 50-80% indicates a moderate level of physical ability; $<$ 50% indicates a low level of physical ability. For people from the United States, the t-test revealed a significant difference for people with BI (M = 69.88, SD = 19.36) and those without BI (M = 94.18, SD = 9.42), $t(49)$ = 2.09, $p < .001$. For people from Bangladesh, the t-test also revealed a significant difference for people with BI (M = 70.39, SD = 12.45) and those without BI (M = 95.2, SD = 7.33), $t(49)$ = 2.08, $p < .001$.

6.4 SSQ Results for Both Groups

There was no significant difference while comparing the pre-study SSQ scores and the post-study SSQ scores for all people in the United States and Bangladesh. For people in the United States, we obtained $t(49)$ = 1.46, p = .09, r = 0.7 for participants with BI and $t(49)$ = 1.17, p = .04, r = 0.64 for participants without BI. For people in Bangladesh, we obtained $t(49)$ = 1.67, p = .08, r = 0.5 for participants with BI and $t(49)$ = 1.55, p = .06, r = 0.41 for without BI group.

7 Discussion and Limitations

7.1 CoP Velocity Comparisons: Virtual Environment vs. Real Environment

CoP velocity was significantly greater in the VR condition with no additional visual feedback than in the real-world condition for both participant groups. Thus, balance diminished in the VR environment without visual feedback, which supported our hypothesis **H1**. Prior studies also indicated that postural instability increases in VR [14, 51], resulting in a higher CoP velocity in VR than in the real world.

7.2 Effect of Visual Feedback Conditions on Balance in VR

As CoP velocity decreases, balance improves, and vice versa [46, 58]. Our experiment results indicated the following effect of visual conditions on balance.

7.2.1 No Visual Feedback in VR vs. All Visual Feedback Conditions

For both tasks, results revealed that the CoP velocity was significantly reduced in static, rhythmic, and CoP visual feedback conditions in VR compared to the no visual feedback in VR condition for people with BI. However, there was no significant difference in CoP velocity for the spatial visual feedback condition compared to the no visual feedback in the VR condition. Therefore, we concluded that static, rhythmic, and CoP visual feedback significantly improved participants' balance in VR, whereas spatial visual feedback had no significant effect, which partially supported our hypothesis **H2**. However, experimental results did not indicate any significant improvement in balance for any condition for participants without BI, which is partially contradictory with the prior studies by Mahmud et al. [32, 33] where they found significant improvement for both people with and without BI. From the experimental results, we hypothesized that the spatial feedback, which is a fixed '+' sign within four frames in front of the participants, did not provide significant feedback. In the static and rhythmic feedback condition, the static frame moved with the movement of the participant's head. Also, in the CoP condition, the boundaries of the frame shifted to the left, right, front, and backward directions based on the CoP directions of the participants. As a result, static, rhythmic, and CoP feedback provided significantly better feedback compared to spatial feedback.

7.2.2 Comparison Between All Visual Feedback Conditions in VR

Experimental results revealed that static and rhythmic visual feedback conditions improved balance significantly better compared to CoP and spatial visual feedback conditions for people with BI, which supported our hypothesis **H3**. CoP visual feedback also improved balance significantly than the spatial condition. However, we obtained no significant difference between static and rhythmic feedback conditions. There was no significant effect of the visual feedback conditions for without BI group. In the static and rhythmic feedback condition, the static frame moved with the movement of the participant's head which was not the case for the CoP and spatial visual feedback condition. Thus, the static and rhythmic conditions might have provided better feedback and outperformed other conditions. The results of our static feedback further supported the results of a previous study focused on static rest frame only [50], where they also investigated the static visual feedback and recruited participants with and without BI. They also did not find any improvement in balance for participants without BI. However, they only investigated the static condition, whereas we investigated static, rhythmic, CoP, and spatial feedback conditions to compare and investigate their effects on balance. However, our results partially contradict the previous findings from the auditory and vibrotactile feedback by Mahmud et al. [32, 33]. For both auditory and vibrotactile feedback, they reported that all conditions (spatial, CoP, static, rhythmic) improved balance significantly for both people with and without BI. However, our current study only found significant improvement for people with BI. We also found no significant effect of the spatial visual feedback method. Our visual feedback methods were entirely different from the prior auditory and vibrotactile feedback methods, which might be the reason for the different outputs. Additionally, prior studies reported that participants with BI relied more on visual cues [16, 50], which might explain why some visual feedback was effective for participants with BI but not for those without BI. However, those previous studies did not find any significant effect on balance for participants without BI. Hasegawa et al. [21] investigated only CoP-based visual feedback in the real world with 18 healthy young adults and found no significant effect on balance. However, we found a significant effect of our CoP-based feedback on balance with 100 people with and without BI. Our CoP-based visual feedback method could provide more feedback in left, right, front, and backward directions with real-time data streaming. In contrast, the prior study by [21] could provide feedback only in forward/backward directions. Also, as the perceptions in the real world and in VR are different, methods that work in the real world might not be effective in VR and vice versa.

7.3 Between Group Comparisons

The ABC ratings suggested that people with BI had diminished physical capability compared to those without BI. From ANOVA and independent sample two-tailed t-tests, we found significant differences between people with and without BI for all conditions (baseline, no visual, spatial, static, rhythmic, and CoP). Our results were contradictory to a prior study by [50], where they found no significant difference for between-group comparisons with 14 participants. Prior auditory and vibrotactile studies [32, 33] only found a significant difference in baseline conditions for between-group comparison with 42 and 39 people, respectively. We hypothesized that the larger sample of 100 people (50 with BI vs. 50 without BI) provided significant differences for between-group comparisons in our study.

7.4 Effect of Different Geographic Locations in Results

There was no significant difference when we compared the BI group in the United States with the BI group from Bangladesh and without BI group from the United States with the without BI group from Bangladesh. Therefore, we concluded there was no significant effect of different geographic locations on balance data. We recruited statistically and symptomatically similar people in both locations, which might be a reason for no significant difference between them.

7.5 Cybersickness

No significant increase in SSQ scores was found for both groups, indicating that participants were not impacted by cybersickness. Participants might have been affected by mild cybersickness because our study consisted of two tasks with many trials and conditions, which took around one and a half hours to complete. When engaging in VR activities for more than 10 minutes, cybersickness is prevalent [7, 28]. As there was no illusory self-motion, our environment was meant to be simple and cybersickness-free [36]. Therefore, we reasoned that cybersickness had no impact on our balance data.

7.6 Limitations

To develop CoP visual feedback, participants' CoP value was used, and the static frame boundaries shifted outward based on the amount of CoP displacement in order to provide participants with CoP visual feedback based on their balance board position. It is unclear, however, how lower levels of latency will modify our outcomes for this condition.

For rhythmic visual condition, we selected a one-second interval to show the static frame based on prior studies [32, 33]. However, we did not investigate this feedback condition for other time intervals (e.g., two-second). Therefore, studies that would apply "rhythmic" visual feedback for different time intervals might find slightly different results for this specific condition.

The table height was not modified based on the height of the participants which might have affected the results. Nonetheless, Table 1 shows that participants has no significant difference in heights. Thus we anticipated that it would have little impact.

For the duration of the experiment, participants wore harnesses to prevent falls, which could have improved their balance marginally. However, all people used harnesses. Thus, the findings of research examining balance without a harness may vary slightly.

The study lasted around one and a half hours, and participants viewed the visual feedback and performed virtual tasks for a long time while standing on the balance board. This often resulted in weariness, requiring participants to rest for a few minutes between trials by removing the HMD which might have skewed the results slightly.

The mean CoP velocity was measured, which is a standard metric for measuring balance [30]. Nevertheless, we did not quantify whole-body movement.

Although prior research reported auditory and vibrotactile feedback, we could not conduct a multimodal study comparing visual, auditory, and vibrotactile methods at this point because the study time would increase significantly with a lot of study conditions, and people with BI who had reduced physical functionality would be unable to participate. However, from the findings of our current and prior studies, we plan to filter out the best visual, auditory, and vibrotactile methods for balance improvement and run a multimodal study in the future, which will be feasible. Also, visual methods are perceptually different from auditory and vibrotactile feedback, which motivated us to investigate the visual feedback methods for our current study.

8 Conclusion

In this study, the impact of various visual feedback systems on VR balance was investigated in two different geographic locations (United States and Bangladesh). We found static, rhythmic, and CoP visual feedback significantly improved balance in VR for both locations. Static and rhythmic visual feedback performed significantly better than the CoP visual feedback. This study was inconclusive between static and rhythmic visual feedback with no significant difference. Researchers will get a better understanding of the various types of visual feedback in immersive virtual reality as a consequence of this study. Moreover, this research will help to create more accessible virtual reality experiences for people with balance impairments. In the future, we will investigate the effect of multimodal feedback (auditory, vibrotactile, and visual) on balance in immersive VR.

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