PhantomLegs: Reducing Virtual Reality Sickness using Head-Worn Haptic Devices

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Abstract

Virtual Reality (VR) sickness occurs when exposure to a virtual environment causes symptoms that are similar to motion sickness, and has been one of the major user experience barriers of VR. To reduce VR sickness, prior work has explored dynamic field-of-view modification and galvanic vestibular stimulation (GVS) that recouples the visual and vestibular systems. We propose a new approach to reduce VR sickness, called PhantomLegs, that applies alternating haptic cues that are synchronized to users' footsteps in VR. Our prototype consists of two servos with padded swing arms, one set on each side of the head, that lightly taps the head as users walk in VR. We conducted a three-session, multi-day user study with 30 participants to evaluate its effects as users navigate through a VR environment while physically being seated. Results show that our approach significantly reduces VR sickness during the initial exposure while remaining comfortable to users.

Index Terms: Human-centered computing—Virtual Reality—Interaction techniques—Locomotion; Human-centered computing—Virtual Reality—Interaction techniques—Haptics

Figure 1: A seated participant navigating in the virtual environment with HTC Vive HMD and controller, assisted by PhantomLegs haptic device.

1 Introduction

Virtual reality (VR) technology has become more mature in past few years, seeing a surge in both user base and application market. Since the early stage of the technology, hardware and software developers have been tackling several technical difficulties to improve the user experience in VR. Thanks to the improved 6-degree-of-freedom (6DOF) tracking technology used in premium VR systems and advance in graphical rendering performance that helps achieve stable frame rate of 90 per second recommended by the manufacturers, the Motion-to-Photon latency is greatly reduced when the user moves or rotates in reality under tracking. However, one of the biggest obstacles that still awaits an ideal solution is the motion sickness experienced by VR users, which causes several symptoms such as headache, nausea, vomit, fatigue and stomach awareness. VR users have reported sickness when they moved in the virtual environment using conventional joystick controls while their physical body remained stationary [25]. This problem is widely known and regarded as *cybersickness* [27]. And researchers have found that the cause behind such sickness is mostly due to the conflict between the perceptions from the visual and the vestibular system [12].

To reduce the sickness caused by sensory conflicts, several workarounds have been brought onto the table albeit with tradeoffs in different aspects. Physical-based moving solves the problem by mapping the user's motion to the avatar, but the cost of installation is not ideal in some implementations, and users may experience fatigue after extended usage. Pure visual solutions such as teleportation, while effective and easy to implement, are sometimes immersion-breaking as it reduces the plausibility of the experience [41]. Applying a subtle dynamic visual cutoff to reduce the field of view (FOV) based on velocity [15] has been proven to reduce sickness, but the visual feedback of smooth movement does not resemble real-life walking experience. Some novel approaches solve the mismatch by stimulating vestibular system based on avatar's movement, but direct stimulations on a perceptual system may be uncomfortable for some users and at worst cause side-effects on the body, which in our opinion might not be justified for sole entertainment purpose.

Our approach to the problem is to produce an illusion to resemble the experience of walking using external haptic feedback. The idea was based on the observation that we receive subtle impact on the head at every step during real-body walking. By re-introducing haptic cues to the user's virtual walking, we hypothesize that our method can reduce the cybersickness caused by sensory conflicts. It should be emphasized that the purpose of our method is not to directly stimulate the vestibular system; instead, our main focus is to create an haptic-vestibular illusion of walking through a non-intrusive method. In this work, we presented a prototypical haptic device called PhantomLegs (Fig. 1) that applies a tactile force on the user's head in synchronization with the user's virtual movement to create such illusion. While the actual psychological or biological effect behind our approach is unclear and under further inspection, our study reported that our method has significantly reduced the cybersickness experienced by the VR users during the initial exposure.

2 Related Work

These works are related to the exploration and solution for the cybersickness, and the studies of illusion used in VR.

2.1 Exploration and Solution for Cybersickness

There are plenty of research [11, 26, 27, 36, 44] about the exploration on cybersickness. Cybersickness is the condition that may occur

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during or after exposure to a virtual environment and it can induce symptoms like headache or nausea [27]. It is also estimated that such symptoms could be found in around 30% to 80% of VR users [36]. While cybersickness brings about similar symptoms with motion sickness or simulator sickness that could be experienced during daily life, they are induced in different kinds of exposure [26, 27, 44] and the theories behind the symptoms are still argued [11]. Nevertheless, there are a clear relation between those three sicknesses, implying the underlying physiological causes may be related too [23]. Based on the solutions to the motion sickness or other similar symptoms experienced in real world, researchers have extended those solutions to address the cybersickness experienced in VR locomotion [2, 4, 21] (one of the most widely used types of interaction in VR applications that move users viewpoint in virtual environment), including methods like visual modification, body movement and visuo-vestibular system recoupling.

Visual Modification Visual solutions are favorable for application developers since no additional equipment is needed and the extra effort for the user is minimal. The most common workaround used in VR applications today is *teleportation* [20]: the viewpoint instantly teleports to the desired position after a visual cutout transition such as blurring, vignette or blink. The cybersickness is hardly present since the user's viewpoint remains stationary with the user's physical body and little self-motion perception is observed. This method, however, might not be suitable for some scenarios where such mechanics may break the user's immersion to the virtual environment [5]. For example, implementing instant-moving mechanics can be problematic for gameplay in multi-player shooter games, and users may find the mechanics diminishing their presence [17,39,49] in a realistic setting of the environment. Furthermore, some may find themselves briefly losing sense of direction after a sudden relocation, taking extra effort to recognize their surroundings [9].

Some researchers approached the problem with a *dynamically changing field of view (FOV)* as a subtle visual cue to reduce the sickness [7, 15]. Their solution is effective, but the visual perception from the smooth movement used in the implementation resembles "sliding" more than walking. To address this, we decided to explore the possibility of a more natural visual behavior (e.g. head-bobbing patterns [3, 29, 35, 48]) for walking in response to conventional joystick input, and to test if a dynamic FOV remains effective in the improved behavior.

Body Movement One way to fix the mismatch between visual and vestibular systems is moving the user's viewpoint through physical body movement. Placing the user on a *treadmill* [22,42,46] could be one of the more straightforward solutions that attempt to match the movement in the virtual environment with the physical movement in reality. This method is also one common instance of the concept called *walk-in-place* mentioned in many previous works [33]. However, the cost and the space needed for installation might be a barrier for a mass-market solution. Other researchers also managed to use rotational chair to reduce 2D cybersickness [38]. Pai *et al.* [34] have implemented an *"armswing"* movement method that fills the role of human legs with arms; the user's view point movement is based on the relative physical movement of the hand-held controllers. While the method is effective against the VR sickness, the ability to interact with the environment during movement is sacrificed as the arms are occupied, and the method may cause fatigue over time, shortening the period of usage. One research further reduced the user's body movement [40], proposing a biomechanically-inspired approach that allow users to tap the controllers' trigger in turn to simulate their steps in VR. Though this method might mitigate user's fatigue, the occupied controllers meanwhile limit the scenario this approach could be applied on.

Visuo-Vestibular System Recoupling One of the options used in combating motion sickness in flight simulation is using *galvanic stimulation* [19,31,51]. However, the potential risk to the body after long exposure is unknown [50]. To find an alternative for vestibular stimulation, Weech *et al.* used *bone-conducted vibration (BCV)* [50] to tackle VR sickness. Although BCV displayed no negative effects on users in previous research, we believe there exists a simpler yet effective alternative that indirectly affects the vestibular system and helps alleviate the cybersickness. For instance, D'Amour *et al.* [10] explored using *airflow and seat vibration* to reduce visually imposed cybersickness. While seat vibration failed to show effectiveness, airflow feedback reduced sickness significantly when watching a bicycle-riding first-person video. Other works also incorporated foot-embedded vibrotactile feedback and footstep auditory to alleviate cybersickness while waking in VR [24, 47]. These results suggest that using an indirect, walking-related haptic illusion to recouple mismatched systems might be a plausible approach.

2.2 Illusion used in Virtual Reality

Pseudo haptics and visuo-haptic illusions have been extensively explored in virtual reality applications. The idea is to fake haptic stimulation with visual modifications taking advantages of low resolution in the human haptic system versus visual system [28]. Visual modifications were made synchronized to user motions, such as repositioning the finger position when touching an object. This trick has been applied to simulate object friction [30] and stiffness [43]. Similarly, introducing perceivable delay or forwarding to body motions can affect user perception of forces [8] and weight [13]. In addition, visual modification was made to object deformation in the respondent to contact with the user's hand to simulate touch sensation.

Meanwhile, the visual illusions of walking have also been explored by previous works [6, 37]. Methods like layered motion [14, 18], contour filtering [16], blindness alteration [45] or contrast inversion [1, 32] have been proposed to induce self-motion illusions in immersive VR. In this work, we opted to apply natural visual illusion [3,29,48] augmented with the haptic feedback which generating the illusion of foot stepping vibration alternatively near the lower part of both ears, to further explore its effectiveness on reducing cybersickness in VR.

3 Prototype Design

Our design strategy for recoupling visuo-vestibular perception was inspired by the walking experience in real life. When we walk, we observed that the impact of stepping on the ground can not only be felt by the contacting foot but also be passed to cervical spine and up to the head, creating a vibration where the visual and vestibular receptors are located. To generate the illusion of a foot-step vibration, we designed a head-mounted device to provide haptic feedback cues that would be synchronized with footsteps of the avatar.

3.1 Haptic Feedback Device

The haptic feedback device is driven by an Arduino board (Uno for the first iteration that was used in the experiment, Nano for the second iteration) fixed onto the back of the Vive HMD. A pair of SG-90 180-degree servo motors are attached to each side of the HMD and connected to the Arduino board via digital ports. The Arduino board communicates with the PC via serial port signal through the additional USB port on the HMD.

A joint made of hard iron is attached to each servo motor. One tip of the joint is bound together with a detachable horn that comes with the motor, and the other tip, which contacts the user when engaged, is bent 180° backwards and covered with a sponge to minimize the discomfort. The wire is bent 90° inwards relative to the user at around 1/3 from the contacting tip. The contacting tip is designed to strike slightly in front of the lower part of the ears, a location both close to the vestibular system and easy to reach from the HMD. In this paper, we refer to this extension as a *joint*.

(a) Idle (b) Engaged

Figure 2: The two states of Phantom Leg device.

The device listens for three types of command:

- Engage Left/Right Servo Motor: When engaged, the servo motor rotates 60° inwards relative to the user as seen on Fig. 2b, and moves back to its original angle as seen on Fig. 2a after a 200ms delay.
- Increase/Decrease Tightness: Adjust the starting angle between two servo motors, namely the perceived tightness when engaged, by a step of 10°. The adjustable range is bound within the maximum range of 180° due to the limitation of the servo motor. The torque provided by the motor is 1.8 kg-cm according to its specification, and its rotating speed 600°/s.
- Reset Tightness

3.2 Visual Feedback and Timing for Haptic Cues

To simulate the walking experience, the vision during movement should feel natural to the user, and the haptic cues should synchronize with the visual feedback. To simulate the vision under real-life walking, a dynamic offset should be applied to the transform of the HMD in a convincing manner during virtual movement. Our hypothetical solution was using the user's self-recorded HMD transform data for playback to simulate walking, which in theory should be more familiar and thus more comfortable to the user. We conducted a pilot study under the following three conditions to compare the effects from using different sources of visual feedback.

- Using self-recorded data: Each participant used their own previously recorded data for playback.
- Using third-party data: Each participant used the same set of data recorded by a participant that did not partake in the experiment. We wanted to examine if using own data has an advantage over using another person's real-walking data in terms of comfort.
- Using computed data: A computer-generated viewpoint modifying technique commonly used in non-VR first-person-view applications to simulate walking. The technique is also known as "head-bobbing".

3.3 Recording walking data

To retrieve walking data of each participant, we attached a Vive Controller to each leg of the participant under the knees for step recognition, and instructed them to walk naturally on a straight line of six meters with the HMD put on while we tracked and recorded the transform data of the HMD and two controllers at a fixed rate of 60 FPS. The retrieved data were analyzed through a self-developed playback system and left/right step events were marked based on the frames they occurred. One of the participants whose data was used in the second condition only participated in recording data but not in the actual experiment.

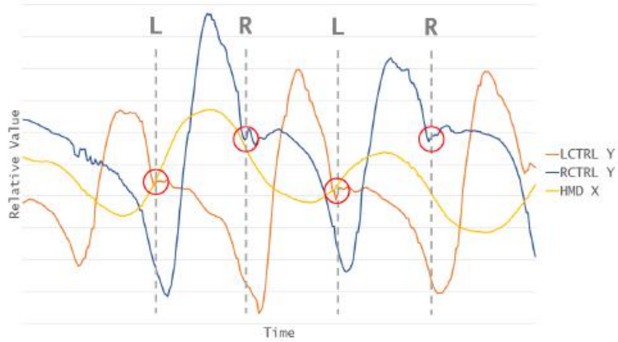


Figure 3: The visualization on a sequence of transform recorded by a participant for the pilot study, with horizontal axis representing the time frame. When recording, participants were asked to walk along the Z-axis seen in the virtual environment. Orange line represents the height of the left controller attached to the left leg, and blue line represents that of the right controller attached to the right leg. A "step" is recognized by the sudden stop in the change of height on either leg, marked with grey lines and L/R indicators. Yellow line represents X position of the HMD, positive being left direction. It can be observed that the head moved back at center every time a step happened.

3.4 Computed data

For comparison, a computer-generated transform animation on the camera was employed in one of the conditions for our pilot study. Camera oscillation for travelling in virtual environment has been explored with positive results on perceptions of motion and distance [3, 29, 48]. However, to work with the haptic device, the timing where a step is dropped during an oscillation period needs to be identified. We modelled a computed head-bobbing pattern using a sine wave based on the analysis on the data as visualized in Fig. 3. We used an angle value α, increasing it at the rate of 320°/s when moving to drive the bobbing effect. Upon releasing the trigger, the value is snapped back to 0° or 180°, whichever is closer. *sin* is used for the horizontal movement instead of *cos* to make the movement start from center when $\alpha = 0°$ or 180°. The formula for current normalized horizontal offset is as following:

$$\delta_x = sin(\alpha)$$

From the analysis on the data, we discovered that when the left or right leg is raised to the highest point, the position of the head offsets towards the opposite direction. Therefore, when α is 90°, δ_x is at the rightmost, implying the left leg is raised, and vice versa. The head reaches its highest point when either leg is raised to the highest point, and its lowest when the raised leg returns to the ground. Thus, the formula for current normalized vertical offset is as following:

$$\delta_y = |\delta_x| \times 2$$

When α reaches 0° or 180° when moving, δ_y returns to 0, signalling a right or left step respectively.

Finally, when the maximum offset of bobbing effect is set to O_x m horizontally and O_y m vertically, the offset vector at angle α is:

$$v_d = (O_x \times \delta_x, O_y \times \delta_y)$$

In the experiment, O_x was set to 0.02m and O_y was set to 0.03m based on the average estimation from the data. When using computed data, the position of the avatar moved towards the next checkpoint at a constant speed of 1.5 m/s, estimated from the average speed of the data.

3.5 Pilot Study

To evaluate the selected approaches, we conducted a three-session pilot experiment each using a different source of data. A total of six participants (3 female, mean age = 23.5), excluding the one whose data was used as third-party data, were present in the pilot experiment. All of the participants recorded their walking data prior to the experiment. Each participant took part in all three sessions, each of which held on a different day.

We set up a virtual environment and an ordered set of checkpoints for the participant to traverse. The environment design of the pilot study was a smaller version of the one used in the formal study explained later in Sect. 4.3, except that each checkpoint was placed six meters away from its predecessor due to the length of our recorded data. The information retrieved was in the format of pre-session and post-session Simulator Sickness Questionnaires (SSQ) [23] and discomfort scores (1-10) over time that were acquired via verbal response in a fixed interval of five checkpoints. The data-retrieving procedure was identical to the one used in the formal study described in Sect. 4.4.

For the two conditions utilizing a set of recorded walking data, when the participant pulled the trigger on the controller, the data were played back and the avatar was transformed based on current time position. The transform was linearly interpolated when the time position fell between two recorded frames. Because the avatar could only walk in a straight line, to eliminate the potential sickness from sudden changes in direction, when the avatar arrived at a checkpoint, an opaque overlay would fade in and then fade out after the avatar was rotated towards the next checkpoint.

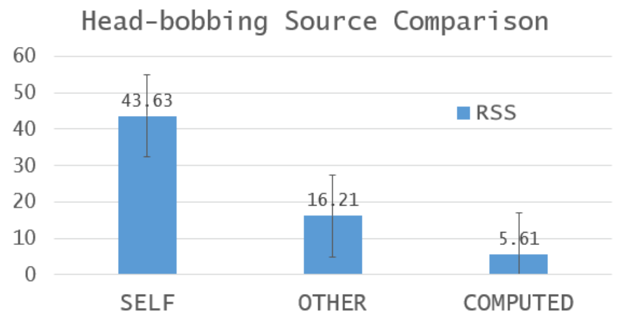


Figure 4: The means and standard errors of relative SSQ score (*RSS*) computed with the pre- and post-session SSQ reported by the participants during the pilot study. The computation procedure was identical to the one used in the formal study explained in Sect. 5.

From the verbal feedback and the evaluated metrics (Fig. 4) of the experiment, we learned that self-recorded data didn't work as well as we had assumed because of the unpredictable jitters during walking. The jitters were expected and instinctively balanced by the participants' body when they walked in person, but not when they simulated the data on a chair. Some participants reported that to their surprise, their head was bobbing more drastically than how they remembered recording. The result may explain the cybersickness experienced by the viewer when playing back a 360° VR video even though the video was self-recorded with a 360° camera.

In contrast, the sickness perceived from using 3rd-party data was far less severe than from using own data. All participants commented that the movement in the data was noticeably smoother and less jittery than in their own data, and some of them considered the experience more natural.

The sessions using computed data were the most favorable experience according to both the metrics and the verbal feedback from participants. They found the bobbing movement smooth and predictable, and one participant described the experience "as comfortable as sitting in a cradle."

From the pilot experiment, we concluded that using own walking data to simulate walking in VR neither provides significant benefit on perceived naturalness, nor guarantees lower cybersickness. Based on the result, we opted for using computed data in our user study.

3.6 Variations of Haptic Feedback

In our pilot study, we also experimented with several kinds of haptic feedback besides striking method described in Sect. 3.1. These variants were separately tested with the aforementioned computed visual bobbing applied. Note that the methods explained here were an initial exploration, and we plan to perform an exhaustive experiment on this topic in our future work.

Vibration on Hand-Held Controllers We mapped the haptic feedback to both hand-held Vive Controllers, triggering the vibration on the correspondent controller when a step was engaged. During experiment, we found it hard to relate the feedback received by the hands to the walking experience perceived in vision, as two receptors were too far apart from each other.

Vibration on the Jawbone We replaced the servo motors with coin vibration motors adhered to the same location where the joints would strike using breathable tapes. The vibrators were hardly felt when idling. However, while the effectiveness was comparable to the original striking method, most participants disliked this form of feedback compared to the original one. Some users stated that having vibration directly to the head felt like being electrocuted.

Compared with aforementioned methods, striking feedback described in Sect. 3.1 appears to be the most comfortable and preferable technique. Based on these results collected from the pilot study, we decided to apply striking haptic feedback on the adjacent location of lower ears, coupled with computer-generated viewpoint modification as an overall feedback mechanism for PhantomLegs. We then compared this method with other techniques in the following user study.

4 User Study

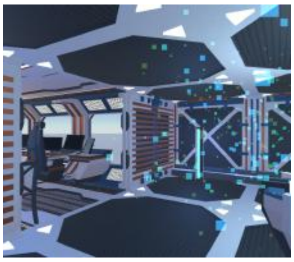
4.1 Experiment Design

We designed a three-session mixed experiment testing the effectiveness on battling cybersickness between three conditions: a) the unmodified condition without external assistance, b) applying a dynamically changing FOV implemented using the specification described by Fernandes *et al.* [15], and c) assisting with the external haptic device. We refer to these conditions as *CONTROL*, *DFOV* and *HAPTIC* respectively. All three conditions have the computed head-bobbing effect applied. Due to the difficulty of effectively removing the sound from the servo motors used in *HAPTIC* sessions as they were installed right next to the ears, we decided to leave the motors active in all three conditions, but the joints were attached only in *HAPTIC* sessions. Each participant was randomly assigned with one of the 6 counterbalancing orders of three conditions. Each participant's three sessions were held on different days, and to minimize the impact between sessions, every two consecutive sessions were separated with a rest day. We scheduled every session of the same participant at the same time of the day, and we maintained the airflow of the testing environment with air-conditioner set to a comfortable temperature. Participants were seated on a rotatable office chair throughout the experiment.

4.2 Apparatus

We used HTC Vive MK1 coupled with a VR-capable PC that operates on Intel i7-8700K CPU and nVidia GTX1080ti GPU to ensure the optimal 90 FPS throughout the experiment.

(a) Outdoor village



(b) Indoor Sci-Fi passage

Figure 5: Screenshots of indoor and outdoor areas in the virtual environment.

Figure 6: The top-down view of the virtual environment built for experiment. White dots represent the positions of 110 checkpoints, white lines connects every two consecutive checkpoints, and the red dot represents the starting position of the avatar. The red arrow indicates the starting direction.

4.3 Environment and Task Design

We constructed the virtual environment for the experiment using several assets available on Unity Asset Store, including various themes such as middle age village and castle, outdoor quarry and forest, and indoor Sci-Fi passages (Fig. 5). To maintain the stability of the rendering performance, we disabled all the shadows in the environment. A total of 110 ordered checkpoints were placed in the environment, each of which was placed 12m away from its predecessor (Fig. 6). There is no difference in height across all checkpoints. The active checkpoint towards which the participant was instructed to move was marked with a 2m-tall cyan-colored torch with flame particles on the top and a spotlight of 0.8m radius on the ground (Fig. 7). When the participant's avatar moved into the area of the spotlight, the next checkpoint in order was activated and the torch was relocated to its position. A line was rendered on the ground to indicate the upcoming turn.

Upon the beginning of the experiment, the participant's avatar was spawned at the location of the first checkpoint, and the experiment was completed as soon as the avatar returns to the first checkpoint after traversing all other checkpoints. The height of the participant was set to their standing height in reality. The participant was given a single Vive Controller to navigate in the environment: when the trigger is pulled to the maximum where it gives a clicking feedback, the avatar moves at a constant speed of 1.5 m/s in the direction that the controller is pointing, ignoring Y-axis of the vector. Although lateral movement was doable, participants were instructed to exploit the rotatable chair for changing direction and only change the rotation of the controller for refined adjustment.

4.4 Procedures

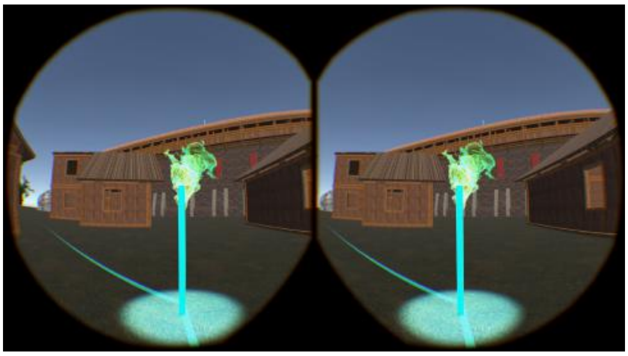


Figure 7: The indicator for the current checkpoint. The line on the ground connects current, last and next checkpoints to guide users.

Each participant was asked to complete a pre-session Simulator Sickness Questionnaire (SSQ) [23] upon their arrival of the session. Each participant was then asked if they had had prior experience with VR. If not, we gave a brief introduction on what to expect in a VR environment.

Before the experiment, we delivered a scripted verbal instruction on the task and the movement mechanics. We then measured the participant's interpupillary distance (IPD). Additionally, for the *HAPTIC* sessions, the participant were informed that the tightness of the haptic feedback could be adjusted by pressing the touchpad on the front face of the Vive Controller, and upon any adjustment, the servo motors on both sides would engage to demonstrate the current tightness. We then instructed them to adjust it to the point where the feedback would give an impression more like a press than a touch while remaining comfortable, and that the sponge on the tip of the joint shouldn't have already contacted them in idle.

After the participant put on the HMD, they were instructed to adjust the IPD setting to the measured distance and make sure that everything in the virtual display looked clear. To avoid the unnecessary visual impact, they were asked to close their eyes before we launched the program, and then stand up briefly to help us calibrate their height for the simulation. The adjusting process for haptic feedback exclusive to *HAPTIC* sessions was conducted before the height calibration.

When the preparation was ready, we removed the opaque overlay on the rendering camera, and the participant was asked to open their eyes and look around to see whether the device was tracking their rotation correctly before they started navigating in the virtual environment.

After they reached every fifth checkpoint, the controller input was temporarily disabled as a semi-transparent black overlay with helper text appeared in their sight. They were then asked the question verbally, "How sick or uncomfortable do you feel on the scale of 1-10, 1 being how you felt before the experiment and 10 being that you have the urge to quit the experiment immediately?" The participant then answered their discomfort score via verbal response. Afterwards, they regained control of their movement. A total of 22 discomfort scores were collected in a session. When the participant answered with a 10, we terminated the experiment immediately, though we decided not to state it explicitly beforehand to prevent intentional abuse. Reported discomfort scores were recorded to track the relative fluctuation of discomfort during the session.

After the experiment was terminated or completed, the participant was asked to complete a post-session SSQ identical to the pre-session one. For the *HAPTIC* sessions, we asked the participants how they felt about the haptic device regarding its comfort. Finally, we asked for additional comments from the participant before ending the session.

4.5 Hypotheses

We formulated hypotheses based on results from our pilot studies. We assumed that the haptic device should be significantly more effective in battling cybersickness under a realistic visual oscillation pattern. All participants in the formal study took part in all three sessions under the control condition (*CONTROL*), the dynamic-FOV-applied condition (*DFOV*), and the haptic-device-assisted condition (*HAPTIC*) in six counterbalanced orders and held on three days (*1, 2, 3*). For reference, the *CONTROL* sessions held on the first day are referred to as *CONTROL1*, the *DFOV* sessions held on the second day are referred to as *DFOV2*, and so on and so forth.

Hypothesis 1 (H1): *The discomfort reported from* HAPTIC1 *will be less than those from* CONTROL1 *and* DFOV1 *under a visual bobbing pattern.*

For the novice user, the relationship is expected on the first day if PhantomLegs reduce cybersickness. Note that the comparison is between participants and involves no order effects, which have been addressed as a non-trivial factor in previous literature related to cybersickness [15].

Hypothesis 2 (H2): *The discomfort reported from all* HAPTIC *sessions will be less than those from* CONTROL *and* DFOV *sessions under a visual bobbing pattern. The comparison is within subjects.*

4.6 Participants

A total of 30 participants were recruited via online groups and on the campus to participate in the experiment. The group of participants consisted of 11 men and 19 women, and their mean age was 21.63 ($SD = 2.46,\ range = [19,\ 27]$). All participants had normal or corrected to normal vision, and had not experienced VR more than three times in past four months. Each participant received USD$10 for each session they attended. No participants were absent in any sessions.

In the study, we refer to each participant as their number assigned with their order on the schedule, for example, the first participant is referred to as 1, and the last participant 30. Participants were divided into 6 groups for counterbalancing, each of which took the sessions in different order. We refer to each group with their order of conditions. For example, the group of participants that had their *CONTROL* session on the first day, *DFOV* session on the second day and *HAPTIC* session on the last day is referred to as group *CONTROL1-DFOV2-HAPTIC3*.

5 Result

To validate our hypotheses, we composed a relative SSQ for each session by subtracting each score in the pre-session SSQ from their counterpart in the post-session SSQ, clamped at 0 if the difference is less than 0. We then computed a *relative SSQ score (RSS)* from the relative SSQ using the guidelines provided by Kennedy *et al.* [23]. The results on the first day and from all sessions are shown in Fig. 8 and Fig. 9. Due to the high variability displayed by the results, we applied a square root transformation on RSS to achieve homogeneity of variance across groups. The transformed data were then statistically analyzed and explored as below.

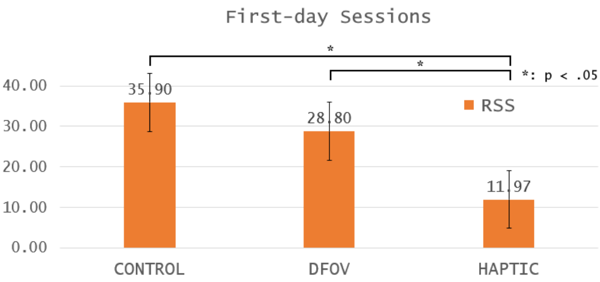


Figure 8: The means and standard errors of RSS from the 30 sessions on the first day. Brackets indicate a significant difference between two conditions reported by post-hoc tests.

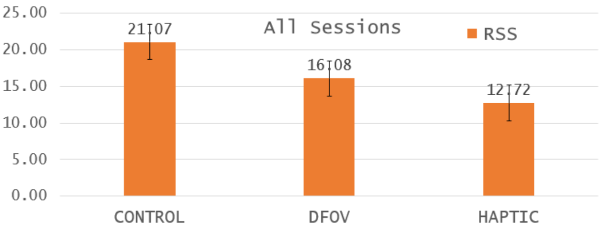


Figure 9: The means and standard errors of RSS from all 90 sessions.

5.1 Hypothesis 1: HAPTIC1 *vs.* CONTROL1/DFOV1

We compared transformed RSS for three conditions using one-way ANOVA, and the result supported the hypothesis ($F(2,27) = 3.684$, $p = 0.038$). The post-hoc test (Fig. 8) shows that RSS in *HAPTIC1* is significantly lower than in *CONTROL1* and *DFOV1*.

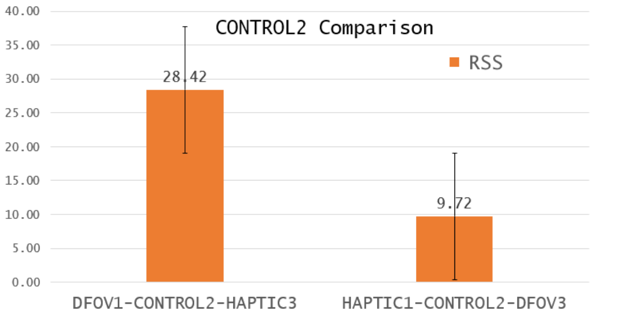
5.2 Hypothesis 2: HAPTIC *vs.* CONTROL/DFOV

We compared transformed RSS for three conditions from all 90 sessions using within-subject one-way repeated measures ANOVA. There is no significant difference between the three conditions ($F(2,58) = 2.040$, $p = 0.139$). However, in the experiment, we have discovered that *HAPTIC* might help the user better and faster accommodate to the VR experience, leading to relatively lower discomfort in the later sessions of conditions *CONTROL* or *DFOV* even when the order effect was considered.

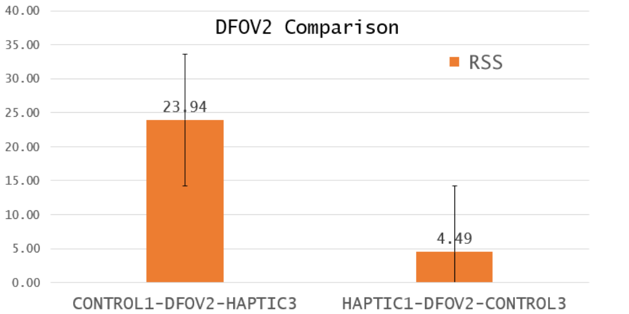
To demonstrate the effect, we compared the *CONTROL2* sessions in two order groups *DFOV1-CONTROL2-HAPTIC3* and *HAPTIC1-CONTROL2-DFOV3*, and the *DFOV2* sessions in group *CONTROL1-DFOV2-HAPTIC3* and *HAPTIC1-DFOV2-CONTROL3*. We chose these two groups because they were purely affected by the prior condition. From Fig. 10 we observed that the sessions that followed session *HAPTIC* displayed lower discomfort than those following either session *CONTROL* or *DFOV*. This phenomenon might explain the lack of significance in *HAPTIC vs. CONTROL/DFOV* comparison as the influence from three conditions were not equal. While it is difficult to assert statistical significance due to the small sample size of 5 in each group, we plan to examine this effect in the future.

6 Discussion

Reception on the haptic device For the *HAPTIC* sessions, we asked the participant post-session for their opinion on the haptic feedback provided by the device. Because we have designed a procedure to help user adjust the tightness of the haptic feedback to their liking, most participants enjoyed the experience with the device. Several participants described the feedback as receiving facial massage, and didn't find it annoying or intrusive. One participant



(a) The means and standard errors of RSS from *CONTROL2* sessions that followed a *DFOV1* or *HAPTIC1* session.



(b) The means and standard errors of RSS from *DFOV2* sessions that followed a *CONTROL1* or *HAPTIC1* session.

Figure 10: The training effect of the haptic feedback used in *HAPTIC* sessions.

found the feedback ”weird” in a neutral sense, unable to elaborate. Another one complained about the inevitable noise from the servo motors, saying ”the sound makes me feel like a walking robot.”

In general, the haptic feedback has shown effect even when operated in a mild and well-accepted behavior. This implies that a subtle and indirect approach can be utilized to effectively reduce the cybersickness.

Unconscious head-bobbing reaction During the *HAPTIC* sessions, we noticed that some of the participants would subtly bob their head along with the provided visuo-haptic feedback. After the study, we informed those participants what we observed, and most of them were unconscious about their head movement. The cause of this phenomenon is unclear. We hypothesized that it is similar to a reflex caused by the vestibular system as a reaction to the illusion of walking created by the haptic feedback. In the future, we will devise a study to further examine this observation to have a better understanding on how the feedback helps alleviate cybersickness.

Training wheel effect From the result of our user study, we observed a promising trend in Fig. 10 that, compared to the other two conditions, using the haptic feedback on the first session resulted in lower discomfort on the second session. We hypothesized that our haptic device may provide a *training wheel effect* on battling cybersickness, which should be proven in our future work.

Increased sickness in enclosed environment In the environment design, we set up an indoor area of Sci-Fi passages in which we saw an increase in discomfort reported by our participants from the pilot experiment. In the formal study, we expected the average discomfort score across sessions would temporarily rise as participants entered the enclosed area, and return to normal as they exited.

From the result of the formal study (shown in Fig. 11), we observed a sudden non-linear increase of average discomfort score in answer 7 and 8, which are located in the indoor Sci-Fi passages, and the score returned to normal as the avatar left the area in answer 9. Some participants reported that, when moving in an enclosed environment, the perception of movement was stronger as they were more aware of the surrounding objects that appeared closer, and some others found the particles as seen on Fig. 5b causing a spike in discomfort when walking through them. In future study, we may discover the relevance between cybersickness and perceived distance of virtual objects during movement, and whether a dynamically adjusting haptic feedback based on the perceived environment could remedy the impact when traversing in an indoor area.

7 LIMITATIONS

The findings from the study suggested that our implementation of a haptic feedback device was successful in reducing cybersickness during the initial exposure and showing an encouraging trend across multiple exposures. However, due to constraints imposed when designing the experiment, a number of controlled factors are left for us to further explore.

Different terrain Because the walking data retrieved in pilot studies were recorded on a flat ground, and the computed method was modelled accordingly, we decided not to include any slopes or elevations in the designed virtual environment so the avatar’s movement would fit the walking model more accurately. To discover whether our approach to the problem can apply to a more diverse environment, further research needs to be done in uphill/downhill walking behavior and how it should be coupled with the haptic feedback.

Variable speed Since we only recorded the movement data from regular walking, the avatar was constrained to move in a constant speed during the experiment, which in practice might pose a limitation on applicable scenarios. To open up freedom of movement for the users, we have to discover the relationship between moving speed and the frequency and strength of the haptic feedback. Is the device or the selected source of feedback suitable when the avatar moves slower or faster, or even when running? More information should be gathered for us to fit our solution into a more flexible implementation.

Lateral movement and rotation Our visuo-haptic feedback model was designed after the data of walking in a straight line. As a result, only forward movement was in the scope of our user study. For a more complete implementation and study in the future, other common locomotion used in on-foot walking, such as lateral movement and rotation around the vertical axis, should be modelled accordingly with analysis on recorded data.

Postures The study was conducted under a seated posture as a controlled condition, and the effectiveness of our approach under other postures, for example standing, is left to be further examined.

Position for haptic feedback The optimal position for receiving haptic feedback can be further explored. In our pilot study, we learned from the hand-held vibration variant that the position should not be too far away from the visual receptor, else the visual and haptic perceptions would appear unrelated to each other even though they’re synchronized. Since one of our main prerequisites for the study is to avoid directly stimulating the vestibular system located roughly behind the ears, we chose the lower back part of the cheeks as a tentative position to receive haptic feedback. As some people or cultures have an aversion on facial contact, further research can go into finding out whether other parts of the body that are close to the head (e.g. shoulders or sides of the neck) hold the same effect on solving the perceptive mismatch.

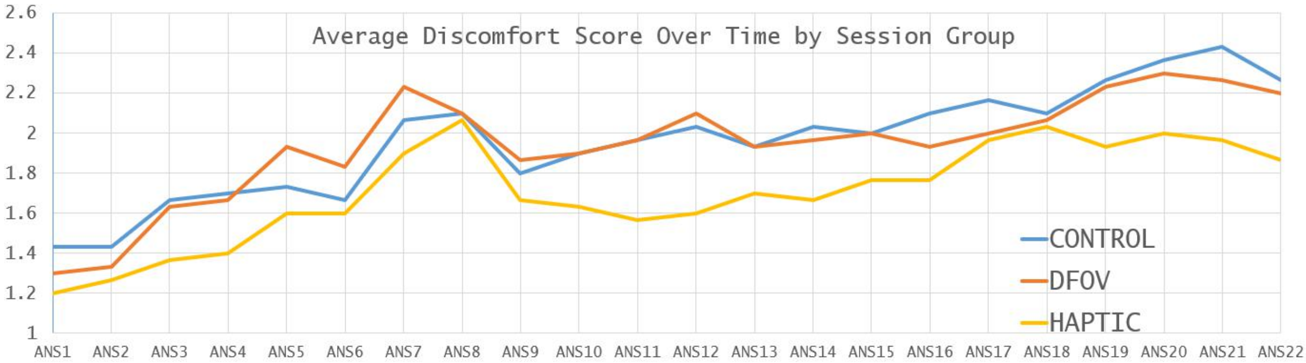


Figure 11: The average discomfort score over every five checkpoints in different conditions.

8 Future Work

Reason behind the effectiveness of the approach Our device has shown a positive effect in alleviating cybersickness based on the result of user study, but the reason behind its effectiveness is uncertain. Here, we propose three possible explanations that would be explored in future study.

- *The illusion of walking created by the visuo-haptic feedback* is strong enough to suppress the conflicting signal from the vestibular system, or to cause the vestibular system to react along.
- *User's attention shifts from the sensory conflict to the applied haptic feedback.*
- *Increased immersion contributes to lowering cybersickness.*

Training wheel effect From the study, we discovered a potential training wheel effect in some participants. This implies that the user might not be required to wear the device all the time since its effect lingers for a while. However, the longevity and effectiveness of the phenomenon have to be proven under an extensive designated study. Should the effect be proven in our future study, the haptic device may serve as a temporary utility to help users accommodate to VR experience in a shorter period. With the aftereffect lingering even without the device, the experience in other VR applications that do not integrate a visuo-haptic feedback may still be improved after a brief exposure to the haptic device.

Implementation of other locomotion methods Besides on-foot movement, we are also curious about the effect of our approach on other locomotion methods such as flying, biking and driving, which may require other forms of haptic feedback to successfully recouple the systems. For example, a mild stimulation in a larger area that resembles airflow might fit flying and biking scenarios, while the driving experience could be strengthened with the perception of inertia.

Haptic assistance for 360° VR videos During our pilot study, we noticed that when the movement was not self-controlled and/or unpredictable, the discomfort seemed to accumulate at a higher rate. This is one of the disadvantages in watching recorded real-life 360° VR videos that contain heavy rotation and jitters on the viewing perspective. We are inspired to research on an implementation to help user aware of the upcoming visual changes with haptic feedback that would improve the video watching experience by reducing cybersickness and further enhance the immersion in the video.

9 Conclusion

In summary, we proposed a novel strategy that generates a possible visuo-vestibular illusion using minimal haptic feedback coupled with a synchronized subtle visual oscillation to mitigate cybersickness in VR. We conducted an experiment to compared our method with dynamic field-of-view and the unmodified condition. The results showed that our technique provides a significant advantage while moving at constant speed on a virtual flat-ground during the initial exposure. While the reason behind its effectiveness is unclear, we believe it is a reliable approach to the problem and will investigate the rationale behind it in the future.

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