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Redirected Tilting: Eliciting Postural Changes with a Rotational Self-Motion Illusion

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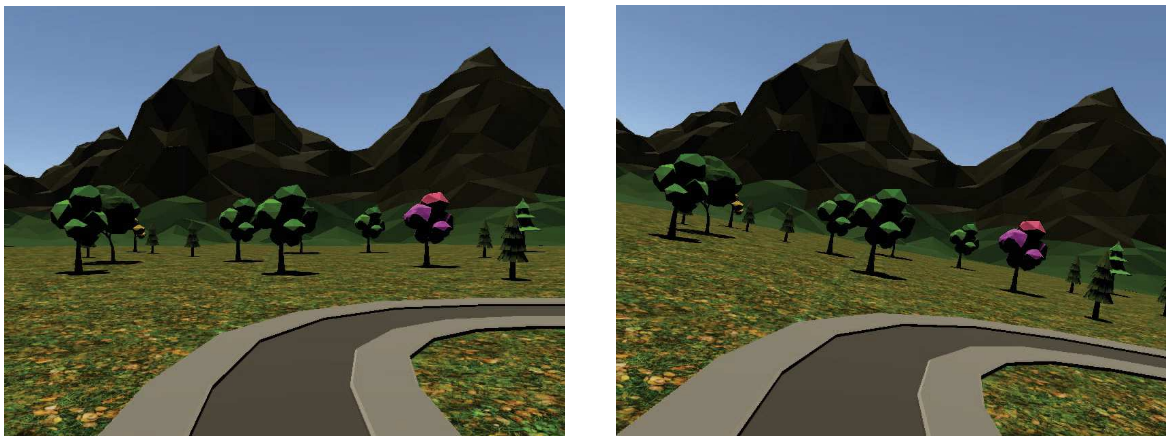

(a) View without redirected tilting

(b) View with redirected tilting

Figure 1: An example of the user's view of a virtual environment with and without redirected tilting. This technique is applied while traveling along a curved trajectory. The virtual environment rotated about the roll axis towards the turning direction, which was to right in this example. In this way, the rotated virtual environment can elicit postural adaptation that could potentially help users maintain their balance.

Abstract

In this paper, we propose a potential cybersickness mitigation technique, redirected tilting, and conduct an exploratory virtual reality (VR) study to determine whether it is possible to visually induce head tilt during virtual locomotion. Redirected tilting involves rotating the virtual environment (VE) towards the turning direction around the VR headset's roll axis, which we hypothesize could lead users to tilt their bodies in the same direction and maintain balance during curved paths. Unlike previous techniques, like field of view (FOV) restriction or rest frames, this method could potentially reduce cybersickness by manipulating egocentric self-motion rather than modifying visual characteristics of the VE. As an initial exploration, we conducted a within-subjects study with 30 participants to evaluate the effect of redirected tilting on postural behavior. The results showed that the proposed technique was successful in eliciting head tilt, although the magnitude of rotation was not as large as we had expected. We conclude that further investigation is needed to understand the mechanics, ideal parameters, and applications of redirected tilting.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Virtual reality; Computing methodologies—Computer graphics—Graphics systems and interfaces—Virtual reality;

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1 Introduction

Cybersickness remains one of the biggest challenges in current VR experiences, especially virtual locomotion. There are several different methods to mitigate cybersickness, such as dynamic FOV modification [1, 8] and static or dynamic rest frames [4]. However, these methods modify display characteristics in the user's visual field, often reducing visibility of the virtual environment, which may have a negative effect on the user's subjective experience.

In this paper, we introduce redirected tilting, a novel method to elicit head tilt while traveling along a curved trajectory in the virtual environment. By manipulating self-motion towards the turning direction, users may be able to better maintain balance and subsequently experience less cybersickness. This strategy does not require reducing the visibility of the virtual environment, and if the tilt remains subtle, the impact on the user's subjective experience should be minimal. If redirected tilting can still successfully reduce cybersickness by stabilizing body posture, this would provide further evidence of the relationship between postural instability and cybersickness.

Redirected tilting attempts to elicit head tilt by rotating the virtual scene towards the turning center. To our knowledge, there is no existing literature in the VR community that has investigated this specific type of self-motion manipulation. Therefore, we conducted a within-subjects user study to evaluate the effect of redirected tilting on people's body posture while standing. The experiment tasks consisted of 50 trials. In each one, participants' viewpoints were moved around a 90° curved path while redirected tilting was applied. We recorded the head mounted display rotation during each trial and calculated the difference in roll rotation when participants are being redirected. Analysis of the data revealed a small but significant effect on head tilt during the self-motion manipulation.

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2 Related Work

Several theories have attempted to explain why motion sickness occurs, and this remains a subject of debate in the literature [13]. One of the earliest proposed explanations, sensory conflict theory [17], remains one of the most commonly cited reasons for the initiation of motion sickness [12]. This theory is based on the hypothesis that our body does not know how to handle sensory inputs that conflict with prior expectations of movement [14]. In the context of cybersickness, the mismatch between physical motion and displayed imagery is often associated with visually induced motion sickness, especially when using virtual locomotion techniques. When we navigate virtually inside VR, the visual cues indicate that our body is moving; however, our vestibular system does not sense this movement. However, although sensory conflict theory is straightforward to understand, it fails to address some important questions in motion sickness [18]. Because internal expectations are impossible to quantify, we cannot use this theory to predict people's motion sickness level after a certain level of VR exposure. Also, this theory cannot explain the different vulnerability to motion sickness between different people, especially between the sexes.

Previous techniques to mitigate cybersickness are often motivated by minimizing sensory conflict by reducing the influence of visual stimulus. Dynamic field of view restriction (FOV) is one of the most popular methods to mitigate cybersickness. It is well known that decreasing FOV can reduce motion sickness [7]. Bolas et al. first described dynamic field of view restriction in a patent in 2014 [1]. Fernandes et al. showed that dynamic FOV restriction can successfully reduce cybersickness [8]. However, research has also shown that decreasing the FOV can result in a significant decrease in users' subjective sense of presence [6]. Recently, static and dynamic rest frames have also been used to reduce cybersickness. These techniques are motivated by the rest frame hypothesis, an alternate theory on motion sickness similar to sensory conflict theory, which claims that humans tend to select things and treat them as stationary references [9]. Researchers have tried to use different virtual objects as the rest frame, such as a virtual nose [20, 21] or an opaque metal net [4], and have shown positive results.

The postural instability theory is another important possible explanation for motion sickness [18]. One of the primary behavioral goals in humans is to maintain postural control in the environment. Postural stability is defined as a state where uncontrolled movements of the perception and action systems are minimized. If a person's postural control ability is partially or completely lost, they would be considered in a state of instability [14]. According to this theory, prolonged exposure to posture instability will cause people to feel motion sick [18]. Unlike sensory conflict theory, postural instability can be quantitatively measured, and the association between motion sickness and control of the body has been well established in the literature. For example, postural precursors of motion sickness have been identified in many visual motion situations [2, 5, 15]. In this work, we are interesting in mitigating cybersickness by modifying system dynamics to promote stability. If it is possible to apply redirected tilting to elicit a more stable body pose, then it could potentially result in a reduction in motion sickness.

Previously, researchers have studied the effect of active head tilt on both car sickness and cybersickness. In 2012, Wada et al. showed that active head tilt against the direction of centrifugal force could help reduce motion sickness caused by lateral acceleration inside cars [19]. Bridgeman et al. studied the effect of active head tilt on the cybersickness in a driving simulator [3]. In their study, they asked participants to tilt their heads towards the turning center for at least 10°. Although they found tilting towards the turning center will increase the discomfort score, the way they treated dropout participants' discomfort score made their result questionable.

Our method is different from Bridgeman's study in two ways. First, instead of instructing users to tilt their heads actively, we use visual redirection to elicit head tilt gradually. Second, we target walking speed rather than driving speed. As the velocity of virtual locomotion decreases, users only need to tilt within a smaller range to compensate for the lateral acceleration they perceive. We hypothesize that this could help them maintain better postural control, which could in turn lead to a reduction in motion sickness. However, as a first step in investigating these effects, we need to evaluate whether user's will adapt their posture in response to redirected tilting.

Table 1: Study Conditions

Condition	LS	LF	GS	GF	Control
Tilting angle (deg)	5	5	10	10	0
Tilting rate (deg/sec)	5	10	5	10	0

3 Redirected Tilting

According to the posture instability theory, disruptions in control of the body will cause people to feel motion sick [18]. Humans have adaptive mechanisms to maintain balance and posture. When people are standing, they will sway back and forth. When they drift in one direction, those balancing mechanisms will sense it and use muscle control to correct this drifting [16]. However, if these mechanisms are in a state where they do not have any strategy to do correct control, postural instability will occur [16]. For example, if a visual cue is telling VR users that they are accelerating laterally during turning, they will lean towards the rotation center to compensate, making their body pose less stable compared to standing still.

Redirected tilting attempts to use visual cues to elicit a more stable body pose. By gradually tilting the virtual scene towards the rotation center during turns (see Figure 1), redirected tilting could induce head tilt. This is similar to the mechanism used by redirected walking: because visual cues dominate perception, users will physically respond to the stimulus. We hypothesize that redirected tilting can compensate for the lateral acceleration that people see in a controllable way. Without tilting, VR users will feel like being 'thrown away' from the rotation center because they are turning without any centripetal force. If this happens in real life, like stepping on ice when walking around a corner, people will lose balance or even fell to the ground. This state is difficult for users' balance mechanisms to handle, and it may cause motion sick. However, with VR view tilting inward, this imitates the visual response of dragging the body to the rotation center using centripetal force. As a result, their balance mechanisms may treat the current state as a banked turn. On the contrary, if we redirect users outward, gravity will drag them away from the curve and may make their body posture more unstable.

4 User Study

Study Design. We conducted a user study to determine if manipulating the virtual environment towards the rotational center of a turn can elicit head tilt in users. The study was a within-subjects design so that we could study the effect of different tilting parameters. The tilt rate ω and max roll rotation θ of redirected tilting each had two different levels. Based on pilot testing, we decided to use $5^\circ/sec$ (slower), $10^\circ/sec$ (faster) as two different levels of ω and 5° (lower), 10° (greater) as two different levels of θ. As shown in Table 1,there were five different conditions in this study; four conditions were combinations of the two levels of ω and θ, while the control condition did not have redirected head tilt. We have labeled the conditions using different combinations of the S, F, L, and G, corresponding to slower, faster, lower, and greater, respectively.

Participant Information. Due to the COVID-19 pandemic, this study was conducted remotely, and participants with existing access to a SteamVR-compatible VR headset were recruited from online forums. Participants were offered a $10 Amazon gift card for their

Table 2: VR headsets used by participants

5	Oculus Rift	2	HTC Vive
5	Oculus Rift S	2	HTC Vive Pro
4	Oculus Quest + Link	5	Valve Index
4	Oculus Quest 2 + Link	3	Windows Mixed Reality

participation. The study was reviewed and approved by our University's IRB. A total 30 participants (6 female, 24 male) participated in the experiment. Ages ranged from 18-44 ($M = 25.50, SD = 6.36$). As all participants owned VR headsets, they were more experienced compared to a group sampled from the general population. Additionally, our original study protocol had called for a balance between the sexes. However, we found it very difficult to recruit women, as it appears that the user base for consumer VR headsets is still predominantly male. Additionally, the ecosystem contains a range of headsets, each of which has its own individual characteristics such as FOV, refresh rate, etc. The specific headset models used by participants are listed in Table 2. We expect all of these issues to remain significant challenges for the VR research community until it becomes safe to resume conducting in-person experiments.

Task. The virtual environment was created using Unity and contained trees, mountains, and a path on the ground (see Figure 2). During the task, participants were asked to use a handheld controller to locomote virtually around a 90°corner repeatedly while standing. The radius of the corner was $10m$. At the beginning of each trial, participants were located at one end of the track facing towards the corner. They could push the controller thumbstick forward or press the upper side of the trackpad to start moving. Participants did not have control over their virtual locomotion once they started. Instead, the program controlled their movement along a fixed path towards the other end of the road. Once started, the virtual locomotion accelerated from 0 to $3m/sec$ at a rate of $2m/sec^2$. The velocity was then fixed. When the participants started turning at the curve, redirected tilting began. The VE that participants saw would gradually rotate towards the turning center at a constant tilt rate (ω) until the rotation reached the maximum tilt angle (θ). During the turn, we recalculated the rotation of the VE in each frame so that the VE was always rotating around the VR headsets' current roll axis in the virtual world. When participants exited the turn, the program rotated the VE back to neutral using the same tilt rate (ω). At the end, the program decelerated to 0 at a rate of $-2m/sec^2$.

Procedures. First, participants were asked to schedule a Zoom meeting with the researcher and were emailed an information sheet detailing the risks of the study a day before the meeting. They were orally screened by the experimenter, the task and controls were explained, and they were given an opportunity to ask questions. Each condition had 10 trials. In half of the trials, the path curved left, while in the other half, the path curved right. There were 50 trials in total and 4 additional training trials at the beginning to familiarize participants with our procedure. Between each trial, there was a head reset step that asked participants to rotate their heads up and down to minimize the effect of previous trials. The whole study lasted about 30 minutes, with about 20 minutes inside VR.

Measures. During each frame, we recorded participants' head position and rotation. We evaluated the effectiveness of redirected tilting by calculating the gain g of the head tilt we observed using equation 1.

$$g = \frac{\theta_{diff}}{\theta} \tag{1}$$

θ is the redirection we applied. Elicited head tilt θ_{diff} was calculated by subtracting the average head roll rotation θ_{head} during each turn from the resting head roll rotation θ_{ave_rest}. For each trial, we also average the head rotation θ_{rest} during a 1 second time period when participants were moving straight forward inside the VE. Then, θ_{ave_rest} is the average of θ_{rest} across 50 trials.

Figure 2: A bird's-eye view of the virtual environment used in the experiment. During each trial, the program moved participants' viewpoints along the curved path from one end to the other.

Between every four trials, participants were asked to provide a Fast Motion Sickness score (FMS) [11] to monitor cybersickness. This measure provides a single numerical score between 0 (no sickness at all) and 20 (frank sickness), which was collected using an in-game slider. If the FMS score was over 15, the study was halted immediately for safety. Participants also completed the Kennedy-Lane Simulator Sickness Questionnaire (SSQ) immediately before and after the VR task [10]. Because the SSQ was designed specifically to assess the magnitude of symptoms associated with several subscales, we also added the yes/no question "Are you motion sick now?" to identify participants that specifically were experiencing motion sickness.

Hypotheses. We formulated the following three hypotheses to evaluate the effects of redirected tilting on users' postural behavior:

- H1: Compared to the control condition, redirected tilting in all four experimental conditions will make users tilt their head towards the turning center.
- H2: Slower tilt rate ω (conditions LS and GS) will result in higher head tilt gain g.
- H3: Larger max roll rotation θ (conditions GS and GF) will result in higher tilt angle θ_{diff}.

Note that although we collected cybersickness data, the purpose of this study was first to determine if we could elicit head tilt in users at all. Studying the effect on cybersickness explicitly is planned for a follow-up study based on the results of this initial experiment.

5 Results

All 30 participants completed the experimental task. On the yes/no question, 10 participants reported feeling motion sick after the study. A Wilcoxon signed-rank test revealed that, for all participants, the post-test SSQ scores ($Mdn = 24.31$, $IQR = 30.86$) were significantly higher than the pre-test SSQ scores ($Mdn = 0.00$, $IQR = 3.74$), $W < 0.001$, $p < .001$. A Mann-Whitney U test showed that the standard deviations (SD) of sick participants' roll head tilt ($Mdn = 0.81, IQR = 1.52$) were significantly higher compared with participants who reported well ($Mdn = 0.37, IQR = 0.72$), $p < .001$.

We identified three outliers (1 female, 2 male) that they may have

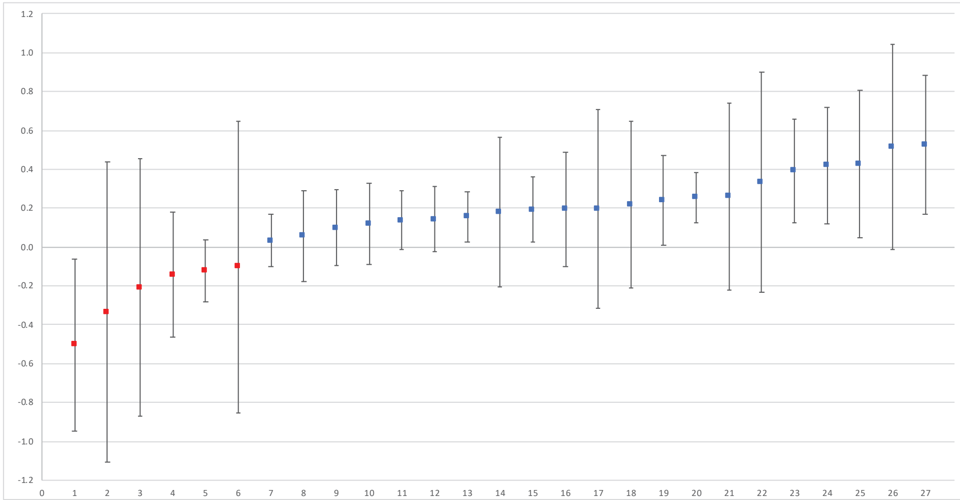

Figure 3: Results for participants' head tilt gain and standard deviation. Head tilt gain is the quotient of the elicited head tilt angle and the amount of redirection we applied. The *x*-axis shows the participants' rank, ordered by their mean head tilt gain. The *y*-axis represents the mean head tilt gain for each of the 27 participants across their 40 trials in experimental conditions.

over-performed during the trials to produce exaggerated tilting behavior. Their data suggested that they were either tilting intentionally or had extremely unstable posture sway. The *SD* of their head tilt gain were 2.08, 1.29 and 1.09, which were much larger compared with the average *SD* (0.35) for all participants. All three reported feeling motion sick after the experiment. Given that their data does not appear reliable, these outliers were excluded from the analysis.

We calculated the average gain g across 50 trials for the remaining 27 participants. As shown in Figure 3, 21 of the participants tended to tilt their heads towards the turning center to some extent. However, 6 participants were tilting their head away from the center despite the redirection, which was unexpected. Based on their response to redirected tilting, we can divide participants into two groups: tilting-inward group ($N = 21$) and tilting-outward group ($N = 6$). Because the amount of participants in tilting-outward group is fairly small, we could not statistically compare the head tilt between these two groups. However, these data should be analyzed separately, because they represent qualitatively different responses to redirected tilting.

Shapiro-Wilk W tests of normality were conducted, and the results indicated that the average tilt gains were not normally distributed across participants. Therefore, we analyze the data using a non-parametric Friedman test and report medians (*Mdn*) and interquartile ranges (*IQR*). The Friedman test showed that there was significant difference among the five conditions in the aspect of average elicited head tilt angle, $\chi^2(4) = 56.19$, $p < .001$. Post-hoc analysis was conducted using a Conover test of multiple comparisons with a Holm-Bonferroni correction. Post-hoc analysis indicated that, compared with the control condition ($Mdn = -0.015, IQR = 0.77$), four experimental conditions elicited head tilt towards the turning center: LS ($Mdn = 1.06, IQR = 1.46, p = .003$), LF ($Mdn = 0.81, IQR = 1.37, p = .022$), GS ($Mdn = 1.86, IQR = 1.42, p < .001$), and GF ($Mdn = 1.06, IQR = 1.46, p = .003$). These results support hypothesis H1. However, the tilt rate did not have a significant effect on the elicited head tilt angle. There were no significant differences between conditions LS and LF, $p = .88$, or between conditions GS and GF, $p = .88$. Therefore, we did not observe any support for hypothesis H2. Finally, we found that the max tilting angle had a significant effect on elicited head tilt. There were significant differences between condition LS and GS ($p = .03$), and between condition LF and GF ($p = .02$). These results support hypothesis H3.

6 Discussion

The results show that redirected tilting was able to induce head tilt in a majority of users. However, the magnitude of redirection was not as strong as we had expected. Surprisingly, a minority of participants tilted their heads towards the opposite direction during the rotation. One explanation is the two tilt rate levels (5° and 10°) we used in this experiment may be too fast for some people to adapt their posture. The visual system is highly sensitive to low-frequency stimuli. If the tilt rate was too high, users may treat the virtual environment's tilting as self-motion instead of compensating in a way similar to redirected walking. As a result, we conclude that slower rotation rates of the tilting redirection should be considered in future studies.

The average SD of head tilt gain g in tilting-outward group (0.52) was higher than tilting-inward group's (0.30). The increase in variability suggests that the tilting-outward group experienced more postural instability during turning. This result is consistent with our hypothesis that tilting towards the turning center will help maintain balance, while tilting outwards has the opposite effect. Moving forward, we believe that further investigation is necessary to determine tilt rates that can lead to the highest head tilt gain. Once the ideal parameters can be determined, the next logical step would then be to formally evaluate the effect of redirected tilting on cybersickness during virtual locomotion.

7 Conclusion

We proposed and evaluated redirected tilting, a technique that could potentially mitigate cybersickness by rotating the virtual scene towards the turning direction around the roll axis of the VR headset. If we can elicit tilting in the same direction, this could help maintain balance along curved trajectories. Results from our initial user study showed that redirected tilting can evoke this behavior in the majority of participants, although the magnitude of the tilting was below our expectations. We conclude that the ideal movement parameters still require further investigation to maximize the gain of head tilt.

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