

Curving the Virtual Route: Applying Redirected Steering Gains for Active Locomotion in In-Car VR

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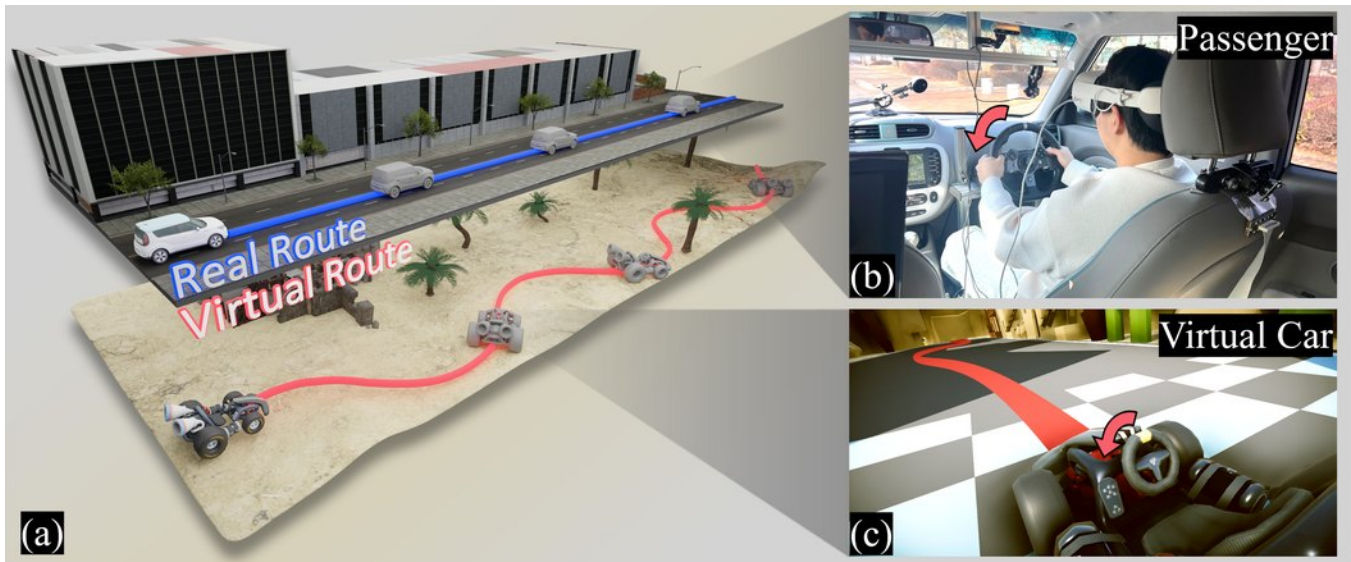


Figure 1: (a) Conceptualization of active locomotion in In-Car VR. The virtual vehicle is actively controlled by the user to deviate from the straight path of the real car. (b) Hardware setup within the passenger seat of a real car, in which a Logitech G290 steering wheel is utilized for the input of user-applied steering gains. (c) Visualization of the corresponding virtual environment, in which the virtual vehicle is steered by the user.

ABSTRACT

This study examines the feasibility of user-applied active locomotion in In-Car Virtual Reality (VR), overcoming the passivity in mobility of previous In-Car VR experiences where the virtual movement was synchronized with the real movement of the car. We

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present the concept of virtual steering gains to quantify the magnitude of user-applied redirection from the real car's path. Through a user study where participants applied various levels of steering gains in an active virtual driving task, we assessed usability factors through measures of motion sickness, spatial presence, and overall acceptance. Results indicate a range of acceptable steering gains in which active locomotion improves spatial presence without significantly increasing motion sickness. Future works will attempt to further validate a steering gain threshold in which active locomotion in In-Car VR can be applicable.

CCS CONCEPTS

• Human-centered computing → Virtual reality.

KEYWORDS

virtual reality, autonomous vehicles, spatial presence, motion sickness, sensory misalignment, locomotion, redirection

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1 INTRODUCTION

Advances in transportation are such that there will be a significant conversion from drivers to passengers in the coming years, owing to the increasing availability and usage of public transport and the impending adoption of autonomous vehicles [28]. Accordingly, advancements in virtual reality (VR) technology have enabled the exploration of VR headsets as entertainment displays for passengers in autonomous vehicles, which we will refer to as In-Car VR [27].

To date, the majority of commercial In-Car VR applications presented for both commercial [1] and research [15, 27, 29, 47] purposes have implemented virtual scenarios in which the In-Car VR user becomes a passenger of a virtual vehicle, while mapping the player's movements within the virtual world congruent with the actual movement of the car. The primary reason for this synchronization of movement is to provide an immersive experience with realistic kinesthetic feedback and also to minimize motion sickness, a key challenge in all in-vehicle platforms [15, 27].

However, synchronizing the virtual movement with the movement of the actual car innately restricts the freedom of mobility of the user. Unless the actual driving task is seamlessly incorporated into the contents such that the user can make driving-related choices, the user plays a comparatively passive role in determining where to go in the virtual environment. Furthermore, various restrictions applied to automotive environments, such as road types and traffic, mean that the user's virtual mobility is dependent on the outside world. Due to these characteristics, locomotion within In-Car VR content is usually automated in the context of the actual driving path.

We aim to address these limitations by introducing a semblance of user-applied active locomotion in In-Car VR, independent of the vehicle's real path. By enabling users to control their spatial position in the virtual world, we are able to introduce freedom of navigation, a fundamental aspect of human interactions in the physical world [3], into existing In-Car VR applications. In addition, active locomotion in virtual reality as compared to passive visualization has been demonstrated to potentially improve spatial learning [6] and reduce motion sickness in both real-life vehicle [2, 39] and virtual contexts [8].

However, the feasibility of active locomotion within In-Car VR has yet to be thoroughly tested, especially regarding the effects of sensory mismatch between the visual and vestibular senses. Such a mismatch has been proven to be a primary cause of both motion sickness [32, 49] and cybersickness [24], as well as loss of immersion and presence [44]. However, there have also been research efforts to successfully manipulate virtual mobility despite

this sensory mismatch, particularly in the form of redirected walking [17, 36, 41]. The principal theory of redirected walking is that there exists a threshold at which virtual orientation can deviate from reality where users do not suffer from negative effects of sensory mismatch [30, 41]. We argue that this principle could be applied in the vehicular context, in that there exists an applicable range in which passengers of In-Car VR will be able to deviate from the real car's movement without harming user experience.

In this study, we first introduce the concept of virtual *steering gains* to quantify the magnitude in which the user-applied virtual movement deviates from the movement of the real car, inspired by previous concepts of redirected walking. Furthermore, we report the results of a user study conducted within an In-Car VR platform designed for the user to apply active locomotion with a virtual steering wheel. This study was centered around measuring spatial presence and motion sickness, which are usability factors relevant to sensory mismatch [34, 44, 49], as well as overall acceptance of the gain condition. Based on the analysis of these results, we discuss effects on user experience according to differing magnitudes of applied steering gains, as well as compare them with a passive baseline condition, to examine the feasibility of user-applied active locomotion in In-Car VR.

2 RELATED WORKS

2.1 Motion Sickness in In-Car VR

Recent applications of VR headsets in vehicles present potential for enhancing passenger experience, particularly with the advent of fully autonomous vehicles [27, 28, 43]. As a result, recent research efforts have been directed towards integrating a fully immersive VR system within a real automobile, with motivations ranging from entertainment and comfort in vehicle-related virtual environments [1, 15, 21, 33] to realistic on-road simulations [11, 47]. McGill et al. addressed the drawbacks of motion sickness and its relationship with the visual perception of movement in In-Car VR [27], presenting the theory of motion sickness for VR in transit as the result of the misalignment between the visual perception of motion and the physically perceived motion. Various efforts have since been made to mitigate motion sickness in In-Car VR applications, including explicit visual matching of the car's motion [15, 27] or incorporating implicit cues within the presented content [13, 35].

Another well-documented cause of motion sickness is the passenger's inability to control, and consequently predict the vehicle's movement. Previous studies emphasized the driver's ability to anticipate the vehicle's trajectory and make compensatory changes to their posture, hereby reducing motion sickness symptoms compared to the passengers [2, 39]. Active locomotion has also proven to be more effective than passive content visualization in combating motion sickness in the virtual context as well [5, 8].

Our proposed active locomotion method in In-Car VR is highly relevant to both aforementioned causes of motion sickness. While motion sickness may decrease due to the user's ability to control and anticipate their own virtual movement, it may also increase because of the sensory mismatch that occurs when the user virtually deviates from the real movement of the car. Through our experimental process, we examined these conflicting causes of motion

sickness in the In-Car VR context, and their role in affecting user experience when active locomotion is applied.

2.2 Redirection in Locomotion

The predominant research area utilizing visual dominance in sensory mismatch to conceive virtual locomotion is redirected walking (RDW). Redirected walking refers to a collection of approaches that control the user's path through the physical environment by manipulating the stimuli used to represent the virtual environment [16, 18, 23, 30, 41]. These methods are made possible by the Colavita visual dominance effect [7], where visual stimuli tend to be more likely to be perceived and responded to when presented simultaneously with other stimuli [36]. The method in RDW most relevant to locomotion is the application of curvature gains, where the user is visually manipulated to walk along a curved path while believing that the path is straight [25, 41].

Evidence suggests that concepts of redirection can successfully be implemented for active locomotion in In-Car VR. Participants from a previous In-Car VR study stated that they completely lost their sense of where the car was moving in the real world, and no one could tell the pathway of the actual track afterwards [15]. Bruder et al. applied vehicular redirected locomotion with an electric wheelchair and found that redirection while driving was less perceptible compared to walking due to the relative absence of reliable physical cues [4]. Similarly, Nybakke et al. examined the benefits of utilizing a motorized wheelchair for active virtual locomotion, stating that the cognitive effect of perceived displacement can be utilized for a potential locomotion method in a moving apparatus [31].

Applying redirection or active control in In-Car VR locomotion has been theorized, but not yet thoroughly tested, in previous works. Hock et al. mentioned the concept of force shifts, where directional forces can be exaggerated, understated, or completely different from the actual movement [15], similarly to RDW. McGill et al. suggested a method of testing users' resilience to motion sickness by allowing the player to control their virtual movement independent of the real vehicle [28]. We built upon these suggestions to examine the achievability of active locomotion, by finding the range in which users can move independently without significantly increasing motion sickness.

3 IMPLEMENTATION AND EVALUATION

3.1 Steering Gains for Active Locomotion

While the concept of active locomotion by the In-Car VR user bears some similarities to existing redirection locomotion techniques, there are substantial differences as well, most important of which is the active role of the user in redirection. To differentiate from existing concepts of redirected walking and to better describe the characteristics that apply to vehicular context, we introduce a new type of redirected gains called *steering gains*.

For the defining of steering gains, we drew from both general automotive steering principles and existing concepts of curvature gains in redirected walking [42]. While most definitions of curvature in RDW refer to the reciprocal of arc radius ($g = 1/r$) [41], this value can also be kinematically interpreted as the amount of rotation per meter traveled ($g = \theta/d$) when assuming constant

velocity, as shown in Fig. 2-(a). Thus, for the implementation of user-applied steering gains, we decided to use a steering wheel as rotational input for the virtual user, so that the virtual curved path is circular with steering gain proportional to the turning angle of the steering wheel.

Formally, we define steering gain as the amount of curvature in which the virtual vehicle deviates from the straight path of the real car at level velocity. The annotation of the magnitude of curvature follows mathematical definition as the reciprocal of arc radius. For example, if the user applies a constant magnitude of virtual steering gain g_s while the real car moves straight at a certain distance, the virtual path curves at a circular arc of radius $1/g_s$ and arc length of same distance. In addition, we denote positive and negative signs for the gain value to indicate steering right and left respectively, as shown in Fig. 2-(a).

3.2 Apparatus

To capitalize on the multitude of possible causes of motion sickness and create a realistic platform to measure usability, we proceeded with our study in a real moving car. We situated our setup in the passenger seat of a KIA EV Soul, inspired by previous iterations of In-Car VR apparatus designs [15, 29]. In addition, a Logitech G290 steering wheel was set up at the forefront of the seat as an input device for the participant to actively steer the virtual vehicle, as shown in Fig. 1-(b). Additional hardware included a laptop to set up the virtual scene with Unity, an Oculus Quest 2 for the VR head-mounted display, and a smartphone for questionnaires. The tracking method used for the In-Car VR platform was rotational 3-DOF (Degrees of Freedom), with the forward translational movement of the real and virtual vehicle being manually synchronized. This allows freedom of viewpoint for the passenger in respect to the virtual vehicle, while also allowing for steering gains to be applied independent of the real vehicle's route.

3.3 Task Environment

To test how different levels of applied steering gain affect spatial presence and motion sickness, while also ensuring the application of active locomotion, we devised a virtual task environment in which the participants were required to follow a curving path within each gain condition. The shape of the virtual path was in the form of a periodic wave consisting of repeated circular arcs with same length and radius, where the participant was guided to turn left and right at the condition-specified steering gain at eight intervals. The arc radius of each interval is the reciprocal of the independent variable g_s . Throughout the duration of the steering task, the forward velocities of the real and virtual vehicles were set to be identical and uniform.

We tested four conditions where the participant actively controlled the direction of the virtual vehicle along the specified path with different levels of steering gain, along with an additional baseline passive condition ($g_s = 0$) where the participant did not steer the virtual vehicle. Each condition was labeled as the corresponding steering gain as $g_s = 0$ (baseline), $\pm\pi/360$, $\pm\pi/180$, $\pm\pi/120$, and $\pm\pi/90$, as shown in Fig. 2-(b).

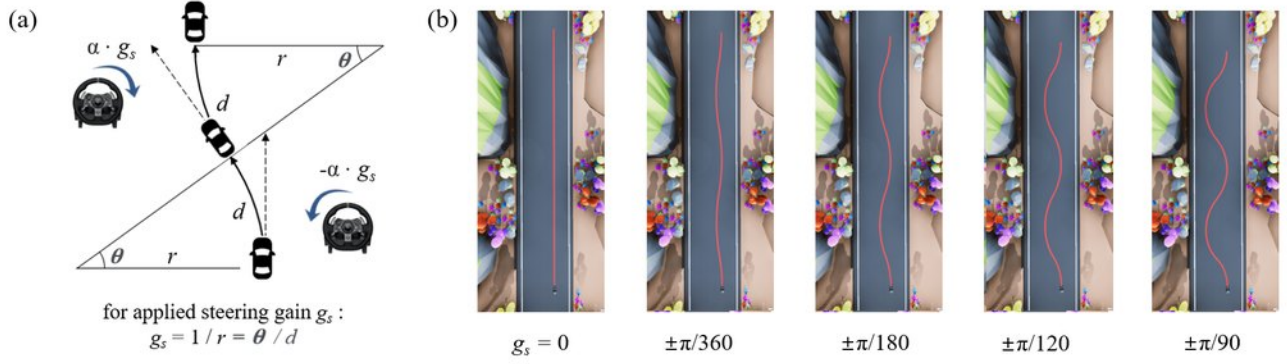


Figure 2: (a) Visual representation of the conceptualized steering gains. Steering gains $-g_s$ and g_s for distance d are applied to the virtual vehicle by turning the virtual steering wheel left and right at a rotational angle proportionate to the steering gain. The resulting circular arcs form circular sectors with angle θ and radius r . (b) Depiction of an overhead view of the designed virtual task environment for the passive baseline condition $g_s = 0$ and four active conditions where steering gain was applied.

3.4 Procedure

We tested 20 participants with ages ranging from 20 to 31 years ($M: 22.8$, $SD: 3.04$, 12 Male, 8 Female) for the study, of which 16 had an active driver's license and 18 had at least some experience with VR. All procedures involving participants were approved by the IRB (20230504-HR-71-06-04).

As an initial screening process, we conducted preliminary interviews asking the participants if they have had experience in any severe symptoms regarding motion sickness, VR sickness, and 3D cybersickness. Additionally, we proceeded with a practice session where participants used the steering wheel to follow the set virtual path for each condition while the real car was stationary. If a participant experienced severe symptoms of nausea during the practice session, the experiment was terminated immediately. Participants were allowed to continue practicing the steering task until they felt confident enough to follow the curving path consistently. After the practice session and prior to the main procedure, participants were provided with a mandatory 15-minute rest period to alleviate residual motion sickness and discomfort, with an additional 15 minutes granted to participants upon request.

The main procedure consisted of participants experiencing the five conditions with varying virtual paths as specified in the previous section. To minimize carryover effects, counterbalancing was applied to the order of the five steering gain conditions via balanced latin square. Each conditional experience consisted of five repetitive trials in which participants were instructed to follow the curving virtual path visualized within the virtual environment as shown in Fig 1-(c). The distances covered and forward velocities for both the real and virtual vehicle were identical at 200 m and 30 km/h respectively. Participants were given no prior or ongoing knowledge of the real car's path or driving behavior, to prevent cognitive bias regarding the real car's movement. Between conditions, participants were given time to rest to alleviate residual discomfort and motion sickness symptoms, in the same procedure as after the practice session.

3.5 Measures

After each of the five repetitions, participants were presented with two questions regarding their immediate experience of steering the virtual vehicle, with respect to self-perceived motion sickness and acceptance of the gain condition. The questions were presented within the virtual environment to maintain immersion and spatial presence within the experience of the condition. The first question was a standard Likert 7-point scale used in past studies to measure self-reported motion sickness symptoms [12, 27], where 1 indicated no symptoms of sickness and 7 indicated severe enough symptoms to wish to cease the experiment. The second question was a forced Yes or No question regarding acceptance of the gain [38], which was presented as the following statement: *I believe that this level of gain is applicable for virtual locomotion.*

After all 5 repetitions of a single condition were completed, participants took off the VR headset and participated in two questionnaires measuring simulator sickness and spatial presence, regarding the experience of each condition as a whole. The Simulator Sickness Questionnaire (SSQ) by Kennedy et al. [20] was used to measure highly correlated symptoms of motion sickness [27, 48], such as nausea and disorientation. We also administered the Spatial Presence Experience Scale (SPES) by Hartmann et al. [14] to measure participants' sense of spatial presence. This questionnaire was chosen over other measures regarding presence because of the high correlation specifically between spatial presence and the self-displacement within the virtual environment applied in our application. The SPES is divided into two subscales regarding Self-Location (SL) and Possible Action (PA): The former includes items regarding the user's feeling of being physically present in the virtual environment, while the latter includes items regarding the user's perceived ability to interact with the objects in the virtual world. For both subscales and total scale of the SPES, higher scores indicate a heightened sense of spatial presence within the virtual environment.

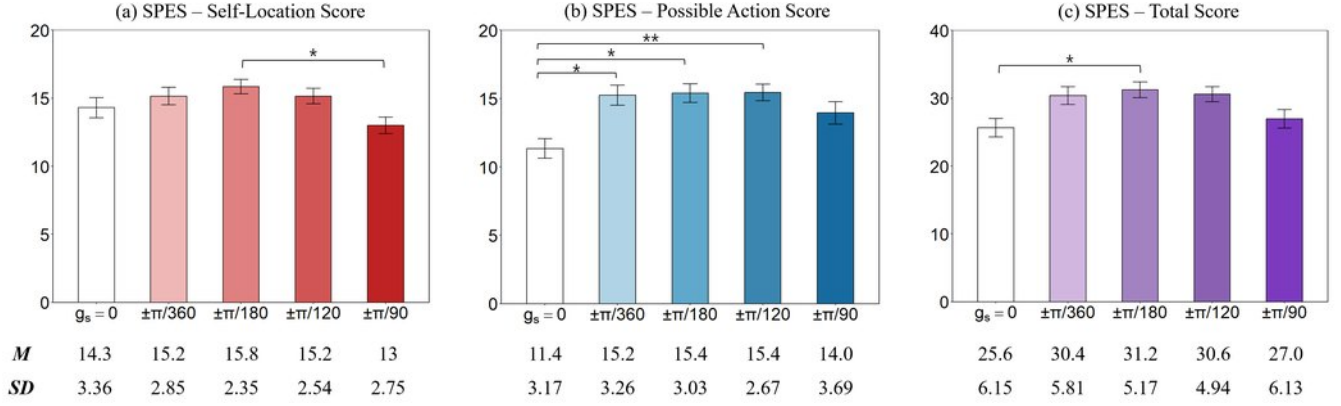


Figure 3: (a) Self-Location Subscores, (b) Possible Action Subscores, (c) Total scores from the SPES questionnaire by gain condition. Error bars indicate standard error from the mean. * $p < .05$, ** $p < .01$

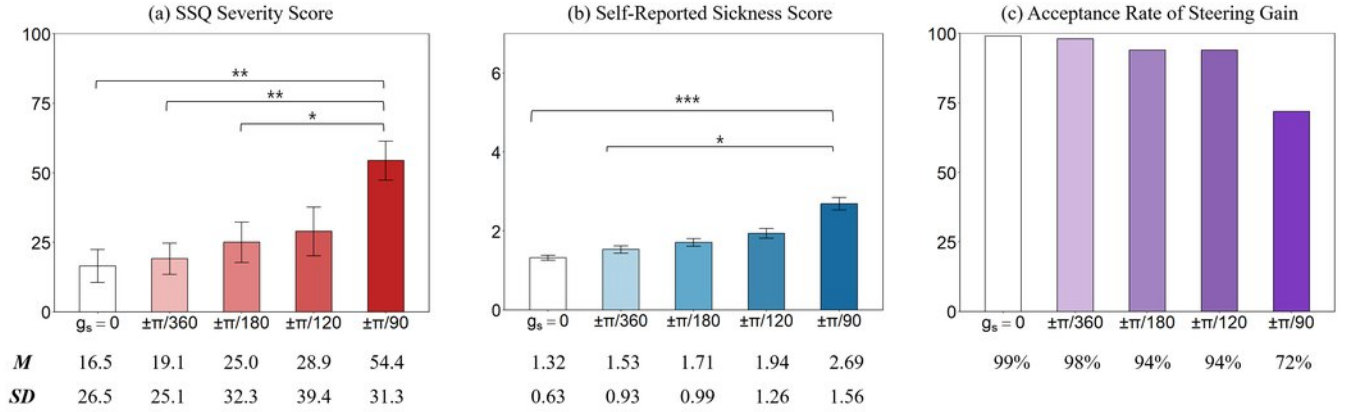


Figure 4: (a) SSQ Severity Scores, (b) Self-Reported Sickness Scores, (c) Gain Acceptance Rate by gain condition represented as percentage. Error bars indicate standard error from the mean. * $p < .05$, ** $p < .01$, *** $p < .001$

4 RESULTS AND DISCUSSION

The results of the SPES and SSQ questionnaires were confirmed to satisfy normality based on measures skewness < 3.0 and kurtosis < 10.0 [22], then subjected to repeated measures ANOVA. When the results of the test demonstrated statistical significance ($p < .001$), we proceeded with post hoc analysis using paired sample t-tests using the Bonferroni correction. The results of the self-reported sickness scale did not satisfy normality, so we proceeded with non-parametric measures Friedman's variance analysis. Since we found a significant difference ($p < .001$), we performed pairwise comparisons using Wilcoxon's signed-rank test and adjusted significance values using the Bonferroni correction.

4.1 Spatial Presence

The results of the SPES questionnaire for spatial presence, including each subscale and the total score, are depicted in Fig. 3. Fig. 3-(a) shows the resulting scores of the Self-Location subscale at each gain condition. The resulting analysis showed a significant decrease in score at $g_s = \pm\pi/90$ compared to $g_s = 0$, while other comparisons did not show significance. Fig. 3-(b) depicts the

scores of the Possible Action subscale, where post hoc tests revealed a significant difference between the baseline condition and $g_s = \pm\pi/360$, $\pm\pi/180$, and $\pm\pi/120$ where steering gains were applied ($p < 0.05$, 0.05 , 0.01 respectively). The results of the total score of the SPES comprise the combined sum of each subscale and are shown in Fig. 3-(c), with significant difference shown between the baseline $g_s = 0$ and $g_s = \pm\pi/180$.

Discussion : Literature suggests that deviating the virtual movement from the real movement may cause a decrease in spatial presence due to the sensory mismatch of locomotive information from the visual and vestibular senses [40, 44]. However, for both the subscale and total scores, we found that a higher sense of spatial presence was measured in moderate gain conditions compared to the passive baseline where visual-vestibular consistency was maintained. This can be explained by two reasons : that visual dominance over the other senses was effective enough to mitigate negative effects on self-location caused by sensory mismatch, much like in RDW [36], and that the ability to control their own mobility increases the sense of being able to better interact with the virtual environment [10], as indicated by the Possible Action

subscale. However, as can be seen specifically in the Self-Location subscale, spatial presence scores significantly decreased at $g_s = \pm\pi/90$, which further confirms the notion that too high a degree of sensory conflict can lead to negative effects on presence [45].

4.2 Motion Sickness and Gain Acceptance

For the SSQ, total scores were weighted from three subscales regarding symptoms of nausea, disorientation, and oculomotor-related discomfort [20]. The distribution of the total severity scores are shown in Fig. 4-(a). Post hoc tests revealed a significant difference between $g_s = \pm\pi/90$ and $g_s = 0, \pm\pi/360$ and $\pm\pi/180$ ($p < 0.01, 0.01, 0.05$ respectively). Results of the self-reported sickness scale are shown in Fig. 4-(b), where $g_s = \pm\pi/90$ shows significant difference between baseline $g_s = 0$ ($p < 0.001$) and $\pm\pi/360$ ($p < 0.05$). Yes and No answers regarding acceptance of the gain condition were pooled and scored as a percentage of acceptance between 0 and 100. The results are shown in Fig. 4-(c), where the average acceptance rate across participants at each condition were 99, 98, 98, 94, and 72 percent for $g_s = 0, \pm\pi/360, \pm\pi/180, \pm\pi/120$ and $\pm\pi/90$ respectively.

Discussion : The results of both sickness measures are highly correlated both in terms of overall trends and statistical significance, where the significant increase shown at $\pm\pi/90$ solidifies the notion that there exists a level of visual-vestibular inconsistency which, when exceeded, leads to a marked increase in motion sickness symptoms [27, 37]. The percentage of acceptance for $g_s = \pm\pi/360, \pm\pi/180$ and $\pm\pi/120$ compared to the passive baseline show that even with heightened levels of sensory conflict, the magnitude of various factors that may harm user experience were not significant enough to warrant rejection of the gain condition. Moreover, the significant drop in acceptance at $g_s = \pm\pi/90$ aligns with the trends from measures of spatial presence and motion sickness, confirming that the aforementioned negative effects play a significant role in participants' willingness to accept the gain as an applicable range of active locomotion.

An overall analysis of the aforementioned factors indicates a nuanced relationship between spatial presence, motion sickness, and acceptance. The significant decrease in sense of self-location, increase in motion sickness, and decrease in acceptance at $g_s = \pm\pi/90$ validate a negative correlation between presence and sickness [34, 45, 46] and their direct effect on usability in virtual reality applications. However, the less significant increase of sickness in lower gain conditions depicts a more balanced range of applied steering gains in which sickness levels do not negatively affect spatial presence or overall acceptance, indicating a possible range in which active locomotion is applicable. Among the four measured gain conditions, $g_s = \pm\pi/180$ yielded positive results in terms of overall usability, with significantly increased spatial presence compared to the passive baseline while maintaining levels of motion sickness and acceptance rate. Conversely, $g_s = \pm\pi/90$ demonstrates a significant increase in sickness without improving spatial presence, while also having a significant drop in acceptance rate. These results indicate the existence of a threshold in this range at which active locomotion can be applied to improve spatial presence and extend freedom of movement while still maintaining acceptable levels of motion sickness.

5 CONCLUSION AND FUTURE WORKS

In this study, we first introduced the concept of user-applied active locomotion within In-Car VR, differentiating from previous applications where the virtual movement was synchronized with the real vehicle's movement. We conceptualized the term of steering gains, inspired from existing works on redirected locomotion, to quantify the magnitude in which the virtual movement deviates from the real car's route. We conducted user studies in an In-Car VR setup within a real car, measuring spatial presence, motion sickness and overall acceptance to examine how different levels of applied steering gain may affect the active locomotion experience. From our results, we demonstrated that active locomotion can be applicable to an extent while maintaining tolerable levels of motion sickness.

Within our study, we implemented steering gains in the specific scenario of the real vehicle moving straight, with level velocity. Thus, in real-life vehicle situations where the real car's vector fluctuates, the effects of the resulting G-forces on the perception of steering gains and its effects on the usability of active locomotion have not been explored. We aim to address these limitations in future works by examining the feasibility of active locomotion in more varied and dynamic driving conditions and road environments, including scenarios where the vehicle moves at different accelerations and directions. Additionally, we plan on exploring the implementation of haptic feedback that can actuate the effects of G-force, such as Electrical Muscle Stimulation (EMS) [9, 19]. Finally, refining of the experimental process through the collecting of qualitative data, as well as implement methods such as conducting experiments that involve discrimination tasks measuring the detection of virtual deviation [42] or analyses of physiological data relevant to motion sickness [26], will lead to conceiving a more definitive gain threshold in which active locomotion may be applicable in both existing and future In-Car VR applications.

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REFERENCES

- [1] AUDI. 2019. Hololride: Virtual Reality meets the real world. <https://www.audi.com/en/experience-audi/mobility-and-trends/digitalization/holoridevirtual-reality-meets-the-real-world.html>. Retrieved August 10, 2019.
- [2] Giovanni Bertolini and Dominik Straumann. 2016. Moving in a moving world: a review on vestibular motion sickness. *Frontiers in neurology* 7 (2016), 14.
- [3] Doug Bowman, Ernst Kruijff, Joseph J LaViola Jr, and Ivan P Poupyrev. 2004. *3D User interfaces: theory and practice*, CourseSmart eTextbook. Addison-Wesley.
- [4] Gerd Bruder, Victoria Interrante, Lane Phillips, and Frank Steinicke. 2012. Redirecting walking and driving for natural navigation in immersive virtual environments. *IEEE transactions on visualization and computer graphics* 18, 4 (2012), 538–545.
- [5] Chih-Hui Chang, Thomas A Stoffregen, Li-Ya Tseng, Man Kit Lei, and Kuangyou B Cheng. 2021. Control of a virtual vehicle influences postural activity and motion sickness in pre-adolescent children. *Human Movement Science* 78 (2021), 102832.
- [6] Elizabeth R Chrastil and William H Warren. 2015. Active and passive spatial learning in human navigation: acquisition of graph knowledge. *Journal of experimental psychology: learning, memory, and cognition* 41, 4 (2015), 1162.

- [7] Francis B Colavita. 1974. Human sensory dominance. *Perception & Psychophysics* 16, 2 (1974), 409–412.
- [8] Xiao Dong, Ken Yoshida, and Thomas A Stoffregen. 2011. Control of a virtual vehicle influences postural activity and motion sickness. *Journal of Experimental Psychology: Applied* 17, 2 (2011), 128.
- [9] Ahmed Elsharkawy, Aya Ataya, Dohyeon Yeo, Eunsol An, Seokhyun Hwang, and SeungJun Kim. 2024. Synchronizing Your Senses to Conquer Motion Sickness for Enriching In-Vehicle Virtual Reality. In *Proceedings of the CHI Conference on Human Factors in Computing Systems (CHI '24)*, May 11–16, 2024, Honolulu, HI, USA.
- [10] Gary Fontaine. 1992. The experience of a sense of presence in intercultural and international encounters. *Presence: Teleoperators & Virtual Environments* 1, 4 (1992), 482–490.
- [11] David Goedicke, Jami Li, Vanessa Evers, and Wendy Ju. 2018. Vr-oom: Virtual reality on-road driving simulation. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. 1–11.
- [12] Michael J Griffin and Maria M Newman. 2004. Visual field effects on motion sickness in cars. *Aviation, space, and environmental medicine* 75, 9 (2004), 739–748.
- [13] Evan Hanau and Voicu Popescu. 2017. Motionreader: visual acceleration cues for alleviating passenger e-reader motion sickness. In *Proceedings of the 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications Adjunct*. 72–76.
- [14] Tilo Hartmann, Werner Wirth, Holger Schramm, Christoph Klimmt, Peter Vorderer, André Gysbers, Saskia Böcking, Niklas Ravaja, Jari Laarni, Timo Saari, Feliz Gouveia, and Ana Sacau. 2015. The Spatial Presence Experience Scale (SPES). *Journal of Media Psychology: Theories, Methods, and Applications* 1 (01 2015), 1–15. <https://doi.org/10.1027/1864-1105/a000137>
- [15] Philipp Hock, Sebastian Benedikter, Jan Gugenheimer, and Enrico Rukzio. 2017. CarVR: Enabling In-Car Virtual Reality Entertainment. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (Denver, Colorado, USA) (CHI '17). Association for Computing Machinery, New York, NY, USA, 4034–4044. <https://doi.org/10.1145/3025453.3025665>
- [16] Seokhyun Hwang, YoungIn Kim, Youngseok Seo, and SeungJun Kim. 2023. Enhancing Seamless Walking in Virtual Reality: Application of Bone-Conduction Vibration in Redirected Walking. In *2023 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. IEEE, 1181–1190.
- [17] Seokhyun Hwang, Jieun Lee, YoungIn Kim, and SeungJun Kim. 2022. REVES: Redirection Enhancement Using Four-Pole Vestibular Electrode Stimulation. In *CHI Conference on Human Factors in Computing Systems Extended Abstracts*. 1–7.
- [18] Seokhyun Hwang, Jieun Lee, Youngin Kim, Youngseok Seo, and Seungjun Kim. 2023. Electrical, Vibrational, and Cooling Stimuli-Based Redirected Walking: Comparison of Various Vestibular Stimulation-Based Redirected Walking Systems. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*. 1–18.
- [19] Seokhyun Hwang, Jungseok Oh, Seongjun Kang, Minwoo Seong, Ahmed Elsharkawy, and SeungJun Kim. 2024. ErgoPulse: Electrifying Your Lower Body With Biomechanical Simulation-based Electrical Muscle Stimulation Haptic System in Virtual Reality. In *Proceedings of the CHI Conference on Human Factors in Computing Systems (CHI '24)*, May 11–16, 2024, Honolulu, HI, USA.
- [20] Robert S Kennedy, Norman E Lane, Kevin S Berbaum, and Michael G Lilienthal. 1993. Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. *The international journal of aviation psychology* 3, 3 (1993), 203–220.
- [21] Gwangbin Kim, Dohyeon Yeo, Taewoo Jo, Daniela Rus, and SeungJun Kim. 2023. What and When to Explain? On-road Evaluation of Explanations in Highly Automated Vehicles. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 7, 3 (2023), 1–26.
- [22] Rex B Kline. 2015. *Principles and practice of structural equation modeling*. Guilford publications.
- [23] Eike Langbehn, Paul Lubos, and Frank Steinicke. 2018. Evaluation of locomotion techniques for room-scale vr: Joystick, teleportation, and redirected walking. In *Proceedings of the Virtual Reality International Conference-Laval Virtual*. 1–9.
- [24] Joseph J LaViola Jr. 2000. A discussion of cybersickness in virtual environments. *ACM Sigchi Bulletin* 32, 1 (2000), 47–56.
- [25] Jieun Lee, Seokhyun Hwang, Kyunghwan Kim, and SeungJun Kim. 2022. Auditory and olfactory stimuli-based attractors to induce reorientation in virtual reality forward redirected walking. In *CHI conference on human factors in computing systems extended abstracts*. 1–7.
- [26] Gang Li, Yu-Kai Wang, Mark McGill, Katharina Pöhlmann, Stephen Brewster, and Frank Pollick. 2023. Resting-state EEG in the Vestibular Region Can Predict Motion Sickness Induced by a Motion-Simulated in-car VR Platform. In *2023 IEEE Symposium Series on Computational Intelligence (SSCI)*. IEEE, 47–52.
- [27] Mark McGill, Alexander Ng, and Stephen Brewster. 2017. I Am The Passenger: How Visual Motion Cues Can Influence Sickness For In-Car VR. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (Denver, Colorado, USA) (CHI '17). Association for Computing Machinery, New York, NY, USA, 5655–5668. <https://doi.org/10.1145/3025453.3026046>
- [28] Mark McGill, Julie Williamson, Alexander Ng, Frank Pollick, and Stephen Brewster. 2020. Challenges in passenger use of mixed reality headsets in cars and other transportation. *Virtual Reality* 24, 4 (01 Dec 2020), 583–603. <https://doi.org/10.1007/s10055-019-00420-x>
- [29] Mark McGill, Graham Wilson, Daniel Medeiros, and Stephen Anthony Brewster. 2022. PassengXR: A Low Cost Platform for Any-Car, Multi-User, Motion-Based Passenger XR Experiences. In *Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology* (Bend, OR, USA) (UIST '22). Association for Computing Machinery, New York, NY, USA, Article 2, 15 pages. <https://doi.org/10.1145/3526113.3545657>
- [30] Niels Christian Nilsson, Tabitha Peck, Gerd Bruder, Eri Hodgson, Stefania Serafin, Mary Whitton, Frank Steinicke, and Evan Suma Rosenberg. 2018. 15 years of research on redirected walking in immersive virtual environments. *IEEE computer graphics and applications* 38, 2 (2018), 44–56.
- [31] Amelia Nybakke, Ramya Ramakrishnan, and Victoria Interrante. 2012. From virtual to actual mobility: Assessing the benefits of active locomotion through an immersive virtual environment using a motorized wheelchair. In *2012 IEEE Symposium on 3D User Interfaces (3DUI)*. IEEE, 27–30.
- [32] Charles M Oman. 1990. Motion sickness: a synthesis and evaluation of the sensory conflict theory. *Canadian journal of physiology and pharmacology* 68, 2 (1990), 294–303.
- [33] Pablo E Paredes, Stephanie Baltes, Kyle Qian, Elizabeth L Murnane, Francisco Ordóñez, Wendy Ju, and James A Landay. 2018. Driving with the fishes: Towards calming and mindful virtual reality experiences for the car. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 2, 4 (2018), 1–21.
- [34] Katharina Margareta Theresa Pöhlmann, Gang Li, Mark McGill, Reuben Markoff, and Stephen Anthony Brewster. 2023. You spin me right round, baby, right round: Examining the Impact of Multi-Sensory Self-Motion Cues on Motion Sickness During a VR Reading Task. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*. 1–16.
- [35] Zhanyan Qiu, Mark McGill, Katharina Margareta Theresa Pöhlmann, and Stephen Anthony Brewster. 2023. Manipulating the Orientation of Planar 2D Content in VR as an Implicit Visual Cue for Mitigating Passenger Motion Sickness. In *Proceedings of the 15th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*. 1–10.
- [36] Sharif Razzaque. 2005. *Redirected walking*. The University of North Carolina at Chapel Hill.
- [37] J.T. Reason and J.J. Brand. 1975. *Motion Sickness*. Academic Press. <https://books.google.co.kr/books?id=JmXrAAAAAAAJ>
- [38] Michael Rietzler, Jan Gugenheimer, Teresa Hirzle, Martin Deubzer, Eike Langbehn, and Enrico Rukzio. 2018. Rethinking redirected walking: On the use of curvature gains beyond perceptual limitations and revisiting bending gains. In *2018 IEEE international symposium on mixed and augmented reality (ISMAR)*. IEEE, 115–122.
- [39] Arnon Rolnick and RE Lubow. 1991. Why is the driver rarely motion sick? The role of controllability in motion sickness. *Ergonomics* 34, 7 (1991), 867–879.
- [40] Mel Slater, Martin Usoh, and Anthony Steed. 1994. Depth of presence in virtual environments. *Presence: Teleoperators & Virtual Environments* 3, 2 (1994), 130–144.
- [41] Frank Steinicke, Gerd Bruder, Jason Jerald, Harald Frenz, and Markus Lappe. 2008. Analyses of human sensitivity to redirected walking. In *Proceedings of the 2008 ACM symposium on Virtual reality software and technology*. 149–156.
- [42] Frank Steinicke, Gerd Bruder, Jason Jerald, Harald Frenz, and Markus Lappe. 2009. Estimation of detection thresholds for redirected walking techniques. *IEEE transactions on visualization and computer graphics* 16, 1 (2009), 17–27.
- [43] Henry Togwell, Mark McGill, Graham Wilson, Daniel Medeiros, and Stephen Anthony Brewster. 2022. In-car gaming: Exploring the use of ar headsets to leverage passenger travel environments for mixed reality gameplay. In *CHI Conference on Human Factors in Computing Systems Extended Abstracts*. 1–7.
- [44] Martin Usoh, Kevin Arthur, Mary C Whitton, Rui Bastos, Anthony Steed, Mel Slater, and Frederick P Brooks Jr. 1999. Walking> walking-in-place> flying, in virtual environments. In *Proceedings of the 26th annual conference on Computer graphics and interactive techniques*. 359–364.
- [45] Séamas Weech, Sophie Kenny, and Michael Barnett-Cowan. 2019. Presence and cybersickness in virtual reality are negatively related: a review. *Frontiers in psychology* 10 (2019), 158.
- [46] Bob G Witmer, John H Bailey, Bruce W Knerr, and Kimberly C Parsons. 1996. Virtual spaces and real world places: Transfer of route knowledge. *International journal of human-computer studies* 45, 4 (1996), 413–428.
- [47] Dohyeon Yeo, Gwangbin Kim, and SeungJun Kim. 2019. MAXIM: Mixed-reality Automotive Driving XIMulation. In *2019 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct)*. IEEE, 460–464.
- [48] Dohyeon Yeo, Gwangbin Kim, and Seungjun Kim. 2020. Toward immersive self-driving simulations: Reports from a user study across six platforms. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–12.
- [49] Li-Li Zhang, Jun-Qin Wang, Rui-Rui Qi, Lei-Lei Pan, Min Li, and Yi-Ling Cai. 2016. Motion sickness: current knowledge and recent advance. *CNS neuroscience & therapeutics* 22, 1 (2016), 15–24.