Directional Multimodal Flow to Help Mitigate VR Sickness

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ABSTRACT

Motion sickness in Virtual Reality (VR) environments poses a significant issue by impeding user immersion and causing discomfort. It mainly arises from the discrepancy between visual information and vestibular system signals or sensory mismatch. To address this, various visual control methods have been proposed, including the Reverse Optical Flow. This method mitigates motion sickness by generating visual feedback in the direction opposite to the movement observed, thus nullifying the vection effect. However, this approach has the drawback of creating visual feedback that disrupts the VR environment, thereby reducing immersion.

In this study, we propose an advanced concept called Directional Multimodal Flow, which extends the idea of Reverse Optical Flow to auditory and haptic senses. By combining the concept of reverse directionality with multimodal effects, we added directional auditory effects and haptic feedback involving wind and vibration to the existing Reverse Optical Flow. This approach aims to reduce motion sickness while enhancing immersion in VR environments.

The first experiment tested the effectiveness of 3D Sound Flow in reducing motion sickness. By extending the reverse directionality of Reverse Optical Flow to auditory feedback, 3D Sound Flow was designed to amplify sound in the direction opposite to the user's movement, thereby simulating the reverse directionality concept in auditory form. Although auditory feedback alone did not significantly reduce motion sickness, adding directional auditory feedback showed potential for positive effects on reducing motion sickness. This finding addresses the limitation of visual feedback potentially diminishing immersion.

The second experiment examined the combined effects of Reverse Optical Flow and 3D Sound Flow on motion sickness. The results indicated that while this combination did not significantly reduce motion sickness, it positively impacted user immersion. This suggests that combining visual and auditory feedback can overcome the limitations of visual feedback alone. This experiment confirmed the potential for reducing motion sickness while maintaining or enhancing immersion.

The third experiment incorporated haptic feedback, developing the Haptic Flow system, which uses hand-held controllers with vibration and fans placed on the left, right, and front to provide various tactile stimuli. The results demonstrated that all experimental conditions involving Haptic Flow showed significant motion sickness reduction, with the multimodal feedback system featuring directional cues proving most effective. This indicates that tactile feedback, particularly the wind and vibration, significantly contributes to reducing motion sickness. Additionally, combining various sensory feedback and directionality further enhances the effectiveness.

The main finding of this study is the positive impact of combining sensory feedback with directionality on reducing motion sickness. Tactile feedback alone showed significant effects, and its combination with auditory and visual feedback maximized the reduction. The multimodal feedback system with

directionality proved highly effective in reducing motion sickness while maintaining or enhancing immersion. This holds significant implications for improving the practicality of VR technology and enhancing user experience.

In conclusion, this study confirmed that multimodal feedback systems play a crucial role in reducing motion sickness and enhancing immersion in VR environments. Particularly, feedback systems with directional cues can overcome existing limitations and significantly improve user experience. Future research should focus on further developing these systems to enhance their effectiveness and applicability.

Keywords: Virtual Reality, VR Sickness, Reverse Optical Flow, Multimodal Flow

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1. Introduction

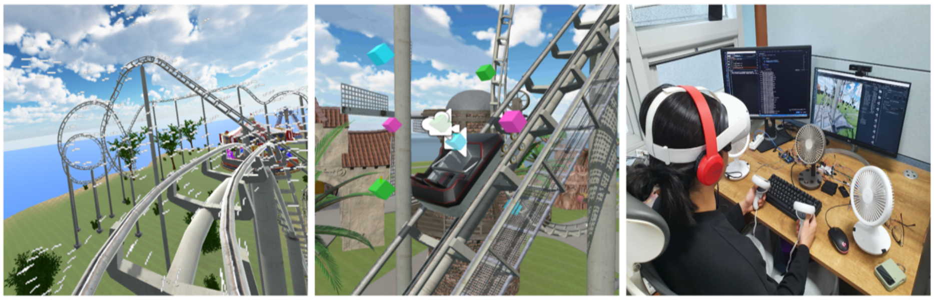


Figure 1 Application of Reverse Optical Flow (left), Directional Sound Flow (center), and Multimodal Flow (right). All three methods are designed to mitigate VR motion sickness. Reverse Optical Flow generates optical flow objects in the opposite direction of vection to nullify its effects. Directional Sound Flow creates directional auditory perception by placing three sound sources along the x, y, and z axes, in the same direction as Reverse Optical Flow. Multimodal Flow combines tactile feedback from vibration and wind devices with both Reverse Optical Flow and Directional Sound Flow to generate directional cues and multimodal effects, thereby mitigating motion sickness

One way to reduce simulation sickness in Virtual Reality (VR) is to adjust the amount of visual feedback conveying perceived movement. This approach is based on the sensory conflict theory between visual stimuli and vestibular system signals [6]. Methods such as dynamic Field of View (FOV) adjustment [3], blurring image processing [1], rest frame methods like Virtual Nose [10], and Reverse Optical Flow have been proposed. However, these visual feedback adjustment methods have drawbacks, including the intrusion of content and negative impacts on immersion and user experience. For example, methods like Virtual Nose can obstruct a significant portion of the content screen, interfering with the user's view.

The first experiment in this study aims to address the issue of reduced immersion associated with these visual content manipulation-based sickness reduction methods by utilizing auditory cues instead. Specifically, the experiment explores the use of 3D sound effects to reduce motion sickness and improve immersion. The idea behind this experiment was inspired by Reverse Optical Flow, which suggests that vection induced by visual movement can be nullified by generating optical flow in the opposite direction, thereby reducing motion sickness.

In this study, the 3D Sound Flow [13] system was developed with the idea that synchronized auditory feedback could also serve as a navigation aid, similar to the directional mitigation effects seen with Reverse Optical Flow [8]. The direction of the Reverse Optical Flow corresponds to the direction of head movement. For instance, when a user rotates their head to the right, the optical flow generated by stationary objects moves to the left, whereas the Reverse Optical Flow moves to the right. In a roller coaster environment, the 3D Sound Flow uses sound sources that move in the same direction as the roller coaster, providing directional auditory feedback to the user's right ear as the cart moves right. This implementation borrows from the concept of Reverse Optical Flow by adding directional cues to the auditory perception, aiming to nullify the cognitive vection induced by sound and observe the navigation effect.

Previous studies have explored the combination of various sensory inputs, such as auditory and tactile stimuli, to reduce motion sickness beyond just visual feedback. While certain sensory combinations effectively reduced motion sickness, other combinations did not yield the same result. For example, using tactile sensations like vibration [9] or airflow sometimes helped reduce sickness, but the effectiveness varied across different combinations. Most experiments on motion sickness reduction focused on sensory combinations, while there has been limited research on directional cues.

Therefore, this study builds upon previous findings by examining the effect of combining different sensory modalities to reduce motion sickness. Additionally, the study aims to expand on the concept of Reverse Optical Flow by incorporating directional cues to provide an added effect on sickness reduction. Given that visual feedback often negatively impacts immersion and user experience, this study also investigates whether combining sensory modalities and adding directionality can positively affect immersion.

The experimental design of this study is as follows. The first experiment tested whether auditory-only feedback could reduce motion sickness. To this end, a 3D Sound Flow system was developed, incorporating the idea of Reverse Optical Flow to generate directional auditory feedback. The second experiment combined Reverse Optical Flow with 3D Sound Flow to determine their combined effect on motion sickness reduction, addressing whether auditory feedback could overcome the limitations of visual-only feedback. Finally, the third experiment added tactile feedback to develop a Haptic Flow system, which was used in conjunction with Reverse Optical Flow and 3D Sound Flow to maximize the motion sickness reduction effect.

This study proposes a novel approach to reducing motion sickness and enhancing immersion in VR environments through the combination of multiple sensory feedback systems. The results showed that combining different sensory modalities and adding directional cues positively impacted both motion sickness reduction and immersion, contributing to improved user experience and the practical applicability of VR technology.

2. Related works

Focusing on the negative impact of visual effects on immersion during VR use for reducing motion sickness, we investigated studies related to multimodal systems as potential solutions. Research involving combinations of tactile and visual or auditory and visual stimuli was reviewed. Notably, tactile effects related to airflow often showed positive results, which led us to investigate related studies as a characteristic feature.

2.1 Single Modality

2.1.1 Blurring Effect

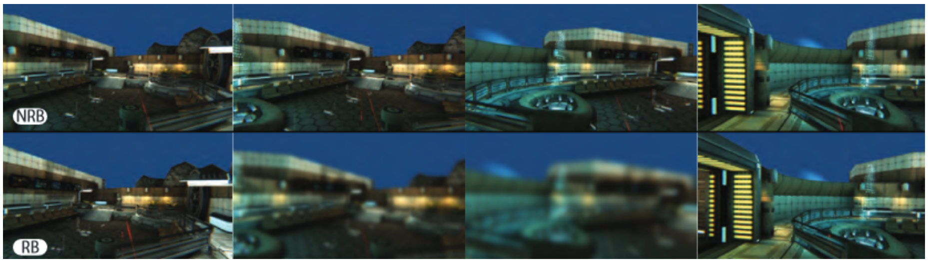


Figure 2 The upper image shows NRB (Rotation Blurring Disabled), and the lower image shows RB (Rotation Blurring Enabled)

Blurring effects [1] are one effective way to reduce motion sickness in Virtual Reality (VR) environments. Specifically, techniques that apply artificial blurring during rotation have been used to decrease sickness. According to previous studies, applying blur during rotation can reduce cybersickness by making visually induced stimuli less realistic.

The Rotation Blurring (RB) technique is implemented using the Unity3D game engine, applying Gaussian blur to the screen in response to mouse movement. The intensity of the blur is adjusted proportionally to the mouse acceleration, enabling smooth transitions during screen rotations. This helps reduce unpleasant visual stimuli experienced during rotation, thereby decreasing cybersickness. The RB technique was designed to mitigate rotation-induced sickness in VR environments, improving user experience and extending gameplay time. Experimental results indicated that participants experienced an overall reduction in cybersickness levels when the RB technique was applied, and the onset of sickness was delayed. This demonstrates that blurring during rotation effectively alleviates visually induced sickness.

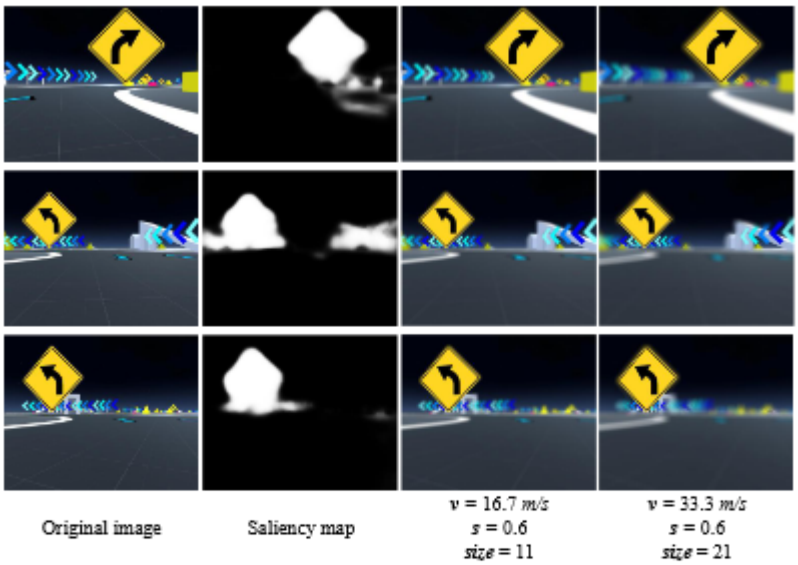


Figure 3 First column: Original scene captured with Unity3D's SteamVR camera. Second column: Saliency map. Third column: Non-salient areas blurred with two different kernel sizes

In a study by Guang-Yu Nie et al. (2019) [18], a method was proposed to alleviate visually induced motion sickness (MS) using dynamic blurring. In this study, 40 participants were exposed to VR experiences under both a control condition without dynamic blurring and an experimental condition with dynamic blurring. In the experimental condition, blurring was applied to the retina during rapid movement or rotation to reduce visual overload. Results showed a significant reduction in motion sickness symptoms in the experimental condition compared to the control condition, suggesting that dynamic blurring effectively mitigates visually induced MS in VR. This approach can help users remain comfortable in VR environments for extended periods, enhancing the quality of user experience and extending VR usage time limited by motion sickness.

These studies suggest that blurring techniques can play a crucial role in reducing visually induced motion sickness in VR environments, indicating the potential for further research and development of various blurring approaches.

2.1.2 FOV

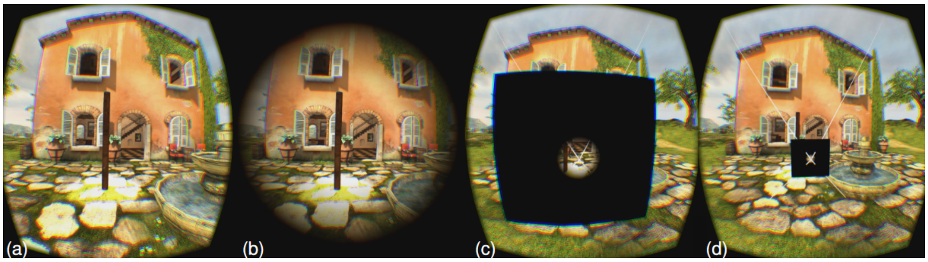


Figure 4 (a) View of the virtual environment without FOV modification, showing the research target (a brightly glowing vertical pillar) at the center. (b) Restricted view with a 90-degree soft edge circular cutout. Although clearly visible at a smaller size, this FOV restriction was mostly imperceptible to participants when gradually applied using an HMD. (c) Geometric structure of the FOV restriction device used to generate subfigure (a), with the cutout sufficiently wide to

not impact FOV. (d) Geometric structure of the FOV restriction device used to generate subfigure (b), scaled relative to the center of the plane without shifting the projection center

Field of View (FOV) is considered one of the primary factors contributing to motion sickness in VR environments. A wide FOV provides users with a greater sense of immersion, but it can also lead to visual overload, causing motion sickness. To address this issue, methods for dynamically adjusting the FOV have been proposed [3].

This study presents a method to reduce VR-induced motion sickness by narrowing the field of view (FOV). Dynamic FOV adjustment works by gradually blurring the edges of the field of vision when the user moves or rotates, thereby reducing visual stimulation. This approach helps alleviate visual overload and, as a result, mitigates motion sickness symptoms. When the user is stationary or moving slowly, the wide FOV is maintained to provide a sense of immersion, while during fast movements or rotations, the FOV is reduced to prevent motion sickness.

The experimental results confirmed that dynamic FOV adjustment is effective in reducing motion sickness. By narrowing the FOV during fast movements or rotations, the severity of motion sickness symptoms was reduced, and there was no significant decrease in immersion. This suggests that dynamically adjusting visual information can be an effective approach to reducing motion sickness in VR environments.

Dynamic FOV adjustment is an approach that can prevent motion sickness by reducing visual overload in VR environments, particularly in fast-moving VR content.

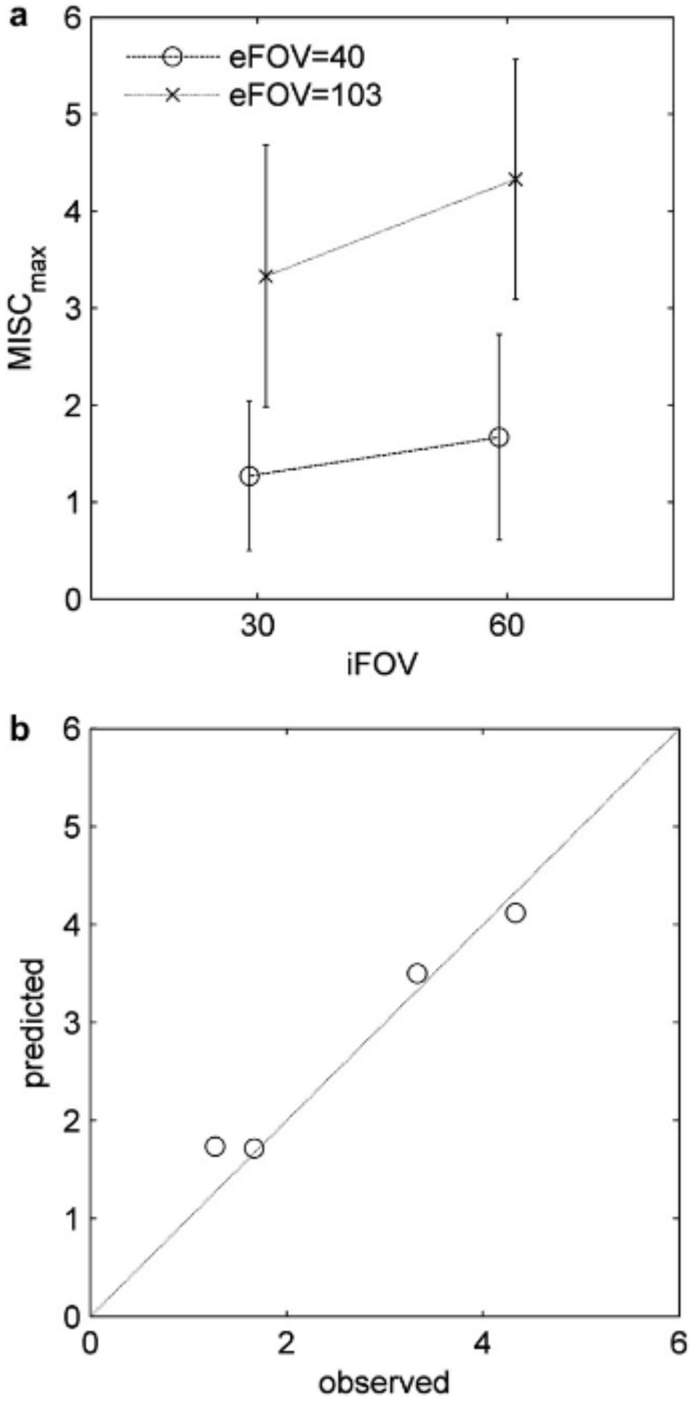

a
6
5
4
3
2
1
0
MISC$_{max}$
eFOV=40
eFOV=103
30
60
iFOV
b
6
5
4
3
2
1
0
predicted
0
2
4
6
observed

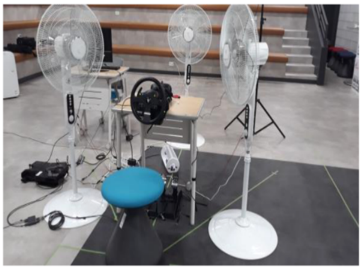
Figure 5 (a) Impact of internal FOV (iFOV) and external FOV (eFOV) on subjective well-being (MISCmax). (b) Graph comparing predicted and observed MISC values, showing a tendency for FOV mismatch to reduce motion sickness

Bos et al. (2010) investigated the impact of iFOV and eFOV on visually induced motion sickness. The study hypothesized that discrepancies between iFOV and eFOV would induce motion sickness and conducted experiments in various computer game environments with different settings. Contrary to expectations, the results showed that a significant discrepancy between iFOV and eFOV tended to reduce motion sickness. This could be explained by the assumption of an internal model that controls body movements, where large discrepancies may reduce conflicts between visual signals and the internal model, thus alleviating motion sickness.

In this study, participants passively viewed a virtual environment tour while being exposed to different iFOV and eFOV settings. Participants evaluated their level of motion sickness using the MISC (Misery Scale), and the results showed that eFOV had a significant impact on motion sickness, whereas iFOV did not have a meaningful effect. The greater the discrepancy between eFOV and iFOV, the more motion sickness was reduced.

These findings confirm the important role of internal and external FOV in visually induced motion sickness, and suggest that a larger discrepancy between iFOV and eFOV, contrary to expectations, can reduce motion sickness. This study emphasizes that conflicts between sensory signals and the internal model can cause motion sickness and shows that large FOV discrepancies may have a more significant impact on players.

2.1.3 Airflow and Motion Sickness



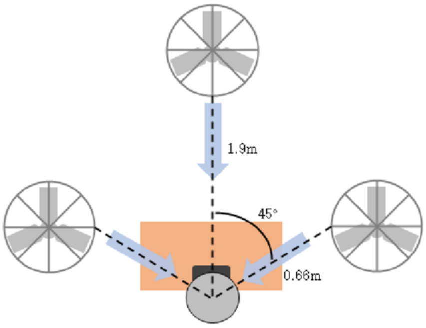


Figure 6 Virtual driving environment setup with three fans positioned at the front (1.9m) and sides (0.66m), each spaced 45 degrees apart. The fans operate simultaneously, either all on or all off

This study tested the hypothesis that airflow, specifically wind, helps reduce motion sickness in VR environments[7]. The experiment was conducted using three fans positioned in front, to the left, and to the right, simulating a driving scenario in a VR environment. The experiment was divided into two conditions: one where all three fans were activated, and another where no fans were used. The results showed that the presence of wind led to a significant reduction in motion sickness. In other words, the tactile effect of wind alone proved to be effective in alleviating motion sickness.

2.1.4 Rest Frame (Virtual Nose)

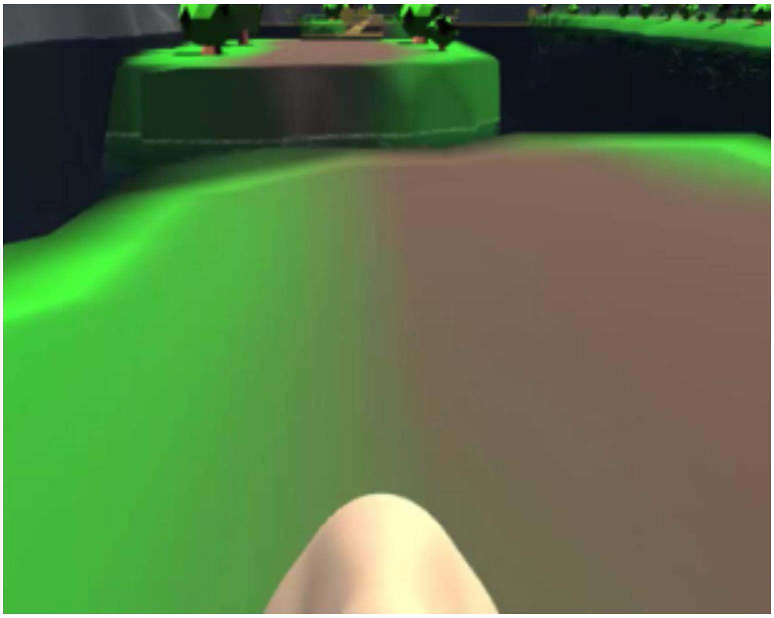


Figure 7 Virtual Nose

The Rest Frame theory[10]suggests that a stable visual reference frame can reduce motion sickness. This study examined the impact of a virtual nose on simulator sickness and gaming experience, as well as the importance of the visibility of the reference frame in reducing motion sickness.

The results showed that using a virtual nose helps reduce simulator sickness, but it did not have a significant effect on the gaming experience. The virtual nose functions as a visual reference frame, providing a stable element in the user's field of view. Additionally, the visibility of the Rest Frame[16]was found to have no significant impact on either motion sickness or the gaming experience.

The experiment compared conditions where the virtual nose was absent, had low visibility, or had high visibility. Participants played a VR game under each condition and were assessed on both simulator sickness and their gaming experience.

The results indicated a significant reduction in simulator sickness when the virtual nose was included in the environment. This suggests that the virtual nose contributes to reducing visual mismatch by providing a stable element in the user's field of view. However, increasing the visibility of the virtual nose did not further reduce simulator sickness, nor did it significantly affect the gaming experience.

This study implies that using reference frames like the virtual nose in VR environments can reduce simulator sickness. Moreover, the mere presence of a reference frame may play a more crucial role in reducing motion sickness than its visibility.

2.2 Multimodality

2.2.1 Sound & Visual and Motion Sickness

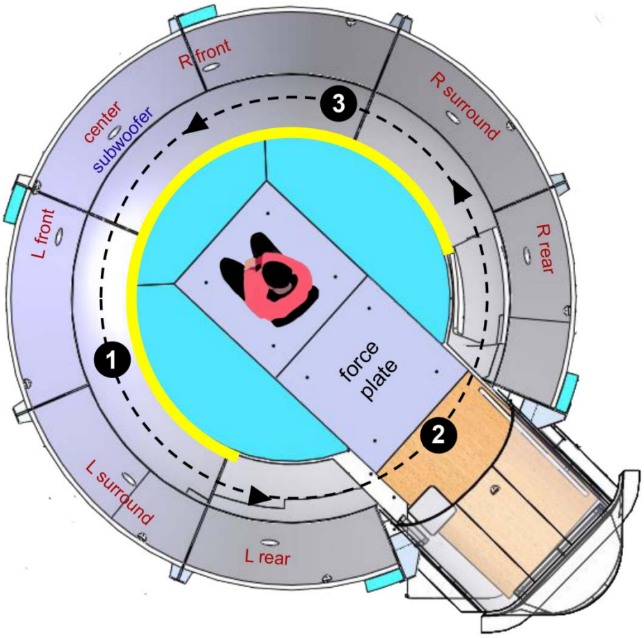


Figure 8 Setup with surround screens and seven-channel speakers to evaluate whether spatial audio-visual environments induce motion sickness

This study involved participants seated at the center of a circular screen setup, surrounded by seven 7.1 surround sound channel speakers, with sound effects positioned at regular intervals around the screen[12]. The experiment consisted of showing visual content on the screen while simultaneously providing related auditory effects. The experimental conditions were divided into three groups: visual effects only, auditory effects only, and a combination of both visual and auditory effects.

The results showed that when auditory effects were combined with visual effects, there was no strong correlation with motion sickness. However, when only visual effects were provided, 18 participants reported experiencing motion sickness, while only 6 participants reported the same when only auditory effects were provided. This study presented results that challenge the conventional understanding that motion sickness primarily arises from a sensory mismatch between visual information and the vestibular system, with little connection to auditory information.

2.2.2 Multimodal Effects of Sound and Vibration on Motion Sickness

Figure 9 Motorcycle simulation in a VR environment with vibration feedback from the motorcycle and corresponding sounds played through headphones

The next experiment aimed to determine whether the combination of sound and vibration helps reduce motion sickness[9]. The participants simulated driving a motorcycle in a VR environment, where vibrations were generated by the motorcycle, and auditory effects were provided through headphones to match the VR environment. The experiment consisted of four conditions: no effects, auditory effects only, vibration effects only, and a combination of both auditory and vibration effects. The results showed that when both auditory and vibration effects were provided simultaneously, motion sickness was significantly reduced compared to the other three conditions. This indicates that the combination of auditory and vibration effects is effective in reducing motion sickness.

2.2.3 Multimodal Effects of Airflow and Vibration on Motion Sickness

Figure 10 Scenario presented on the front screen with seat vibration feedback and operation of side fans

The following study aimed to investigate whether the tactile effects of wind and vibration contribute to reducing motion sickness【2】. The experiment was conducted by showing video content on a screen, while the experimental environment involved vibrations generated by the chair and wind provided by fans placed on either side. The experiment was divided into four conditions: no effects, wind only, vibration only, and a combination of both wind and vibration.

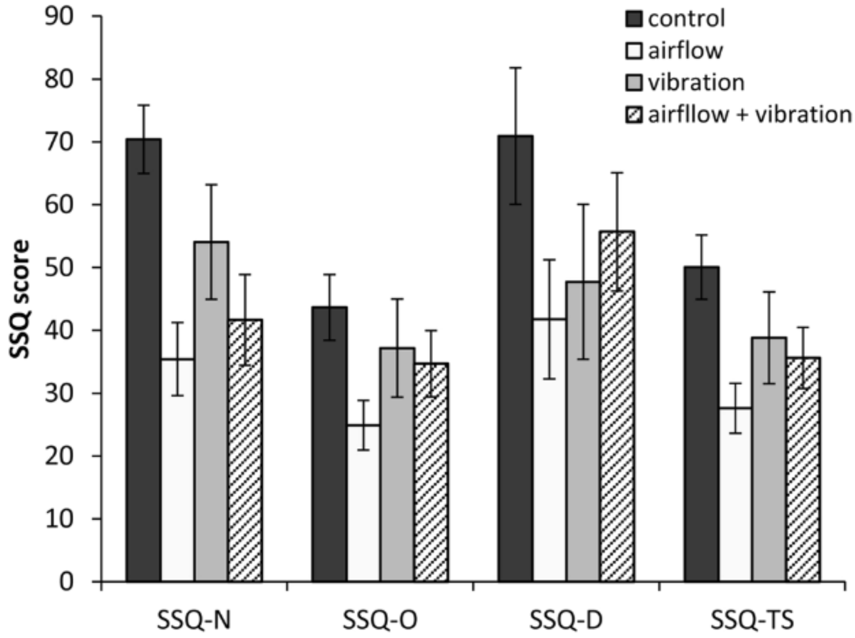


Table 1 SSQ Results of the Environment with Wind and Vibration Feedback

The results showed that when wind was provided alone, there was a significant reduction in motion sickness. All three experimental conditions showed a reduction in motion sickness compared to the no-effect condition, but the vibration-only and combined wind-and-vibration conditions did not demonstrate significant effects. According to the results graph, the wind-only condition had the lowest motion sickness scores across all scenarios, while the vibration-only condition had the highest motion sickness scores (except for the SSQ-D score), compared to the no-effect condition. In the combined wind-and-vibration condition, the reduction in motion sickness was less than that of wind alone, but it was more effective than vibration alone in all cases except for the SSQ-D score.

2.3 Summary

In summary, the related research results confirmed that wind alone is effective in reducing motion sickness. However, the combination of sensory inputs showed mixed results in reducing motion sickness. The combination of wind and vibration did not produce significant effects in reducing motion sickness and was less effective than wind alone. On the other hand, the combination of auditory and vibration effects showed a significant reduction in motion sickness. Vibration alone also resulted in reduced motion sickness on average, but the reduction was not statistically significant. Auditory effects alone were found to have the potential to induce motion sickness. However, when auditory effects were combined with visual effects, there was no significant impact on motion sickness.

These experimental results suggest that sensory inputs other than vision can influence the reduction of motion sickness. For example, wind, as a tactile effect, was found to be effective in reducing motion sickness on its own. Additionally, a multimodal system that combines multiple sensory inputs was found to further help in reducing motion sickness. Specifically, the combination of auditory and visual effects reduced the likelihood of motion sickness compared to using a single sensory input, and the combination of auditory and vibration effects also reduced motion sickness. Wind, whether used alone or in combination, showed the potential to reduce motion sickness.

Based on these findings, the experiments in this study were designed and conducted. The first experiment focused on whether auditory effects alone could reduce motion sickness. The next experiment examined whether combining auditory and visual effects could reduce motion sickness while enhancing immersion. Finally, the last experiment added the tactile effects of vibration and wind to auditory and visual effects, testing whether the combination of these three sensory inputs in a multimodal system could reduce motion sickness and increase immersion.

3. Directional Sound Flow

3.1 Design

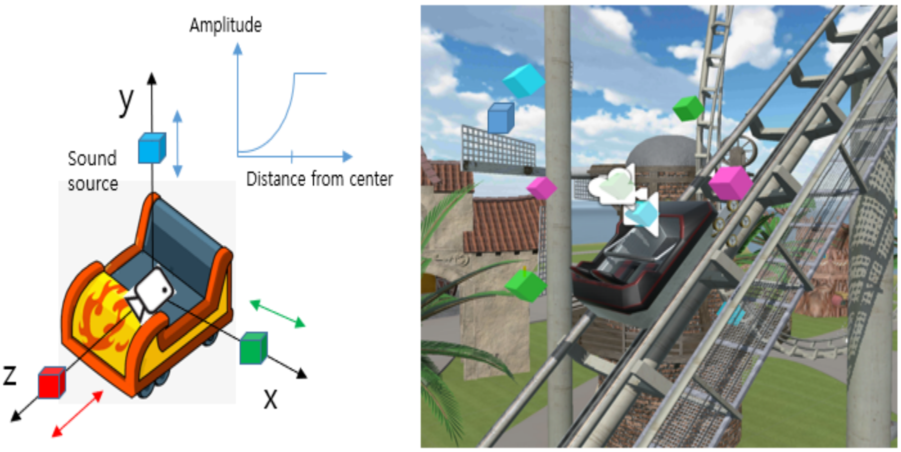


Figure 11 Configuration of Directional Sound Flow (left) and its application in a roller coaster (right). Sound sources positioned along the x, y, and z axes move according to the speed and rotation of the roller coaster cart, creating directional auditory perception. As the sound source moves, the sound gradually increases in volume to provide an inverse effect relative to the actual rotation

Based on the analysis of related research results, this study first aimed to verify the independent effects of sensory inputs other than vision on reducing motion sickness[5]. First, 3D Sound Flow is a system that applies the concept of directionality from Reverse Optical Flow and extends it to auditory effects[8]. 3D Sound Flow consists of sound sources positioned along the x, y, and z axes, with each sound source moving linearly in the direction corresponding to its respective axis[13]. In the roller coaster environment, each sound source moves along the axis in the direction opposite to the Optical Flow, matching the speed and rotation angle of the cart.

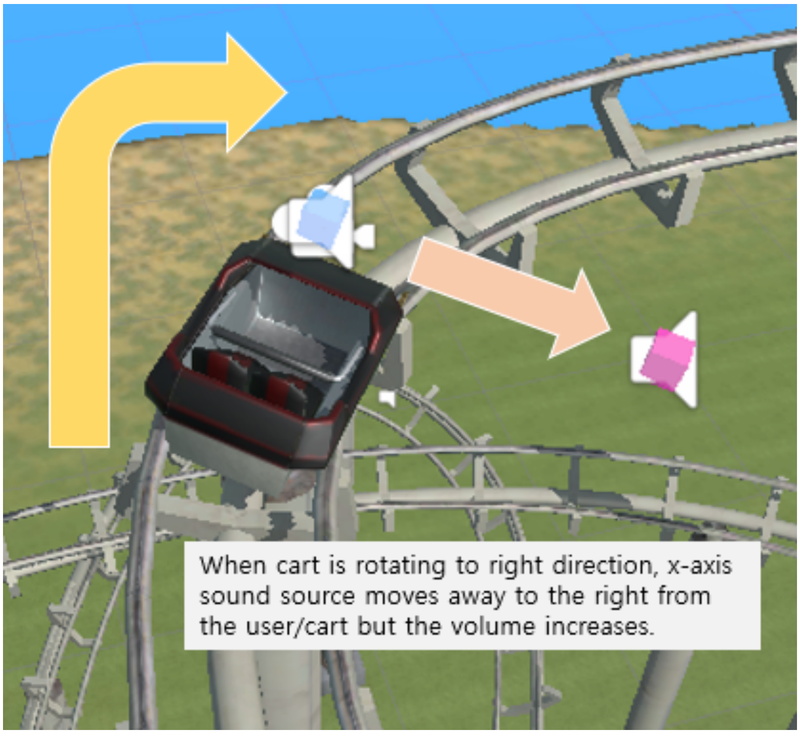


Figure 12 Example of Directional Sound Flow applied. As the cart rotates right, the sound source moves rightward along the x-axis (in the same direction as Reverse Sound Flow), increasing in volume

For example, when the sound source along the x-axis moves, if the cart rotates to the right or left, the x-coordinate value will move in the positive or negative direction, with the cart's center as 0, according to the cart's rotation angle on the x-axis. When the cart rotates to the right and the x-axis rotation value increases from 0 to 20, the sound source on the x-axis moves to the right from the cart up to a certain limit. Once the rotation ends and the value returns to 0, the x-axis sound source also returns to the cart's center, bringing the x-value back to 0. The speed at which the sound source moves away from or closer to the cart's origin along the x-axis is proportional to the rotation speed. If the cart rotates to the right quickly, the sound source will also move away from the cart quickly. For the y-axis, the sound source moves according to the up-and-down rotation values. For example, when the cart rotates upward, the sound source on the y-axis moves upward from the cart up to a certain limit, with the speed proportional to the cart's rotation speed. Similarly, when the cart rotates downward, the sound source on the y-axis moves downward and returns to the origin when the rotation ends. Lastly, the sound source on the z-axis moves toward the front of the cart as the speed increases in the roller coaster environment, with the movement speed proportional to the cart's velocity.

As each sound source moves along its axis, the volume of the sound increases simultaneously. When the cart rotates to the right, the sound source moving along the x-axis moves in the same direction and increases in volume up to a certain limit. Likewise, when rotating up or down, the sound source on the y-axis increases in volume as it rotates along the axis. For the z-axis sound source, when the speed exceeds a certain threshold, it moves farther away, and the volume increases. This adjustment of sound volume is designed to emphasize the sense of reverse directionality. In real-world situations, as a sound source moves away from a listener, its volume decreases. Therefore, if the volume of the sound decreases with rotation, it would contradict the theory of Vection nullification in Reverse Optical Flow. Specifically, as the rotation intensity increases in Reverse Optical Flow, more visual objects are generated to counter the Vection effect【8】. Similarly, 3D Sound Flow also needed to increase the sound intensity of moving sound sources to nullify auditory Vection.

The reasoning behind 3D Sound Flow following the Reverse Optical Flow theory of Vection nullification and adjusting the intensity accordingly has been explained. Beyond adopting the idea of reverse directionality from Reverse Optical Flow, there is another reason for the reverse directionality of auditory Vection: in the case of sounds generated by friction and vibration, such as wind noise, louder sounds occur on the side with stronger friction. For example, in the real world, when a listener rotates to the right, stronger centrifugal forces act on the left side, causing the auditory sensing mechanism on the left ear to rotate at a higher linear speed than the right ear. As air resistance increases proportionally to the square of speed, the left ear experiences faster rotation, leading to greater air resistance and the formation of stronger turbulence. Sound sources like wind noise generate louder sounds when subjected to stronger friction, meaning that when the cart rotates to the right, the left ear will perceive louder sounds. Based on this principle, 3D Sound Flow is designed so that when the cart rotates to the right, the sound source moves to the right of the cart, and the volume increases accordingly. This is seen as proceeding in the reverse direction of auditory Vection.

3.2 Experiments

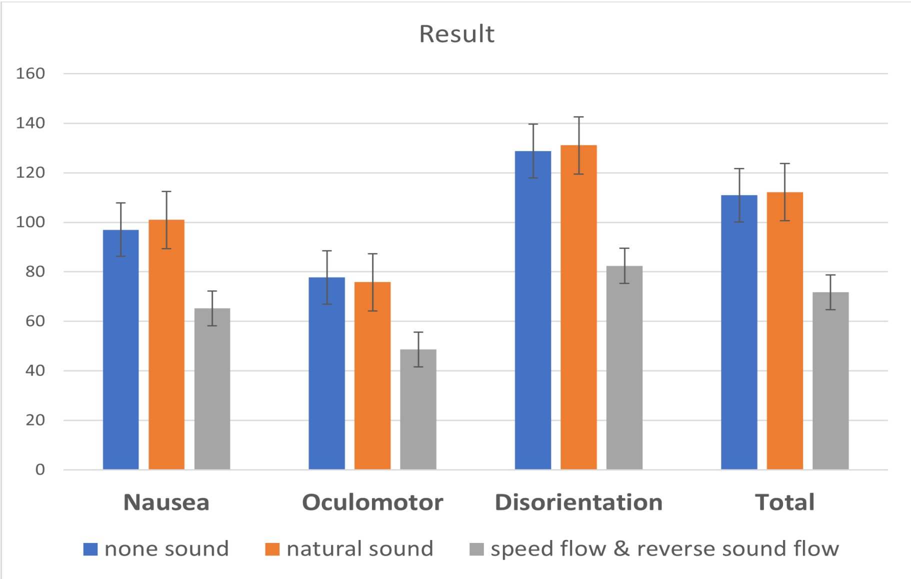


Table 2 SSQ Results for Directional Sound Flow

To verify the motion sickness reduction effect of 3D Sound Flow, a simple pilot test was conducted. The experiment involved six participants, and it was carried out in a VR roller coaster environment for 2 minutes. There were three experimental conditions: the first condition had no effects, the second condition played wind sounds without directional cues for 2 minutes, and the third condition played 3D Sound Flow with directional cues for 2 minutes. Motion sickness was evaluated using the SSQ questionnaire【4】, and each participant was given sufficient rest before moving on to the next condition to ensure that any symptoms of motion sickness were fully resolved.

The VR roller coaster environment was designed to provide participants with an immersive experience using the Unity platform, Oculus 2 VR HMD, and spatial audio-capable headphones. The system provided real-time visual and auditory immersion based on the roller coaster's direction, allowing users to feel as if they were riding a real roller coaster (as noted in post-experiment interviews).

The first condition, with no additional effects, served as a baseline for measuring basic motion sickness responses, allowing for comparison with the other two conditions. The second condition used non-directional wind sounds played equally in both ears to evaluate the impact of auditory stimuli on motion sickness. While this condition did not provide a sense of spatial immersion, it aimed to assess how auditory stimuli in sync with visual feedback could affect motion sickness.

The third condition applied 3D Sound Flow, giving the wind sound directional cues to match the roller coaster’s rotation. This is similar to the directionality in Reverse Optical Flow. In contrast to the second condition, where a constant wind sound was used, the third condition featured changes in the spatiality and volume of the sound based on the direction and speed of the roller coaster. This condition focused on evaluating how the combination of sound directionality and volume adjustments in sync with visual stimuli impacted motion sickness. 3D Sound Flow was designed so that the sound moved in the same direction as the rotation of the roller coaster, which is the opposite of Optical Flow, and aligned with the perceived visual rotation.

Each experimental condition lasted for 2 minutes, and after each condition, participants completed the SSQ questionnaire to assess their motion sickness symptoms. Participants were given enough rest between each condition to ensure full recovery from any motion sickness. The SSQ questionnaire evaluates the intensity and frequency of motion sickness, with scores classified into N, O, D, and TS values【4】.

The results showed that in the second condition, where non-directional wind sounds were played, there was little difference from the first condition, or in some cases, an increase in motion sickness symptoms was observed. This suggests that constant wind sounds are not effective in alleviating motion sickness. In contrast, the third condition, where 3D Sound Flow was applied, showed a significant reduction in motion sickness symptoms. This suggests that the spatial effect and volume adjustments in 3D Sound Flow, which matched the direction of the visual rotation, were key factors in reducing motion sickness.

These results indicate that auditory stimuli alone can affect motion sickness symptoms, and that directional sound can help reduce motion sickness. In other words, auditory stimuli can either exacerbate or alleviate motion sickness, and additional effects, such as directionality, can further enhance the reduction of motion sickness. This experiment demonstrates that in VR environments, 3D Sound Flow can contribute to reducing motion sickness through auditory effects. Based on these results, the next experiment was designed to combine visual effects, such as Reverse Optical Flow, with auditory effects to further explore motion sickness reduction. The main goal of the next experiment was to address the primary limitation of Reverse Optical Flow, which was reduced immersion, by enhancing the auditory effects and to design a system that could further reduce motion sickness through the combination of Reverse Optical Flow and 3D Sound Flow.

4. Directional Visual & Sound Flow

4.1 Design

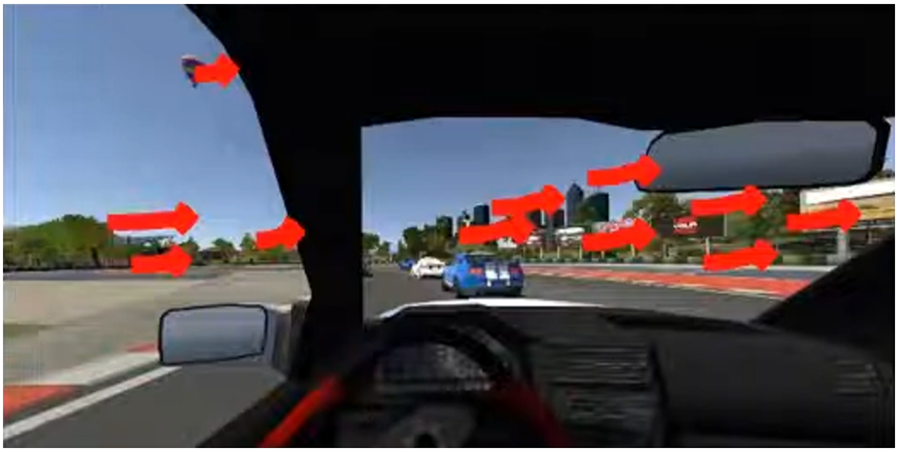


Figure 13 Example of Forward Optical Flow

Figure 14 Example of Reverse Optical Flow

Reverse Optical Flow is a theory derived from the concept of Optical Flow, where an object within the line of sight moves in the opposite direction to the eye movement. People experience motion sickness from the Vection that occurs when an object within the line of sight moves in the opposite direction to their gaze and disappears from their field of vision. Reverse Optical Flow counters this Vection, intentionally creating visual objects in the field of view that are expected to cognitively nullify the Vection effect. For example, when looking at a chair in front of you and turning your head to the left, the chair appears to move to the right in your field of view. This creates Vection, and to cancel out the motion sickness caused by this Vection, white visual objects are intentionally generated in the opposite direction of the chair's Optical Flow. This process helps nullify the Vection effect. Additionally, the idea of Reverse Optical Flow can be considered effective, as previous studies have suggested that expansive visual attention plays a role in reducing motion sickness【17】.

Figure 15 Application of Reverse Optical Flow in a roller coaster environment. Optical Flow is generated in the direction opposite to the

vection, creating white objects in the same direction as the rotation (shown on the right) to nullify the vection effect and mitigate motion sickness

Research has shown that Reverse Optical Flow helps reduce motion sickness. In addition to the Vection nullification effect, this reduction in motion sickness could also be attributed to other factors such as the creation of visual objects that act similarly to a Rest Frame【10】or the Navigation effect, which helps users perceive the direction of rotation. The synergy between these various mechanisms might have contributed to the reduction in motion sickness. However, while these visual effects help alleviate motion sickness, they also result in reduced immersion by not showing a complete screen in the VR environment. This reduction in immersion is a common limitation of visual methods for mitigating motion sickness. The reason for developing an auditory method for reducing motion sickness, as explored in the earlier experiments, was to overcome the limitations of visual motion sickness reduction techniques.

4.2 Experiments

Since the earlier experiment showed that 3D Sound Flow, which adopted the idea of Reverse Optical Flow, had a positive effect in reducing motion sickness, the subsequent experiment aimed to determine whether the combination of Reverse Optical Flow and 3D Sound Flow could reduce motion sickness while also enhancing immersion. The experiment was conducted with a total of 19 participants, with an average age of 23.89 years. Motion sickness and immersion were assessed using the SSQ questionnaire【4】and the IPQ questionnaire. The experimental conditions were divided into four groups: the first with no effects, the second with non-directional sound, the third with only 3D Sound Flow applied, and the fourth with a combination of Reverse Optical Flow and 3D Sound Flow.

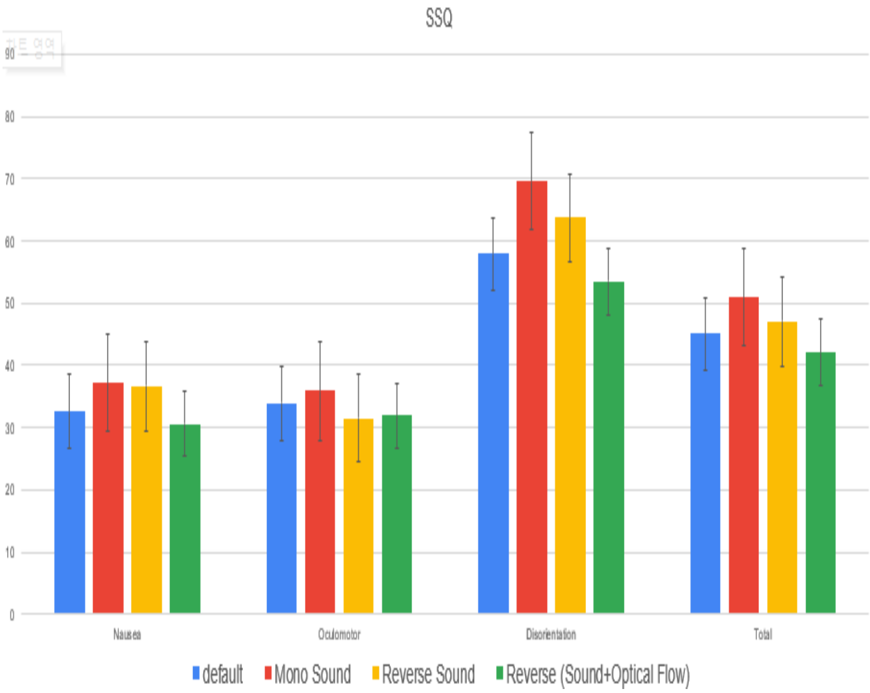


Table 3 SSQ Results of Combined Experiment with Reverse Optical Flow and Directional Sound Flow

The experimental results showed outcomes that were contrary to the previous experiment. In the earlier experiment, applying 3D Sound Flow resulted in reduced motion sickness compared to the environment with non-directional sound. However, in the later experiment, motion sickness increased compared to the environment with no effects. When Reverse Optical Flow and 3D Sound Flow were combined, there was a trend of reduced motion sickness, but the difference was not statistically significant. In other words, when only auditory effects were applied, even with directional cues, motion sickness increased. When both auditory and visual effects were applied, although the reduction in motion sickness was not significant, a decreasing trend was observed.

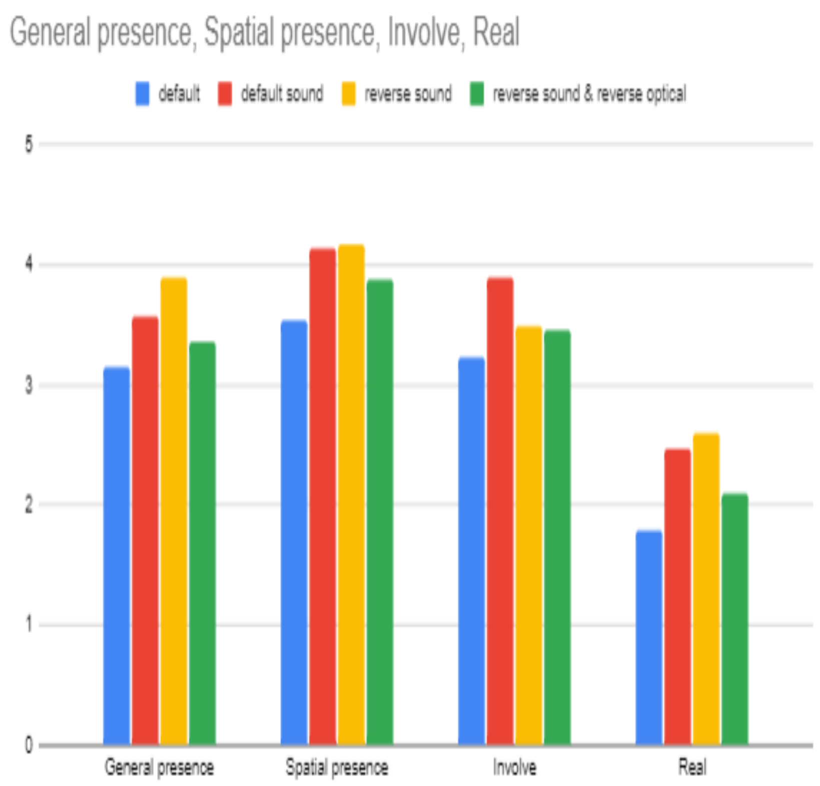


Table 4 IPQ Results of Immersion from Combined Experiment with Reverse Optical Flow and Directional Sound Flow

In the IPQ immersion survey, applying only auditory effects resulted in higher immersion compared to the no-effect condition, regardless of whether directional cues were present. When both auditory and visual effects were applied, immersion was lower than with auditory effects alone, but it still showed an increase compared to the no-effect condition.

To summarize the experimental results, auditory effects alone did not reduce motion sickness, but they had a positive effect on immersion. When auditory and visual effects were combined, there was a slight trend toward reduced motion sickness, though the results were not statistically significant. However, immersion increased compared to the no-effect condition. Based on these results, the hypothesis that auditory effects alone can reduce motion sickness was rejected, and a new hypothesis was formed—that a multimodal approach combining visual and auditory effects could reduce motion sickness while simultaneously enhancing immersion. This hypothesis served as the basis for planning the next experiment.

5. Directional Flow of Visual, Auditory, and Haptic/Tactile Modalities

5.1 Design

Figure 16 Experimental setup for Directional Multimodal Flow.

Participants experience Reverse Optical Flow while wearing headphones (Directional Sound Flow), holding hand controllers (vibration haptic), and sitting in front of fans positioned on the left, right, and front (Wind Tactile) in a roller coaster environment. Directional Sound Flow and Haptic Flow are executed in the same direction as the Reverse Optical Flow

There are various methods for tactile stimulation【13】, but according to previous experimental results, wind effects are effective in reducing motion sickness on their own, while vibration effects may produce a synergistic effect when combined with other sensory inputs. In this experiment, under the assumption that wind has a positive effect on reducing motion sickness, a method was devised to apply both wind and vibration effects simultaneously, which was named "Haptic Flow." Haptic Flow involves holding Oculus handheld controllers in both hands to feel vibrations while being exposed to wind from fans placed on the left, right, and front.

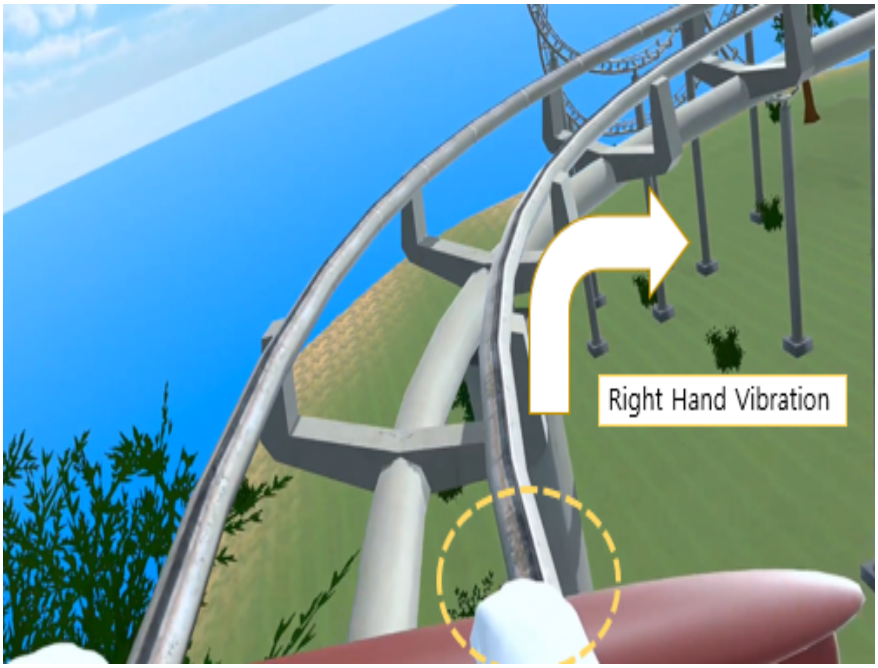


Figure 17 Example of Haptic Flow. Vibration occurs on the right hand during rightward rotation of the roller coaster, with the vibration intensity increasing as the rotation strengthens (following the sensory enhancement approach of Reverse Optical Flow and Directional Sound Flow)

Similar to the auditory 3D Sound Flow, Haptic Flow was also applied in the same manner as the directionality of Reverse Optical Flow. For example, when the roller coaster rotates to the right, Reverse Optical Flow occurs to the right, and in the case of tactile feedback, vibrations were applied to the right-hand controller. The intensity of the vibration was designed to increase up to a certain threshold as the rotation speed intensified. For the wind effect, the fans on the left, right, and front operated in accordance with the intensity of the rotation, and their strength was set to increase up to a certain threshold depending on the rotation intensity. The front fan was set to increase its intensity as the speed increased, borrowing the method used by the z-axis sound source in 3D Sound Flow, which increases sound intensity as the speed increases.

In Haptic Flow, just like with the auditory effects, the controllers and fans on the left and right sides were designed to increase intensity on the opposite side of the rotation, considering that greater centrifugal force and air resistance occur in the opposite direction as the speed increases. For example, when the roller coaster rotates to the right, stronger centrifugal force acts on the left side, increasing the linear speed, which proportionally increases air resistance on the left. Thus, it is natural to experience stronger wind on the left side. By assuming this as tactile Vection, a method was devised to cancel out this tactile Vection by providing strong stimulation to the right side, which is the reverse direction. In terms of forward movement, unlike up-and-down vibrations or left-and-right rotation, it is less related to motion sickness, so similar to the auditory effects, the strength of the front fan's wind was adjusted to increase in proportion to speed.

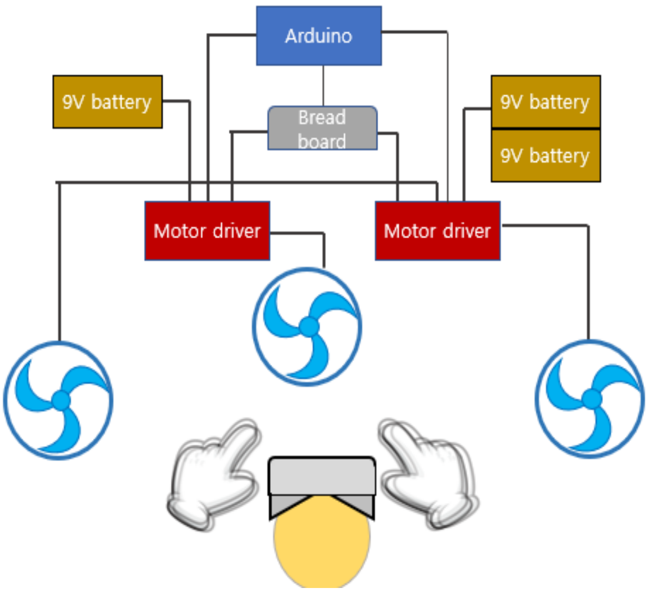


Figure 18 Directional Multimodal Flow system architecture. Participants wear headphones, use hand controllers with vibration

feedback, and experience wind from fans positioned at the left, right, and front

As can be seen from the system architecture, the experiment was conducted with the user facing a VR monitor, wearing stereo headphones, holding vibrating controllers, and feeling the wind from fans placed on the left, right, and front. The strength of the fans was synchronized with the VR environment using Arduino, while other effects were adjusted within the VR environment itself.

5.2 Experiments

The third experiment was conducted with a total of 19 participants, excluding one exception, with an average age of 24.72 years. The experiment took place in a roller coaster environment for 2 minutes and was divided into four conditions. The first condition had no effects, the second provided non-directional auditory and tactile effects (controller vibrations and wind) throughout the experiment, the third applied directional 3D Sound Flow (auditory effect) and Haptic Flow (tactile effect), and the final condition combined directional Reverse Optical Flow, 3D Sound Flow, and Haptic Flow. Based on the results of previous experiments, which suggested that multimodal approaches help reduce motion sickness and enhance immersion, all experimental conditions were designed to be multimodal. The experiment was structured to analyze the effects of directionality and the advantages and disadvantages of adding visual effects by varying the presence of directionality and visual effects. The results were evaluated using the SSQ motion sickness questionnaire【4】and the IPQ immersion questionnaire. The experiments were conducted randomly, with each subsequent experiment taking place only after motion sickness was completely resolved, as assessed by a preliminary questionnaire.

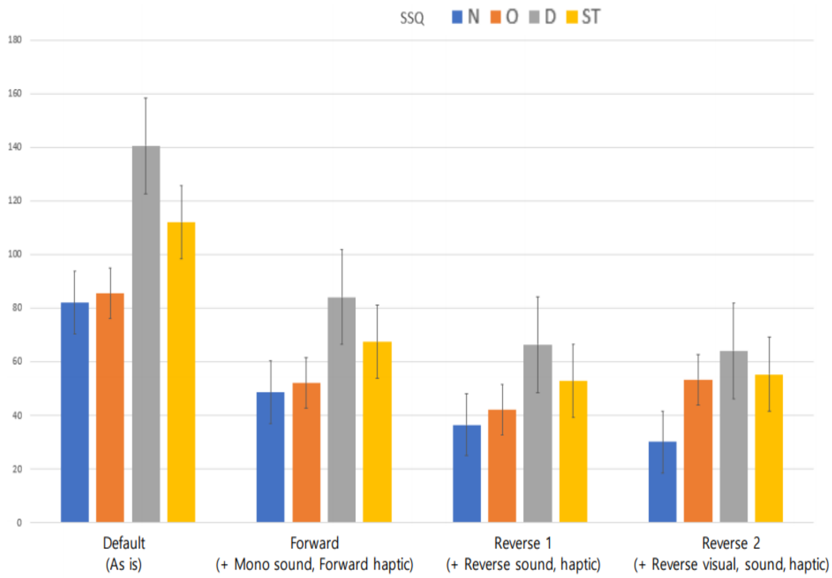


Table 5 SSQ Results for Directional Multimodal Flow

SSQ Average	N	O	D	TS
A(1) Default	82.15	85.49	140.75	112.20
(2) Mono (S+MH)	48.76	52.22	84.29	67.53
(3) Reverse (S+MH)	36.57	42.11	66.51	52.98
(4) Reverse (S+MH+OF)	30.21	53.48	64.19	55.48
SSQ Standard deviation	N	O	D	TS
(1) Default	40.12	32.73	57.37	43.19
(2) Mono (S+MH)	23.77	29.35	48.10	32.57
(3) Reverse (S+MH)	23.42	24.13	36.99	26.86
(4) Reverse (S+MH+OF)	18.61	30.68	39.95	29.51

Table 6 Mean and Deviation Values for SSQ Results of Directional Multimodal Flow

The experimental results showed that all three experimental conditions provided a significant reduction in motion sickness compared to the no-effect condition. There was a trend of reduced motion sickness as directional cues and visual effects were added, but in the t-test comparing the combination of non-directional auditory and tactile effects with the combination of Reverse Optical Flow + 3D Sound Flow + Haptic Flow, a significant difference was observed only in the SSQ-N value.

paired T Test	N	O	D	ST
Default - Mono (Sound+Multi Haptic)	0.00040***	0.00001***	0.00196***	0.00011***
Default - Reverse (Sound+Multi Haptic)	0.00052***	0.00001***	0.00031***	0.00006***
Default - Reverse (Sound+Multi Haptic+Optical Flow)	0.00027***	0.00323***	0.00057***	0.00046***
Mono (Sound+Multi Haptic) - Reverse (Sound+Multi Haptic)	0.10620	0.09322	0.11740	0.07081
Mono (Sound+Multi Haptic) - Reverse (Sound+Multi Haptic+Optical Flow)	0.00218**	0.81850	0.10110	0.07589
Reverse (Sound+Multi Haptic) - Reverse(Sound+Multi Haptic+Optical Flow)	0.32070	0.13560	0.83850	0.74750

Table 7 Paired T-Test Results for SSQ of Directional Multimodal Flow. After confirming significance through ANOVA, the paired t-test was conducted. When compared to the default (no effect), significant differences were found in NODST values for combinations without directionality (Sound + Haptic) and combinations with directionality (Reverse Optical Flow + Sound + Haptic). Additionally, significant differences were observed in N values between the combinations of Sound + Haptic without directionality and those with Reverse Optical Flow + Sound + Haptic with directionality

When interpreting the trend of reduced motion sickness and the significant difference in SSQ-N values between the non-directional combination and the multimodal combination with added directionality and visual effects, it can be concluded that directional cues alone are insufficient to provide additional motion sickness reduction. Instead, a multimodal combination that includes both directionality and positive visual effects may produce a synergistic effect that further reduces motion sickness. All three experimental conditions included wind effects, and all showed significant motion sickness reduction. Considering previous related research, where the wind effect alone was effective in reducing motion sickness, and the combination of auditory and visual effects in earlier experiments, it is reasonable to conclude that the wind effect had the greatest impact on reducing motion sickness in this multimodal experiment. Additionally, the multimodal combination with other sensory inputs showed the potential for further reducing motion sickness, and the addition of directionality demonstrated a stronger synergistic effect.

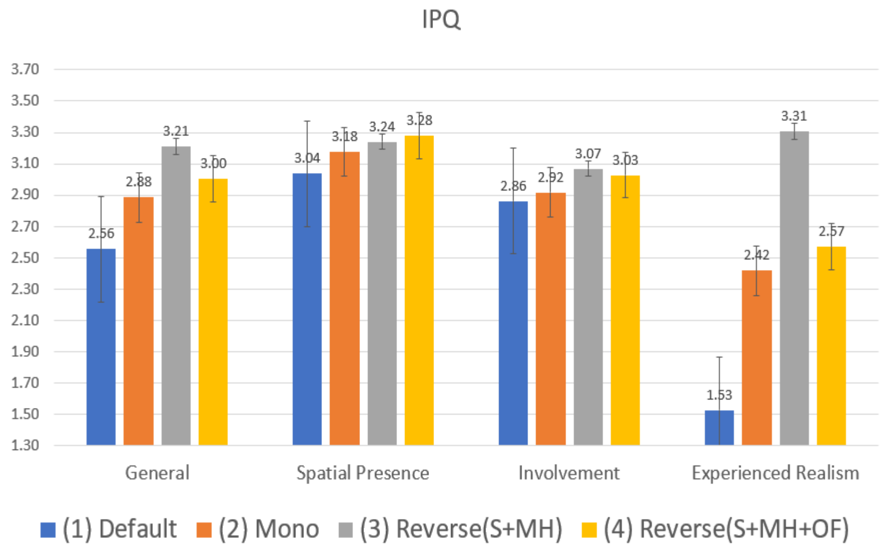


Table 8 IPQ Results for Immersion Evaluation of Directional Multimodal Flow

The immersion survey results showed that all three experimental conditions resulted in higher immersion compared to the no-effect condition. Considering that visual effects can negatively impact immersion, it seems reasonable that the combination of 3D Sound Flow and Haptic Flow with directional cues exhibited the highest overall immersion. However, the combination of Reverse Optical Flow + 3D Sound Flow + Haptic Flow outperformed the non-directional auditory and tactile combination in all measures, particularly showing the highest results in spatial presence. This suggests that, unlike previous experiments, when directionality and tactile stimuli were applied in a multimodal setup, the application of visual effects did not cause a decrease in immersion. In other words, when both directionality and a multimodal environment were provided, a synergy effect occurred, not only reducing motion sickness but also overcoming the limitations of visual effects in reducing immersion. In earlier experiments, applying visual effects resulted in a reduction of motion sickness but also led to lower immersion compared to other sensory inputs. However, this experiment demonstrated that this limitation was overcome.

In summary, the experimental results indicate the following: First, wind effects significantly contribute to reducing motion sickness. Second, combining wind effects with a multimodal approach can lead to positive effects in reducing motion sickness. Third, when multimodal and directional cues are applied simultaneously, additional synergistic effects can occur, further reducing motion sickness. Finally, the combination of multimodal stimuli and directional cues not only reduces motion sickness but also addresses the immersion reduction issue, which had been a limitation of visual effects.

6. Discussion

The main purpose of this study was to utilize a multimodal feedback system, including visual, auditory, and tactile feedback, to reduce motion sickness in VR environments. The experimental results showed that auditory feedback alone did not significantly reduce motion sickness, but when combined with visual and tactile feedback, it produced meaningful results in reducing motion sickness and enhancing immersion. In particular, the combination of Reverse Optical Flow, Directional Sound Flow, and Haptic Flow played a key role in reducing motion sickness and increasing immersion.

One of the key findings from the experiment was that while auditory feedback alone did not have a significant effect on reducing motion sickness, a synergistic effect was observed when combined with other sensory feedback. This aligns with previous research that visual feedback can reduce immersion, but it also demonstrates that adding auditory and tactile feedback can solve this issue. While Reverse Optical Flow was effective in nullifying visual Vection, it could reduce immersion, whereas Directional Sound Flow and Haptic Flow were able to compensate for this decrease in immersion.

This study is significant in that it presents a new approach to reducing motion sickness in VR environments. Specifically, the study demonstrated that a multimodal feedback system with directionality is effective not only in reducing motion sickness but also in enhancing immersion. This can contribute to improving the practicality of VR technology and enhancing the user experience.

This study has some limitations. First, the number of participants was limited, which may affect the generalizability of the results. Second, the experiment was conducted in a specific VR environment, so it is difficult to guarantee the effects across various VR scenarios. Third, the experiment was short-term, and thus, the long-term effects of usage were not evaluated.

Future research needs to verify the effects of the multimodal feedback system in various VR environments and scenarios. Furthermore, studies that incorporate additional sensory feedback, such as smell and temperature, could further expand the potential for reducing motion sickness. Long-term studies evaluating the sustainability of the motion sickness reduction effects over prolonged use are also necessary. Finally, developing personalized feedback systems tailored to individuals' physiological and psychological characteristics would be a promising direction for future research.

Through this study, it was confirmed that a multimodal feedback system can play a significant role in reducing motion sickness and enhancing immersion in VR environments. Specifically, feedback systems with directionality have great potential to overcome existing limitations and improve user experience. Further research is needed to continue developing these systems.

7. Summary and Conclusion

This study proposed and tested a multimodal feedback system incorporating visual, auditory, and tactile feedback as a new approach to reducing motion sickness in virtual reality (VR) environments. The main objective of this study was to reduce motion sickness in VR while enhancing user immersion.

In the first experiment, the effects of auditory feedback were investigated. By applying the concept of Reverse Optical Flow, the 3D Sound Flow system was developed to test whether directional auditory feedback could reduce motion sickness. The results showed that 3D Sound Flow helped reduce motion sickness. However, since the experiment had only six participants and non-directional sound did not show any reduction in motion sickness, it was concluded that auditory effects alone do not reduce motion sickness. The results suggested that adding directional cues to auditory effects could lead to motion sickness reduction, which became a premise for the subsequent experiments.

The second experiment investigated the combined effects of Reverse Optical Flow and 3D Sound Flow on motion sickness. The results showed that while this combination did not significantly reduce motion sickness, it had a positive effect on enhancing immersion. This suggests that the combination of auditory and visual feedback can overcome the limitations of visual feedback alone. Although no significant reduction in motion sickness was observed, there was a slight decrease in symptoms compared to the no-effect condition, indicating the potential for reducing motion sickness. Additionally, the combination of multimodal feedback helped address the reduction in immersion caused by visual feedback.

In the final experiment, tactile feedback was added to develop the Haptic Flow system, which was used in combination with Reverse Optical Flow and 3D Sound Flow to maximize the reduction of motion sickness. The results showed significant motion sickness reduction in all experimental conditions involving Haptic Flow, with the multimodal feedback system with directionality showing the greatest effect. Based on previous research and the results of the first two experiments, the findings demonstrated that wind effects alone significantly reduce motion sickness and that their combination with other sensory feedback can further enhance this effect. Although the combination of auditory and visual feedback showed no significant synergy, the combination with tactile feedback did show a clear significant effect in reducing motion sickness, as previous studies have also shown a positive effect of wind feedback, whether combined with auditory feedback or used alone.

This study explored the potential of a multimodal feedback system to reduce motion sickness and enhance immersion in VR environments. The first experiment confirmed that auditory feedback alone was not effective in reducing motion sickness, but adding directional cues showed potential. It was also found to positively affect immersion, an important discovery given that visual feedback alone can reduce immersion.

The second experiment showed that while the combination of Reverse Optical Flow and 3D Sound Flow did not significantly reduce motion sickness, it had the potential to reduce symptoms and positively affected the maintenance or enhancement of immersion. This indicates that combining visual and auditory feedback in VR environments could overcome the limitations of visual feedback and improve the user experience.

The final experiment validated the effects of a multimodal feedback system that included tactile feedback. By adding Haptic Flow, the study examined how tactile feedback from wind and vibration contributed to reducing motion sickness. The results showed that tactile feedback alone had a significant effect on reducing motion sickness and that its combination with other sensory feedback further maximized this effect. The multimodal feedback system with directionality proved highly effective in both reducing motion sickness and maintaining or enhancing immersion.

This study has some limitations. The number of participants was limited, and the experiments were conducted in a specific VR environment, making it difficult to generalize the results to various VR scenarios. Additionally, the short duration of the experiment did not allow for the evaluation of long-term effects. To address these limitations, future research should verify the effects of multimodal feedback systems in different VR environments and scenarios, and evaluate the sustainability of the motion sickness reduction effects through long-term usage.

Future studies could also explore the potential for further reducing motion sickness by incorporating additional sensory feedback, such as smell and temperature. Moreover, developing personalized feedback systems tailored to individuals' physiological and psychological characteristics would be a promising area of research. These studies could help improve the user experience in VR environments and develop the optimal feedback system for reducing motion sickness.

In conclusion, this study confirmed that a multimodal feedback system plays an important role in reducing motion sickness and enhancing immersion in VR environments. Specifically, feedback systems with directionality have great potential to overcome existing limitations and improve the user experience. The combination of multimodal feedback and directionality was shown to reduce motion sickness and solve the problem of reduced immersion that had been a limitation of visual feedback.

References

[1] P. Budhiraja, M. R. Miller, A. K. Modi, and D. Forsyth. Rotation blurring: use of artificial blurring to reduce cybersickness in virtual reality first person shooters. arXiv preprint arXiv:1710.02599, 2017.

[2] S. D'Amour, J. E. Bos, and B. Keshavarz. The efficacy of airflow and seat vibration on reducing visually induced motion sickness. Experi- mental brain research, 235(9):2811–2820, 2017.

[3] A. S. Fernandes and S. K. Feiner. Combating vr sickness through subtle dynamic field-of-view modification. In 2016 IEEE symposium on 3D user interfaces (3DUI), pp. 201–210. IEEE, 2016.

[4] R. S. Kennedy, N. E. Lane, K. S. Berbaum, and M. G. Lilienthal. Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. The international journal of aviation psychology, 3(3):203–220, 1993.

[5] B. Keshavarz and H. Hecht. Visually induced motion sickness and presence in videogames: The role of sound. In Proceedings of the Human Factors and Ergonomics Society Annual Meeting, vol. 56, pp. 1763–1767. SAGE Publications Sage CA: Los Angeles, CA, 2012.

[6] J. LaViola Jr. A discussion of cybersickness in virtual environments. ACM Sigchi Bulletin, 32(1):47–56, 2000.

[7] D. Lim, Y. Lee, Y. Cho, T. Ryoo, and D. Han. A study on the reduction in vr cybersickness using an interactive wind system. Journal of the Korea Computer Graphics Society, 27(3):43–53, 2021.

[8] S. H. Park, B. Han, and G. J. Kim. Mixing in reverse optical flow to

mitigate vection and simulation sickness in virtual reality. In CHI Conference on Human Factors in Computing Systems, pp. 1–11, 2022.

[9] Y. Sawada, Y. Itaguchi, M. Hayashi, K. Aigo, T. Miyagi, M. Miki, T. Kimura, and M. Miyazaki. Effects of synchronised engine sound and vibration presentation on visually induced motion sickness. Scientific reports, 10(1):1–10, 2020.

[10] C. Wienrich, C. K. Weidner, C. Schatto, D. Obremski, and J. H. Israel. A virtual nose as a rest-frame-the impact on simulator sickness and game experience. In 2018 10th international conference on virtual worlds and games for serious applications (VS-Games), pp. 1–8. IEEE, 2018.

[12] Keshavarz B, Hettinger LJ, Kennedy RS, Campos JL (2014) Demonstrating the Potential for Dynamic Auditory Stimulation to Contribute to Motion Sickness. PLoS ONE 9(7): e101016. https://doi.org/10.1371/journal.pone.0101016

[13] S. Lee and G. J. Kim, "Reverse 3D Sound Flow Can Decrease VR Sickness?," *2022 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct)*, Singapore, Singapore, 2022

[14] S. -H. Liu, N. -H. Yu, L. Chan, Y. -H. Peng, W. -Z. Sun and M. Y. Chen, "PhantomLegs: Reducing Virtual Reality Sickness Using Head-Worn Haptic Devices," *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, Osaka, Japan, 2019

[15] Kostrova, Marina, and Victoria Yuri-Andersson. "Designing with Sound to Reduce Motion Sickness in VR." (2020)

[16] Cao, Zekun. *The effect of rest frames on simulator sickness reduction*. MS thesis. Duke University, 2017.

[17] Fukuchi, M. Tsuchiya, N. Koch, C.. The focus of expansion in optical

flow fields acts as a strong cue for visual attention . Journal of Vision, 9(8):137. 2009

[18] G. -Y. Nie, H. B. -L. Duh, Y. Liu and Y. Wang, "Analysis on Mitigation of Visually Induced Motion Sickness by Applying Dynamical Blurring on a User's Retina," in *IEEE Transactions on Visualization and Computer Graphics*, vol. 26, no. 8, pp. 2535-2545, 1 Aug. 2020

[19] Jelte E. Bos, Sjoerd C. de Vries, Martijn L. van Emmerik, Eric L. Groen, The effect of internal and external fields of view on visually induced motion sickness, Applied Ergonomics, Volume 41, Issue 4, 2010.

Appendix

A. Modified/Reduced Igroup Presence Questionaire (IPQ)

Space Presence (SP)	Q1	Somehow I felt that the virtual world surrounded me.	1 (fully disagree) ~ 7 (fully agree)
	Q2	I felt like I was just perceiving pictures.	1 (fully disagree) ~ 7 (fully agree)
	Q3	I felt present in the virtual space.	1 (fully disagree) ~ 7 (fully agree)
Involvement (INV)	Q4	I was not aware of my real environment.	1 (fully disagree) ~ 7 (fully agree)
	Q5	I still paid attention to the real environment.	1 (fully disagree) ~ 7 (fully agree)
	Q6	I was completely captivated by the virtual world.	1 (fully disagree) ~ 7 (fully agree)

Experienced Realism (REAL)	Q7	The virtual world seemed more realistic than the real world.	1 (fully disagree) ~ 7 (fully agree)