Mixing in Reverse Optical Flow to Mitigate Vection and Simulation Sickness in Virtual Reality

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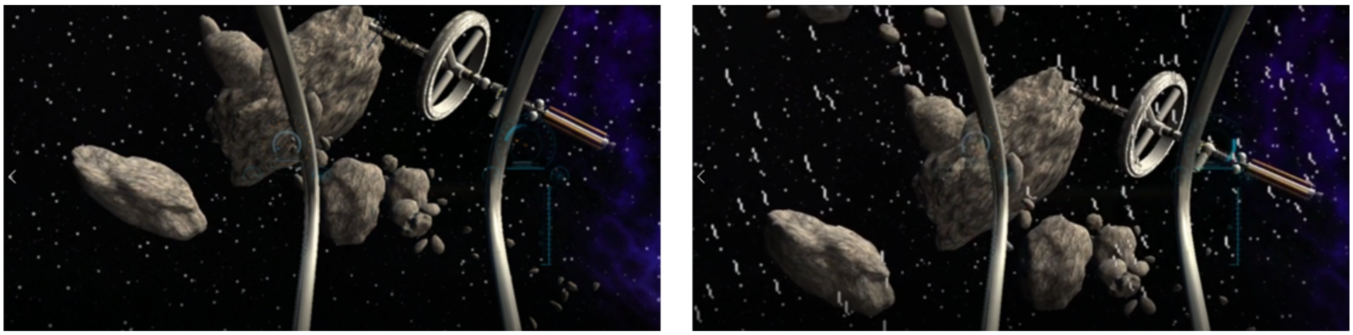


Figure 1: Original virtual reality navigation scene (left) vs. the same scene mixed in and overlaid with the reverse optical flow as short line segments.

ABSTRACT

Simulator sickness has been one of the major obstacles toward making virtual reality (VR) widely accepted and used. For example, virtual navigation produces vection, which is the illusion of self-motion as one perceives bodily motion despite no movement actually occurs. This, in turn, causes a sensory conflict between visual and actual (or vestibular) motion and sickness. In this study, we explore a method to reduce simulator sickness by visually mixing the optical flow patterns that are in the reverse direction of the virtual visual motion. As visual motion is mainly detected and perceived by the optical flow, artificial mixing in the reverse flow is hypothesized to induce a cancellation effect, thereby reducing the degree of the conflict with the vestibular sense and sickness. To validate our hypothesis, we developed a real-time algorithm to visualize the reverse optical flow and conducted experiments by comparing the before and after sickness levels in seven virtual navigation conditions. The experimental results confirmed the proposed method was effective for reducing the simulator sickness in a statistically significant manner. However, no dependency to the motion type or degrees of freedom were found. Significant distraction and negative influence to the sense of presence and immersion were observed only when the the artificially added reverse optical flow patterns were rather visually marked with high contrast to the background content.

CCS CONCEPTS

• **Human-centered computing**; • **Human computer interaction (HCI)**; • **Empirical studies in HCI**;

KEYWORDS

Virtual Reality, Vection, Simulator Sickness, Optical Flow

ACM Reference Format:
Su Han Park, Bin Han, and Gerard Jounghyun Kim. 2022. Mixing in Reverse Optical Flow to Mitigate Vection and Simulation Sickness in Virtual Reality. In *CHI Conference on Human Factors in Computing Systems (CHI '22), April 29-May 5, 2022, New Orleans, LA, USA.* ACM, New York, NY, USA, 11 pages. https://doi.org/10.1145/3491102.3501847

1 INTRODUCTION

Simulator sickness is one of the main obstacles and concerns that hampers the wide adoption of virtual reality (VR) technology[1]. Such sickness arises mainly in virtual navigation, which is one of the most typical content types in VR. During virtual navigation, sensory mismatch occurs, as the user is typically stationary and in place (sensed as such by the vestibular organ), while the visual field receives moving images and recognizes visual motion (known as vection). This sensory conflict is considered the most prominent cause of simulator (or VR) sickness[24]. Visual (or apparent) motion is detected and felt as a major part of general motion perception, by the difference between the incoming consecutive images (caused by the motion of the viewer or the objects in the image)[26]. Such difference can be characterized by the optical flow - the relative offsets/movements of corresponding pixels/features between consecutive images[11]. Changing images of a static scene will result

CHI '22, April 29-May 5, 2022, New Orleans, LA, USA

ACM ISBN 978-1-4503-9157-3/22/04…$15.00
https://doi.org/10.1145/3491102.3501847

in an optical flow pattern (e.g., expanding or contracting with respect to a vanishing point) to reflect a particular type of motion or movement direction. However, if there are moving objects in the scene, the optical flow may produce confusing cues in the sensation of the apparent motion (e.g., one part of the image seems to produce apparent motion in one direction, whereas a different direction is perceived in another part). In this regard, a viable question is whether the "confusion" can be further used to produce a "cancellation" effect by making the total optical flow sum to zero, accomplished by artificially adding the optical flow reverse to the actual. The perceived visual motion, ideally reduced to zero using this strategy, may result in a lower extent of the aforementioned sensory conflict in a typical virtual navigation situation, as well as simulator (or VR) sickness. In this study, we explored this method.

One potential problem of the proposed method is that the added/overlaid visual effect (see Figure 1, 4, and 8) may interfere with or become a significant distraction to the original content. This could lead to a reduction of the sense of presence, immersion, and degraded user experience. Although the amount of added visualization of the reverse optical flow may be controlled to minimize this negative effect, insufficient density may hinder the obtainment of the intended effect. Depending on the content, sufficiently dense reverse optical flow visualization may not be possible in any case because of the lack of computationally extractable visual features. Several factors can affect the efficacy of the proposed method. In this work, we primarily focus on two aspects: (1) the potential and the basic validity of whether the mixed-in reverse optical flow can indeed help mitigate simulator sickness, and (2) how the degrees of freedom (DOF) and directions of the virtual navigational movement and visual composition of the scene might influence the effect.

In the next sections, we first review previous research on motion/simulator/VR sickness and previously suggested methods for sickness reduction. We also review the background literature on visual motion perception, particularly through the optical flow. Section 3 details the proposed method for visualizing and overlaying the optical flow and its implementation. In Section 4 and 5, we present the validation experiments. Finally, in last two sections, we discuss our findings, limitations and summarize the implications and possible manners to extend our approach in the future.

2 RELATED WORK

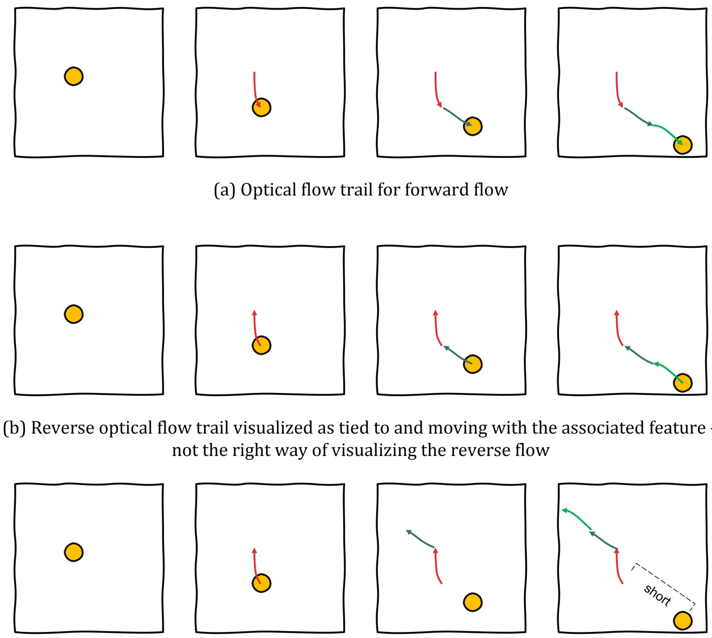
Motion sickness refers to the sickness that occurs when riding or moving, due to the difference between actual and expected motion. Major symptoms include disorientation, headache, nausea, and ocular strain [25, 30]. Humans perceive motion through several sensory channels (as well as cognitive processing), mainly through their eyes (visual) and vestibular organs. The vestibular organ detects sudden changes in linear or rotational motion and assists in the balance with respect to the direction of gravity. Usually, humans, while in motion, receive sensor stimulation in a manner consistent with that of the visual and vestibular senses. Motion sickness is mainly explained by the “sensory mismatch” theory between visual and vestibular stimulation [19]. For example, while riding a car, if a person looks down, instead of moving to the scenery, the static visual view conflicts with the bodily motion sensed by the vestibular organ, leading to the aforementioned symptoms. Motion sickness is also known to occur because of the difference between actual and “expected” motion [10, 30]. The driver, as compared to the passenger, is less likely to experience motion sickness because it has complete control and knowledge of the imminent motion profile. The passenger might have a general notion of the expected path, but not of momentary vehicle motion dynamics.

Cyber or simulator sickness is similar to motion sickness, but arises when using simulators such as VR systems. Thus VR sickness is a type of a cyber/simulator sickness. The simulator can be purely visual (with the user being stationary) or involve limited user motion (as in the cases of redirected walking [29], in-place walking [33], or employing motion platforms). The sickness, in this case, is caused by the same sensory mismatch as in motion sickness, but in the opposite context: the user’s body is normally stationary (or limited), but the visual feedback provides apparent motion. There are other causes of simulator sickness, such as system (motion to photon) latency, vergence and accommodation conflict in stereoscopic viewing, and distorted imagery from the optics of the headset [19]. However, in this study, we focus only on reducing the effect of sensory mismatch by vection. Few techniques have been proposed to reduce simulator/VR sickness, such as the use of reference objects [36], peripheral blurring [2], adjustment of the size of the field of view [6], and use of change blindness [29]. Most of these approaches are based on opportunistically reducing visual motion information as much as possible, which would in turn reduce the degree of sensory conflict. In [4], a method to mix in the "actual" motion information of the car to the VR content was proposed to reduce the sensory mismatch and sickness, while riding a car and using VR with a headset.

Optical flow has been extensively investigated in relation to self-motion and motion sickness. Gibson was the first to propose that human visual motion perception is based on optical flow [8],which was further confirmed by researchers in brain science [5, 35]. The human brain is also capable of differentiating between the visual motion caused by oneself and those caused by objects in the visual field, particularly with the help of the vestibular sense [37]. Note that, in the context of this work, the (computational) optical flow serves only as the estimation of the actual motion flow (or apparent motion), which humans may perceive more accurately through means other than distinct feature-based optical flow.

In other studies, methods to modulate the degree or characteristics of the vection (and motion sickness) have been proposed by manipulating the form of the optical flow [7], for example, by overlapping different directional/rotation flows [14] and even mixing in visual noise [15] to suppress vection. These works strongly indicate the possibility of manipulating the optical flow and reducing sickness from apparent motion.

In contrast, investigations on the effects of different types of motion or visual complexity on motion or simulator sickness are scarce. Motions unfamiliar to humans or those that do not occur on a daily basis, such as 6DOF space travel and riding on ships or rollercoasters with many pitch and roll motions, may cause more sickness. This phenomenon may also be explained by the aforementioned "motion expectation" theory. As for visual [21] and scene complexity, it can be considered that the more complex the scene, the more visual motion information will be present and increase the extent of the sickness [17].



(a) Optical flow trail for forward flow

(b) Reverse optical flow trail visualized as tied to and moving with the associated feature – not the right way of visualizing the reverse flow

(c) Reverse optical flow trail visualized "near" the moving feature – trail independently moves from a fixed location in the reverse direction as desired.

Figure 2: Possible visualization of the reverse optical flow. The top row shows the forward moving feature and its flow. The middle row shows the visualization of the reverse optical flow as tied and moving with the forward flow - which is not desired. The bottom row shows as our algorithm draws the moving trail as growing line segments independently moving to the reverse direction, but close to the associated feature.

3 REVERSE OPTICAL FLOW VISUALIZATION ALGORITHM

An ideal approach to our objective is to overlay the reverse motion information as to nullify the as-is visual motion to accurately extract the true motion flow of the objects in the scene (or as caused by the viewer motion) and visualize the reversed motion. This approach would require a 3D understanding of the scene, which is not always viable (e.g., for videos or 3D graphic contents without the sources). Moreover, the motion flow computed from the projection of moving 3D vertices cannot easily reflect the movements of image/texture features.

Another possibility is to generate pseudo-optical flow patterns from the virtual camera motion (regardless of the scene/image content) and visualize the reversed. Again, depending on the content type, camera motion information may not be readily available, particularly in real time (e.g., 360° videos). Another limitation of this approach is in cases where the original images do not contain considerable visual features (such as when looking into the plain blue sky), but there is apparent motion by camera movement. In this case, the viewer may not actually feel sick in the first place–that is, adding in the camera motion-based reverse flow can actually inadvertently cause sickness. Accordingly, in this work, we used optical flow as an estimation of the (apparent) motion flow and visualized its reverse. Other suggested approaches and their effects are subject to future research.

The motion flow can be estimated (and reversed), just from the sequence of image frames, by methods based on feature matching or optical flow. In general, the former involves the use of feature descriptor, require more iterative computation and suited for higher accuracy or for image sequences with large motion or significantly different viewpoint change. We chose the optical flow based approach which may be less exact, but faster. While we put forth a requirement that reverse optical flow trails should be "near" the very features associated with the forward (or original) flow to localize and ensure the cancellation effect, we expect a reasonable approximation would still be sufficiently effective. The most accurate approach to compute the reverse optical flow between two images is to extract features from each image, establish correspondences, and apply subtractions reversely. This method has two problems: (1) this full computation can cause a noticeable delay (depending on the computational platform or number of features extracted) and (2) difficulty in continuously visualizing the flow. In our case, we chose to visualize the flow in the form of connected line segments, growing (to a fixed length) in the reverse direction (i.e., reverse moving trail). If the extraction and establishment of the correspondences of features are conducted to every frame, the continuity of the feature trails can be interrupted owing to the inherent uncertainty. We chose the form of "short" line segments

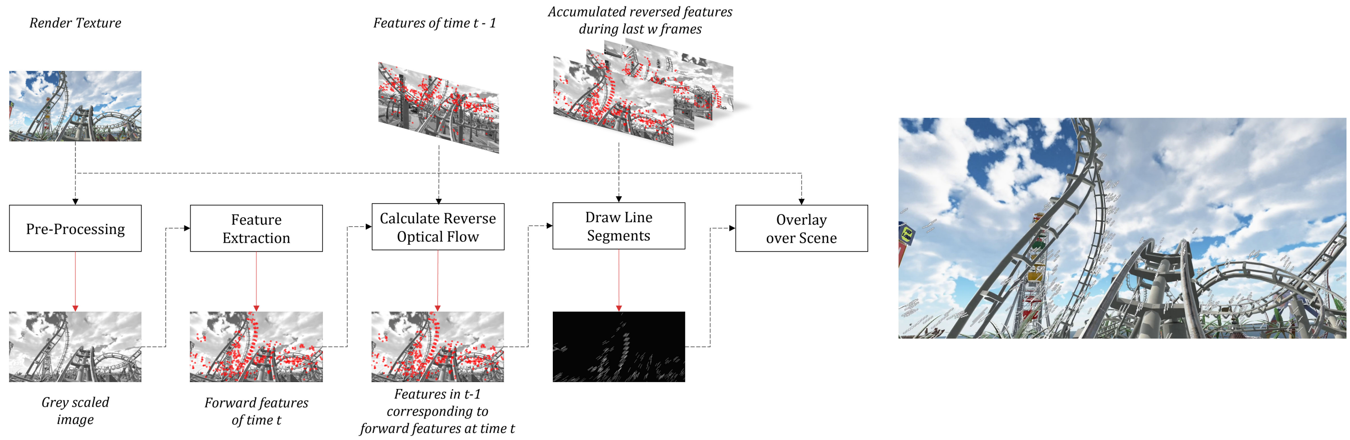


Figure 3: Computational flow for computing the reverse optical flow and overlaying the results as line segments connected by correspondingly moving feature points on the VR scene.

because its simple form can minimize any interference with the original content. However, note that, unlike the forward flow (if it were to be explicitly visualized), the reverse trail should not be tied to that forward flow causing features (see Figure 2) because the entire reverse trail (connected line segments) would follow and move forward, thereby defeating the very purpose of the reverse flow.

Therefore, our reverse optical flow visualization algorithm works in the following manner: First, we extract features (set to be extracted up to 800, but this value can be controlled depending on the system performance), using the Shi-Tomasi corner detectors [28], only every w frames. Once the features are extracted, their locations are copied (and saved) to the next frame, F_t. These locations are close to their corresponding locations in this next frame, F_t, resulting from the apparent motion. We considered the common assumption that the motion is typically not drastic and the images are mostly similar between two consecutive frames. The Lucas-Kanade's fast optical flow algorithm [20] is applied, reversely, to those copied feature locations to find the corresponding features in the previous frame, F_{t-1}. This algorithm similarly assumes that the flow is essentially constant in the local neighborhood of the feature under consideration, and solves the basic optical flow equations for all the pixels in that neighborhood by the least squares criterion.

Figure 4: Illustration of the reverse flow visualization. The reverse flow is shown as short green line segments (left). To illustrate the direction, arrow heads were added, although not actually drawn in practice. The forward flow of the associated features is shown in red arrows (right).

Ideally, these features newly found by the optical flow estimation would be equal to the features originally extracted at $t-1$. At least, for all practical purposes, they should be close to them. These locations are connected as line segments, and passed to the next round of consecutive image frames to add new reverse trail segments. The process is continued and is reset every w frames, meaning that w will be the maximum length of the growing polyline trail. The parameter w also has the effect of limiting the length of the trails for minimizing their invasiveness to the content. Our current implementation includes a step to check and limit the length to a preset value r as well. In summary, the moving trails drawn following this

Algorithm 1: Polyline components extraction for reverse optical flow given two consecutive image frames

Result: Set of points to connect as polylines
if *mod(t,w) == 0* **then**
  // new time window, compute new feature points and clear line components
  pts.clear() ;
  f_t = FeatureExtraction(F_t);
  // save them as starting points of the reverse flow line segments
  pts.push(f_t) ;
end
if *Number of pts >= 0* **then**
  // compute correspondence to previous frame by reverse optical flow
  f_{t-1} = OpticalFlow(F_t, F_{t-1}, f_t);
  f_{tmp} = pts.at(lastIdx);
  if *Distance*(f_{t-1}, f_{tmp}) > r **then**
    // save them as end points (starting points for next round)
    pts.push(f_{t-1});
  end
end

Table 1: Treatments by the two independent variables: whether the reverse optical flow was overlaid and what type of and degrees of navigational motion freedom were present.

No. of DOFs	Directions	As-is	With reverse optical flow
2	forward, yaw	2DOF-w/o	2DOF-w
3	forward, roll, yaw	3DOF-w/o	3DOF-w
4	up/down, forward, pitch, yaw	4DOF-w/o	4DOF-w
5	up/down, forward, roll, pitch, yaw	5DOF-w/o	5DOF-w

method start at the first feature locations (extracted at $t-1$) and grow from these fixed locations (but do not follow their forward movement) in the reverse direction for w frames; in sequence, they reset (see Figure 4). As w is relatively small (empirically set as 5 in this study), the reverse moving trails are still sufficiently close to the features associated with the forward movement during this time window. In our trials-and-errors for our test contents, w set at 2 (the minimum) or at larger than 6 resulted in the flow being reset to quickly, and its presence and interference effect was noticeable.

The VR content was modeled using the Unity [32] and the proposed visualization, and implemented using the OpenCV [13] version of the Lucas-Kanade optical flow (calcOpticalFlowPyrLK()) and Shi-Tomasi feature extraction (cv.goodFeaturesToTrack()) algorithms. The entire system was run at an interactive rate of 80–90 fps on a regular graphics PC (NVidia RTX 2080 Ti GPU) with the given test contents. The detailed algorithm for extracting the polyline components for the reverse flow between two consecutive image frames is outlined as follows, and the overall system is shown in Figure 3.

4 VALIDATION: EXPERIMENT 1

Two validation experiments were conducted. The purpose of Experiment 1 was to validate the intended simulator sickness reduction effect of mixed-in reverse optical flow visualization. Different treatments in Experiment 1 were conducted using a single VR content (to minimize any bias introduced by the content type). A supplementary experiment (Experiment 2) was also conducted to reaffirm the same effects, but with more typical navigational VR contents (see Section 5).

4.1 Experimental Design

Experiment 1 investigated the effects of two independent variables on sickness reduction: (1) whether the reverse optical flow was overlaid (indicated with "w") or not (indicated with "w/o"), and (2) the type and DOFs of the navigational motion– four different cases (DOF = 2, 3, 4, 5) were tested, a total of 2 × 4 = 8 treatments (see Table 1).

The main dependent variable was the sickness level, measured using the Simulator Sickness Questionnaire (SSQ) by Kennedy et al. [18]. The level of user-perceived presence and immersion was also measured via the modified SUS presence questionnaire [34] as an indicator of the VR user experience. In summary, the experiment was designed as 2×4 within a subject single measure. Our main hypotheses were that the overlaid reverse optical flow would result in a significant reduction in the sickness level, but possibly causing a degradation in the user experience because of the added visual effect unrelated to the content.

4.2 Experimental Subjects

At first, more than 50 potential subjects were recruited through a closed university on-line community. This was in part to keep the subjects homogeneous in terms of their age and educational/ generational background (e.g. university students). They filled out a self-reporting survey about their basic demographic backgrounds (including the extent of any prior VR experience) and tendency/ sensitivity toward motion and simulator sickness (3 USD compensation). We used a reduced version of the MSSQ [9] for the latter. We manually examined each potential subject profile and excluded those who indicated very high or low sensitivity to either regular motion sickness or simulator sickness, and also those who had only minimal prior experience with VR. That left us with only 20 final subjects (14 men and 6 women between the ages of 21 and 31, mean = 26.4/ SD = 2.55) for the actual experiment. Surely more subjects would result in more solid and credible results. However, the current COVID-19 situation prevented us from securing more at the time. We judged 20 subjects was still sufficient (but barely) to render a valid result. The reason for the exclusion was two-fold. One was to see the effects of the proposed approach to the average (moderately sensitive to sickness) user - if the effect was indeed found, it is plausible to think it would equally be so to the more sensitive ones, and irrelevant anyway for those who are rather insensitive. The other was to minimize the occurrences of subjects giving up and discontinuing in the middle of the experiment because of the sickness. In addition, the IRB guideline also recommended such a practice. Those 20 final subjects were paid 33 USD for their participation (for the two experiments / 11 USD per hour). One subject (not part of the 20 final) who gave up in the middle after one hour was paid 11 USD.

4.3 Experimental Procedure and Setup

The final subjects were told and advised to have sufficient sleep (7-8 hours) in the night before and not to take any meals with 2-3 hours of the pre-scheduled experimental sessions. In the actual experiment, the subjects first filled out the content form, were briefed about the purpose of the experiment, and explained the experimental task. Before and after each test treatment, the subjects filled out the SSQ (by Kennedy et al. [18]) to measure the baseline and later comparison.

The subject sat on a chair (to avoid falling or losing balance due to possible sickness) and the administrator helped to correctly adjust the headset. The subject experienced seven (4 contents in

Table 2: p-values (and t-values) for the effect of the reverse optical flow - difference between the before and after sickness levels. The * mark indicate statistically significant effect.

No. of DOFs / Sickeness Catergory	2DOF	3DOF	4DOF	5DOF
Nausea	0.025* (-2.438)	0.003* (-3.371)	0.083 (-1.829)	0.006* (-3.111)
Oculomotor	0.017* (-2.616)	0.021* (-2.520)	0.125 (-1.605)	0.016* (-2.633)
Disorientation	0.013* (-2.727)	0.002* (-3.614)	0.007* (-3.007)	0.004* (-3.286)
Total	0.013* (-2.727)	0.003* (-3.331)	0.038* (-2.235)	0.003* (-3.386)

Experiment 1, and 3 in Experiment 2) different treatments, as shown in Table 1 and 5, in a balanced Latin square order. Note however, that for each treatment, the subject had to experience the original content and the one with reverse flow visualization. Thus, while the balanced order with size 7 results in only 14 unique order combinations, the remaining 6 subjects could be differentiated with the sub-order (to experience the original content or one with reverse flow first). For each treatment, the subject simply viewed the virtual space as automatically navigating a fixed path through a virtual space. The subject was instructed (only loosely) to stay looking forward, however, one's head was not fixed (allowed to rotate if wanted). Note that the proper reverse optical flow would be visualized according to the viewing direction of the headset. The instruction was given to prevent any external bias as much as possible, while keeping the minimum comfort for the subject.

As each treatment lasted approximately 3 min, there were some limitations in assessing the momentary varying levels of sickness along the navigational course with the post-survey method. However, an online interface (like a slider bar or multiple-choice menu) would affect the users' concentration. Thus, we provided a simple hand button for the user to indicate moments (by a simple press) at which he/she felt a severe level of sickness. The subject was allowed to stop and discontinue the experiment for any reason, including extreme and unbearable level of sickness.

Between treatment trials, the subject was allowed to rest (at least 10 min) and/or until reaching a sickness level considered negligible and safe, such as to continue to the next treatment. This was ensured by administering the same SSQ and continuing with the sessions only if the score was below 30 (and also confirming with the subject himself about one's well-being and willingness to continue) - otherwise, the subject continued to rest. The experiment lasted up to 3 hours over two days.

To encompass all types of motions and DOFs using the same content across all conditions, virtual "Space" exploration was chosen as the test content. The scene included various objects such as distant planets, debris, and other spaceships, some moving or not (see Figure 1). All the navigation treatments lasted approximately 3 min, and the motion profile of each treatment was individually designed to reflect and sufficiently include the types of and motion degrees as specified for the given condition and with variations in the velocity. The VR content was designed and developed using Unity [32], executed on a high-end graphics workstation, and the output was presented by a cable-connected HTC Vive headset [12]. Figure 5 illustrates a sample of the navigation paths for the conditions of 3DOF and 5DOF, and a snapshot of a subject during a treatment.

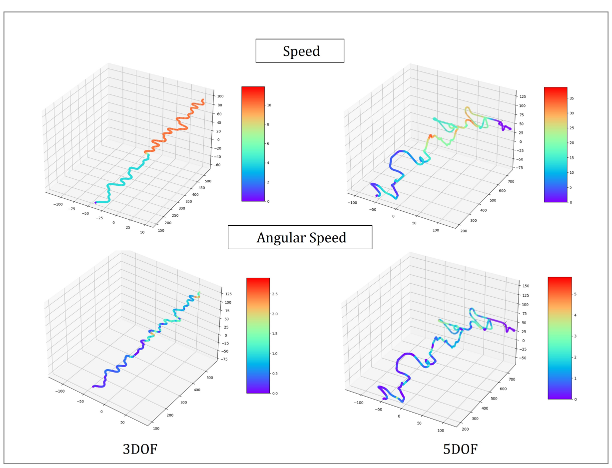


Figure 5: Fixed navigation paths and velocity variation for the conditions of 3DOF (left) and 5DOF(right) and, a subject experiencing a treatment.

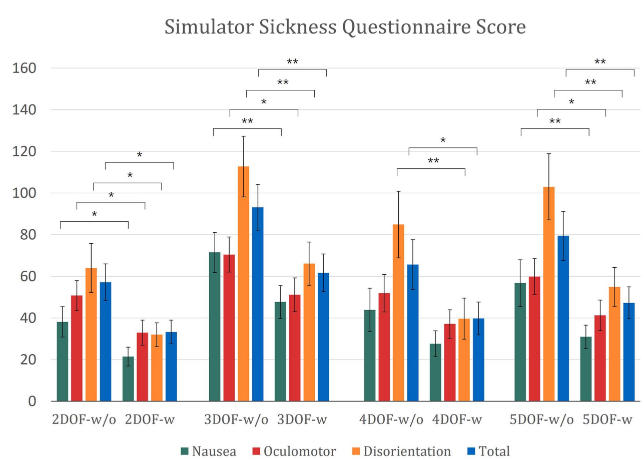


Figure 6: Sickness level experienced (scaled SSQ scores) with (right) and without (left) the mixed- in reverse optical flow for navigation with 2 DOF, 3 DOF, 4 DOF and 5 DOF.

After each treatment, the subjects, as they rested, filled out the simulator sickness questionnaire again to record the after-effects. The subcategory scores were scaled by the weight factors, as indicated in [18] for later comparison. The level of user-perceived presence/immersion was also measured as an indicator of the VR user experience, using the modified SUS presence questionnaire [34]. After experiencing all treatments, some additional questions (e.g. self-reported degradation in presence/immersion by the reverse optical flow) were asked regarding their preferences, and post briefings were taken. All survey questions were answered on a four-level Likert scale (we omitted the details due to lack of space). The experiment was approved by the Korea University Institutional Review Board (IRB No. KUIRB-2021-0281-01).

4.4 Results

One-way ANOVA with Tukey honestly significant difference (HSD) pairwise comparison was applied to analyze the effects of the sickness reduction technique. Figure 6 shows the experimental results of the after-sickness levels for the four conditions listed in Table 1. The four bars (in green, red, orange, and blue) correspond to the scaled scores for the three subcategories of simulator sickness, namely nausea, disorientation, and oculomotor. As previously indicated, in all cases, the user proceeded with each treatment (before removing the headset) only after verifying that he/she was not feeling sick, and after confirming that the SSQ score was sufficiently low (below 15 in all three categories). The subject continued resting until such was the case to move onto the next treatment. Figure 6 clearly shows that the mixed-in visualization of the reverse optical flow had an effect in reducing the extent of the sickness compared to the nominal cases without such a provision. In particular, statistically significant differences were found between 2DOF-w/o and 2DOF-w, 3DOF-w/o and 3DOF-w, and 5DOF-w/o and 5DOF-w (but not between 4DOF-w/o and 4DOF-w). For between 4DOF-w/o and 4DOF-w, the statistically significant difference was found only for the subcategory of Disorientation and the Total. Detailed statistical figures (p-values) are given in Table 2.

Figure 7 (left) illustrates the effects of sense of presence and immersion. In all four comparison cases, statistical differences were observed - i.e. there was a negative effect toward the sense of presence and immersion by the mixed-in reverse optical flow. The subjects were also directly asked about any perceptual effects of the reverse optical flow, as depicted in short line segments overlaid on the content. Figure 7 (right) indicates that it generally had a negative effect on lowering the sense of immersion.

ANOVA results did not strongly or consistently (in a statistically significant way) show any effects toward sickness (see Table 4) or immersion/presence by the factor of Motion type.

Table 3: p-values (and t-values) for the effect of the reverse optical flow - difference in the level of presence/immersion - between without the reverse flow and with it. In all cases, statistically significant differences were found.

2DOF	3DOF	4DOF	5DOF
0.007*(-3.016)	0.002*(-3.571)	0.016*(-2.629)	0.000*(-4.412)

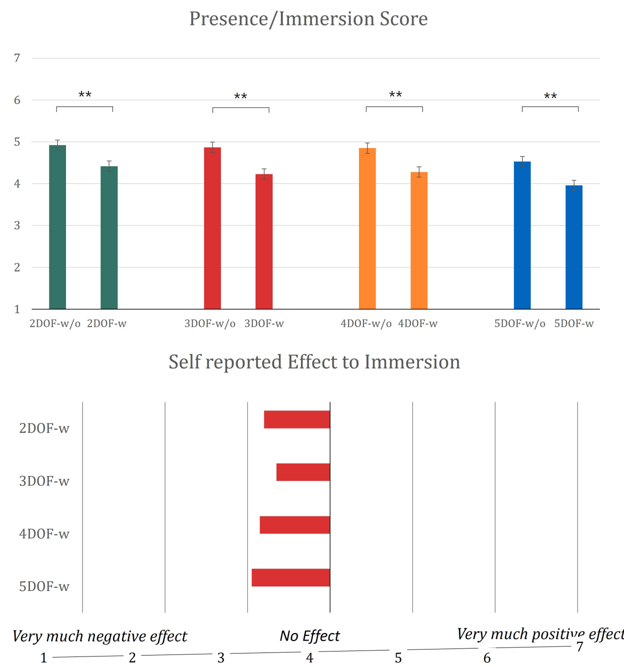


Figure 7: Sense of presence as felt with and without (left) the mixed in reverse optical flow and self reported user perceived change in the sense of immersion for navigation with 2 DOF, 3 DOF, 4 DOF, and 5 DOF,respectively.

5 SUPPLEMENTARY EXPERIMENT

5.1 Experimental design and procedure

Experiment 2 was conducted to confirm the same effects, but in a more typical navigational VR content. We considered three VR contents: (1) rollercoaster ride, (2) ship ride, and (3) car race, each of which differed in the type and degrees of motion freedom and visual complexity. Table 5 lists these characteristics. Note that, usually, visual complexity is not an inherent attribute of a particular

Table 4: p-values (and F-values) from the ANOVA for the effect of the Motion type to the sickness level. In most cases, no statistically significant effects were found. The * indicates the two isolated cases where significant differences were found - the post hoc analysis revealed the effects existed only between 2 and 3 DOF when the reverse optical flow visualization was applied.

	With out reverse optical flow	With reverse optical flow	2DOF vs 3DOF
Nausea	0.082(2.322)	0.025*(3.285)	0.019*
Oculomotor	0.320(1.188)	0.317(1.195)	-
Disorientation	0.102(2.144)	0.041*(2.879)	0.044*
Total	0.110(2.078)	0.064(2.523)	-

Table 5: Treatments by the content type in Experiment 2. The * mark indicates that the respective motion was minimal.

Content Type	No. of DOFs	Directions	As-is	With reverse optical flow
Rollercoaster	5	up/down, forward, roll, pitch, yaw	Roller-w/o	Roller-w
Ship Ride	4	up/down, forward, pitch, yaw*	Ship-w/o	Ship-w
Car Race	3	up/down*, forward, pitch, yaw	Car-w/o	Car-w

Table 6: p-values (and t-values) for the effect of the reverse optical flow - difference between the before and after sickness levels. The * mark indicates statistically significant effect.

	Rollercoaster	Ship Ride	Car Race
Nausea	0.008*(-2.943)	0.051(-2.090)	0.001*(-3.726)
Oculomotor	0.027*(-2.389)	0.062(-1.985)	0.001*(-3.857)
Disorientation	0.002*(-3.677)	0.027*(-2.394)	0.003*(-3.390)
Total	0.005*(-3.179)	0.034*(-2.282)	0.001*(-3.932)

content type, as it depends on how the content is modeled. However, in general, in the case of ship riding, a significant part of the scene is comprised of the ocean, which usually lacks distinct image features. Thus, the visual complexity (in computational terms) may be relatively lower. As indicated in our review of related works, the optical flow, normal or reversed, is relatively less explicit with contents of less visual complexity and associated features, which may affect the levels of sickness and the mitigation effect of the reverse flow. Figure 8 illustrates the typical scenes from the three tested VR contents.

The overall procedure and setup for the supplementary experiment were mostly the same as those of the main experiment, but conducted completely separately on another day with the same subjects from Experiment 1.

5.2 Results

Paired t-test was applied to analyze the effects of the sickness reduction technique. Figure 9 shows the experimental results - the after-sickness levels for the three conditions listed in Table 5. The figure shows a similar tendency as that in Experiment 1: the mixed-in visualization of the reverse optical flow reduced the extent of sickness compared to the nominal cases without such provision. However, statistically significant differences were found only for the rollercoaster and car racing cases, and not for the ship riding content. Figure 10 (left) shows a tendency similar to that of the main experiment. No noticeable changes were observed in terms of the sense of presence. Figure 10 (right) shows that the self-reported effect of reverse optical flow was also minimal.

6 DISCUSSION AND LIMITATIONS

The sickness reduction, as measured by the SSQ, was somewhat less effective in the case of the ship riding contents which had relatively less number of feature points (than the other tested contents) with which to visualize the reverse optical flow. Sea sickness, which the ship riding content attempted to emulate, arises even when the riders look out to the ocean - the movement of the wide and large ocean is perceived as not exactly matched to that of the ship (which possess lots of roll and pitch rotations to which average person is not accustomed to). This also seem to have attributed to the lessened effectiveness of the proposed method for the case of Ship ride. Exaggerating the reverse optical flow, or adding in the reverse flow extracted from the camera motion could be an option to handle this issue.

Figure 11 shows the changing trends in the motion profiles of navigation (magnitudes of the linear and rotational velocities), number of feature points in the images and the total number of times the subjects pressed the "sickness" button between without reverse optical flow was shown and with it for two content cases (5DOF and Ship riding). Although no statistical analysis were applied, naked observation finds: (1) sickness arises when the motion gets faster (in the latter part of the navigation) and (2) sickness is much reduced with the reverse optical flow. Note that the feature points in the Ship riding contents is much less (about 80-90 on the average) compared to that of the 5DOF content (about 300). However, from this graph, it was difficult to see any close relationship between the number of feature points to the sickness level, with or without the reverse optical flow. We postulate that the more feature points there are, the higher level of sickness would be caused, but also the reduction effect of the associated reverse optical flow would be bigger as well. The Ship riding case is an exceptional case because of the peculiar nature of the "unmoving" look of the ocean. Similar trends were observed for other cases as well.

The post-briefings by the subjects mostly echoed the quantitative results. Most of them acknowledged the sickness reduction effect of the mixed-in reverse optical flow, while also professing that their user experience was affected - some in the negative way and others in the positive way. With regards to the latter case, it was reported that the line segments interfered but since they did so only at high motion at which the detail visual perception was not important. Some subjects became self-aware of the sickness reduction effect of the line segments (reverse flow) and stated its benefit outweighed the little distraction. The line segments were even seen ironically as helpful speed lines [16]. Significant distraction and negative influence to the sense of presence and immersion were observed only with the "Space" travel contents, with which the line segments (white) had much higher contrast to the background (black). That is, their presence was more marked. This can explain why the negative effect to presence/immersion was not significant in the cases of other three contents which were more colorful and the line segments not being so conspicuous.

As our work is only the beginning in the investigation of the effect of the visualization of the reverse optical flow, there exist

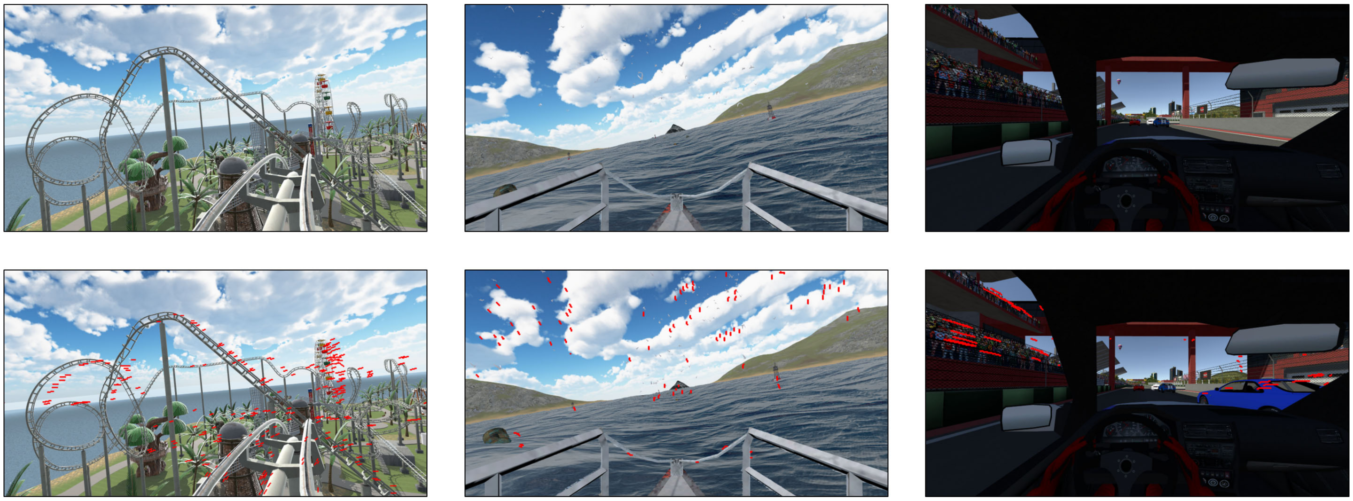


Figure 8: Scenes from the three tested virtual navigational contents - rollercoaster, car race and ship ride. The visual complexity of the ship ride scene is generally lower than the other two.

many limitations, many of them being subjects for future investigations. Several parameters used in our algorithm were set empirically in an ad hoc manner. Our algorithm is inexact, especially being based on the Lucas-Kanade differential algorithm, and it is not clear how inaccuracies may affect the sickness or user experience. By our logic, the sickness would be zeroed out only when there is an equal amount of mixed-in flow reverse to the original. Our current implementation only mixes in a partial amount, and thus should not be able to completely eliminate the sickness. Furthermore, the proposed method must be validated in terms of its safety and any possible after-effects.

In terms of the experimental procedure and set-up, there were few aspects we have overlooked and might have influenced the experimental results. For instance, in the cases of rollercoaster and car racing contents, as the rail and race course (unlike in the space exploration and ship riding) are shown, subject is aware of upcoming movement direction. In addition, in the car racing and space exploration content, view was significantly occluded by the

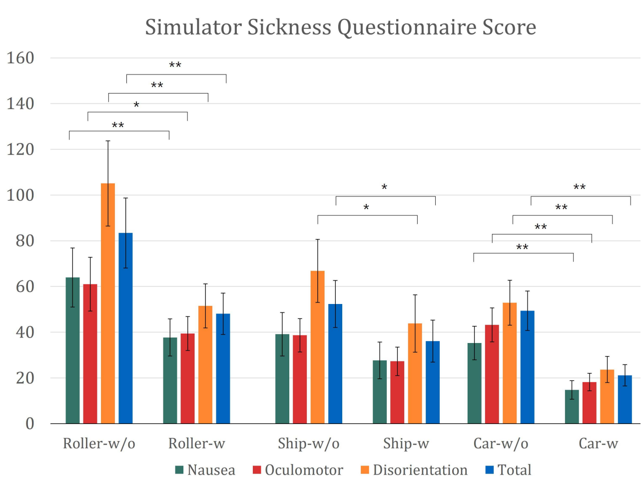


Figure 9: Sickness levels (SSQ scores) experienced with (right) and without (left) the mixed in reverse optical flow for navigation with the rollercoaster, car race and ship ride.

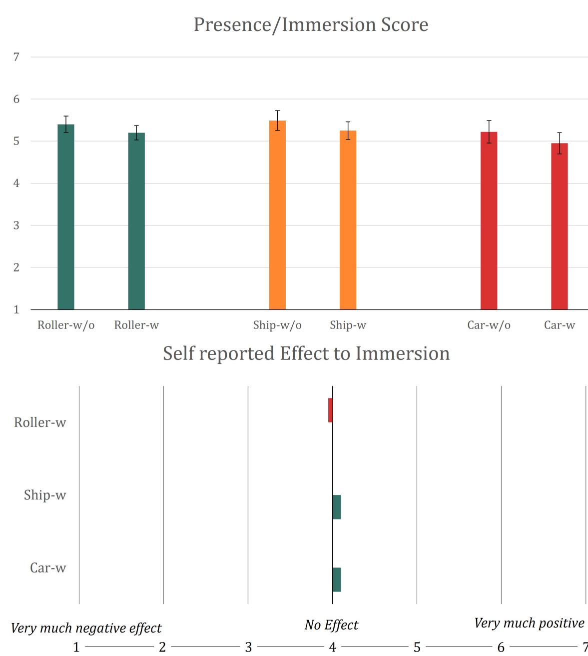


Figure 10: Sense of presence as felt with and without (left) the mixed in reverse optical flow and self reported user perceived change in the sense of immersion for navigation with the rollercoaster, car racing and ship riding, respectively.

dashboard and front window frame. These are small factors that can affect the degree of motion sickness [3, 27].

One outstanding, yet not sufficiently explored, question is if the overlaid reverse optical flow indeed canceled out the original forward motion flow, will the subject perceive any motion at all. Based on our observation of the subjects, we posit that although physiologically visual motion was significantly diminished, subjects still were quite cognizant of the motion due to the high level cognitive scene understanding. Note that some subjects reported that the reverse flow line segments were seen as speed lines. However, a deeper and formal study is needed.

Finally, a provision is needed for a situation where the user is not moving (or equivalently the virtual camera), yet there is a relatively large object moving on its own. This will possibly create apparent motion within the virtual space. Such a case can be handled by monitoring the motion of the camera.

7 CONCLUSION AND FUTURE DIRECTIONS

In this work, we presented a new method to reduce the VR sickness by visually mixing in the reverse optical flow to the virtual visual motion. Our validation experiment has clearly shown such effects for various types of motions in terms of the directions and degrees of freedom in both the neutral test and typical navigational contents. As for the factor of the motion type, the statistical analysis did show the effect of the DOF to the sickness reduction effect when the reverse flow was mixed in (p-value = 0.025). However, no noteworthy pattern between the different cases of DOF/contents was observed. Without the reverse flow, the sickness levels could not be correlated to the motion types (p-value = 0.818). The proposed approach (and its basic principle) is simple and applicable to any types of contents with visual motion such as videos and 2D interfaces (e.g. fast scrolling).

Our experiment only took a glimpse into the issue of how the reverse optical flow relates exactly to linear/rotational motion profiles and visual complexity - e.g. the data collected for Figure 11 were not detailed enough to draw definite conclusions at this time about "when" the reverse flow would be most effective with respect to the linear/rotational acceleration or the number of visual features appeared. In fact, it is generally known that sickness tends to worsen with sudden rotation or high acceleration [23], and there are recent works that predicts the point of severe sickness based on such a phenomena. Combining our work with sickness prediction techniques (e.g. to visualize reverse flow only on demand) can minimize the content intrusiveness aspect of the reverse flow visualization. For the same reason, surely, other visualization methods should be explored as well e.g. in terms of the amount, length, color, form of the reverse flow. Once some of these issues are resolved, they can be used to build a managed and flexible sickness reduction scheme in a way to minimize the content interference problem. One interesting idea is limit the reverse flow visualization in the visual periphery (vs. wherever features exist as was done in this work), especially as the peripheral region is more sensitive to motion [31].

As indicated Section 2, camera motion based (rather than visual feature based) pseudo reverse optical flow is another direction for future work. An ultimate challenge might be to flexibly combine different approaches to sickness reduction like those by [2, 6, 22, 29, 36].

ACKNOWLEDGMENTS

This research was supported in part by the IITP/MSIT of Korea, under the ITRC support program (IITP-2021-2016-0-00312) and, also by the IITP/MSIT and KEA/KIAT/MOTIE under the Competency Development Program for Industry Specialist (N000999).

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Figure 11: The changing trends in the motion profiles of navigation (magnitudes of the linear and rotational velocities), number of feature points in the images (above) and the total number of times the subjects pressed the "sickness" button between "no reverse optical flow (w/o)" and "with reverse optical flow (w)" (below) - for two cases (5DOF and Ship riding).

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