Visually-Induced Motion Sickness Reduction via Static and Dynamic Rest Frames

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Abstract

Visually-induced motion sickness (VIMS), also known as cybersickness, is a major challenge for wide-spread Virtual Reality (VR) adoption. VIMS can be reduced in different ways, for example by using high-quality tracking systems and reducing the user's field of view. However, there are no universal solutions for all situations, and a wide variety of techniques are needed in order for developers to choose the most appropriate options depending on their needs. One way to reduce VIMS is through the use of rest frames–portions of the virtual environment that remain fixed in relation to the real world and do not move as the user virtually moves. We report the results of two multi-day within-subjects studies with 44 subjects who used virtual travel to navigate the environment. In the first study, we investigated the influence of static rest frames with fixed opacity on user comfort. For the second study, we present an enhanced version of rest frames that we call *dynamic rest frames*, where the opacity of the rest frame changes in response to visually perceived motion as users virtually traversed the virtual environment. Results show that a virtual environment with a static or dynamic rest frame allowed users to travel through more waypoints before stopping due to discomfort compared to a virtual environment without a rest frame. Further, a virtual environment with a static rest frame was also found to result in more real-time reported comfort than when there was no rest frame.

Index Terms: H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems—Artificial, augmented, and virtual realities

1 Introduction

Virtual reality (VR), as an interface for the military [1], medical [31], manufacturing [16] and entertainment [9] industries, is rapidly being adopted across a wide range of applications for its capability to simulate real environments at a relatively low cost. Because of the rising use of VR, more and more users are experiencing a common problem–visually induced motion sickness (VIMS) [12, 15], sometimes referred to as cybersickness [17], which is caused by the visually perceived motion of virtual travel and is expressed by headaches, stomach awareness, nausea, vomiting, pallor, sweating, fatigue, drowsiness, and disorientation [13]. It has been speculated that, if users have an unpleasant initial VR experience, they will be reluctant to try it again [12]. Thus, it is imperative to provide VR experiences that are safe against VIMS.

Among techniques demonstrated to reduce VIMS are real walking [3], the use of advanced input devices such as treadmills [11], and reduction of the field of view (FOV) [8]. However, such techniques are not always desirable, for example, when users are seated or need to navigate in very large virtual environments (VEs). Long distance physical navigation may cause physical exhaustion and decreased FOV may increase misjudgment in critical tasks as well as reduce presence [5].

We draw inspiration to our work from the fact that users are able to tolerate projection-based VR experiences (e.g., CAVEs [4]) longer than with head-mounted displays (HMDs) [7, 32]. One major difference between these types of systems are rest frames (RFs)–portions of the virtual environment that remain fixed in relation to the real world even as the user performs virtual travel tasks. In projection-based systems, the edges of the display, seams between screens, and elements of the real world visible beyond the screens act as RFs. Previous research in traditional simulators found that motion sickness (MS) decreased when more expected vertical visual references were aligned with the subjective vertical senses obtained from gravity, and visual and idiotropic cues [2]. Rest frames can be defined as the vertical references provided by visually and idiotropically vertical cues which are relatively stationary to subjects. These findings hint that similar methods could be applied to HMDs.

Stable RFs have historically not been possible with HMDs due to the need for low latency and high quality tracking and calibration. However, RFs can now be rather stable with modern VR technology. A direct way to investigate how RFs may impact VIMS is to evaluate whether users experiencing VEs with RFs report higher comfort, remain longer in VEs, and report lower Simulator Sickness Questionnaires (SSQs) scores. To that effect, we modified a commercial VR game [21] as the platform for evaluating the effects of RFs on VIMS. An Oculus Rift was used along with an Xbox controller for virtual travel of seated subjects. We performed two formal studies to determine the influence of static and dynamic RFs on the reduction of discomfort, which we consider a proxy to VIMS.

2 Previous Work

The research community has long focused on seeking efficient solutions to reduce or eliminate MS. The Sensory Conflict Theory, which states that MS is caused by conflicting signals received by visual and vestibular systems, and the Postural Instability Theory, where MS is explained by the persistent loss over postural control [10, 13, 28–30] are two predominant theories that illustrate the mechanism of MS. Nishiike et al. [22] explored the possibility of using VR as a rehabilitation tool for patients suffering from dizziness. According to the Sensory Conflict Theory, locomotion techniques that stimulate the vestibular system through rebuilding the walking pattern–the moving of legs–to navigate [24], such as redirected walking [27], walking-in-place [37], and treadmill walking may be helpful to reduce MS. However, these physical walking techniques have potential issues, such as the requirement of large tracked spaces, need for specialized hardware, and physical exertion.

The Rest Frames Hypothesis (RFH) offers an alternate theory on MS, where the emphasis is on the role of spatial-perceptual references [25, 26]. It can be verified in the real world. For instance, a widely-accepted way to avoid MS in a moving vehicle is to look at the horizon rather than at near references. From an RFs perspective, observing the horizon reestablishes the stationary feeling of ground

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and also offers the same reference for a long time. In contrast, using close references, such as trees on the roadside, leads to difficulty in choosing and recognizing cues because of their high relative velocity. The RFH has been verified in VR, but most studies have been done in projection-based systems [4, 18, 19]. Our contribution is the formal evaluation of virtual RFs applied to HMD-based systems.

In a similar fashion to the RFH, Whittinghill et al. [38] proposed that adding a virtual nose could increase comfort and the experience period in VR games. The use of the virtual nose on applications that did not require intensive virtual rotation operations increased the experience period in VR by 94 seconds on average. In applications with intensive virtual rotation operations, it still had an increase of 2 seconds and lower sickness scores. No subject in the study noticed the existence of the virtual nose. We note that a virtual nose is different than a typical RF in that the nose is in the head reference frame rather than in the real-world reference frame. Also, a virtual nose does not allow users see through the environment unlike a typical RF. Other similar studies and practices [23, 24] also explored the utilization of a frame of reference to alleviate MS.

Lin et al. employed a Virtual Guiding Avatar, which provided visual cues of what virtual motion was about to occur and a relatively stable cue to alleviate VIMS [18]. The results from a revised SSQ indicated that a Virtual Guiding Avatar with rotational cues alone or with translation can reduce VIMS. Independent visual background and vertical visual references–two different kinds of RFs–also have shown to be effective in alleviating VIMS [19, 20]. However, these studies did not explore the utilization of RFs in HMD systems, where symptoms tend to be more severe than with screen-based simulators [20, 34, 35]. Additionally, in some cases, the references were stable in relation to users' eye movement, rather than the real-world's reference frame. Motivated by previous work, we propose a novel design of RFs for HMDs.

3 Design of the Rest Frame Technique

Our RF design evolved out of development of the Game VR Apocalypse [21]. While this game contains a combination of static and dynamic RFs, we decided to separate and simplify static and dynamic RFs in our research in order to maintain experimental control.

In designing the RFs for our studies, we wanted to ensure that the visibility of the VE wasn't entirely reduced. In this regard, we attached a see-through metal net–surrounding users above and below their seat–which was kept stationary relative to the real world and moved virtually with the cockpit (Figure 1 right). This provides better visibility than reducing the FOV [8], or using an opaque cockpit [24]. The metal net acts as an RF as a visually stabilized structure that does not move with the users head or with virtual motion. Figure 1 left shows a view from the VE without RFs. Note that there is no visible structure, and the user has an unrestricted view of the VE.

4 Hypotheses

According to the results from pilot studies and our understanding of the RFs hypothesis, we formulated six hypotheses.

Figure 1: View of the VE in the condition (left) without RFs, and (right) with the black metal net acting as an RF. Note that the VE can still be seen through the metal net RF.

H1: VEs with static RFs result in more comfort than VEs without RFs.

H2: VEs with static RFs result in longer periods of comfort than VEs without RFs.

H3: VEs with dynamic RFs result in more comfort than VEs without RFs.

H4: VEs with dynamic RFs result in longer periods of comfort than VEs without RFs.

H5: VEs with static RFs result in more comfort than VEs with dynamic RFs.

H6: VEs with static RFs result in longer periods of comfort than VEs with dynamic RFs.

5 User Study 1: Static Rest Frames

We conducted a user study to evaluate the effect of a static RF on VIMS. In this study, we used an opaque metal net, which we call a "static RF" (as opposed to a "dynamic RF"–section 6). We chose a different form of RF for this study than what is used in the game VR Apocalypse in order to increase experimental control by simplifying to a pure static RF form, reduce distraction of the cockpit interior, and to make the RF more obvious to users.

5.1 Apparatus

5.1.1 Hardware

An Oculus Rift CV1 with 6 degrees-of-freedom (6DOF) position and orientation tracking was used, driven by Oculus APP 1.11.0.34 on an Alienware X51 R3 Edition Quad Core Processor (2.7 GHz) with 8GB RAM and an Nvidia GeForce GTX 970 running Windows 10. 6DOF head tracking allowed the system to render the static RF stable relative to the real world even as the user freely moved his head while seated (Figure 2). In addition to the 6DOF Oculus rift head tracker, an Xbox One Gamepad wireless controller was used to virtually translate and rotate the viewpoint through the scene.

5.1.2 Software

The experimental platform was a modified version of VR Apocalypse [21]–a first person shooter game where the user sits in a cockpit to navigate through the environment.

With the intention to simplify the evaluation, we assured the time and motion of users in the application would be similar by requiring all subjects to follow equidistant arrows on the ground (Figure 3, lower right). Along the path, there were 6 arches acting as waypoints to let subjects report their discomfort level (Figure 3, upper left). Modeled after Fernandez and Feiner's real-time VR comfort assessment [8], the scale of comfort level ranged from 0 to 10, 0 being most comfortable and 10 being most uncomfortable (shown in Figure 4). When subjects reached a waypoint, the travel and virtual

Figure 2: Experimental environment.

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Figure 3: Map of Path with arrows and arches in Application. Upper left inset: how arrows appear from a first person perspective. Lower right inset: zoomed-in top-down view of the arrows.

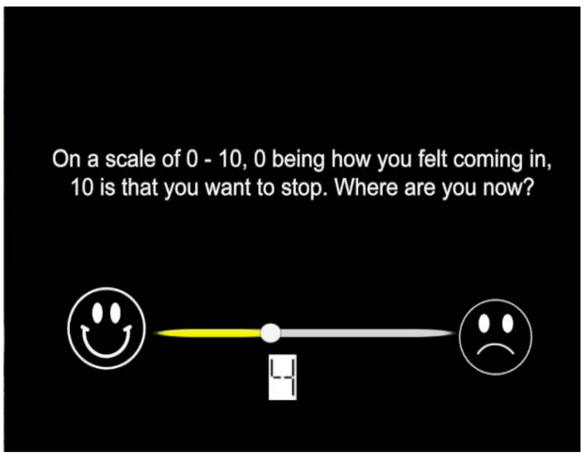

Figure 4: Question Shown at Each Waypoint

rotation in the VE were paused and the view was blacked out until subjects selected the level via a joystick and button command.

To ensure that users would remain on the path, a warning message was shown if the position was more than 4 meters off path. If a subject selected 10 as the discomfort score (DS), the application exited as a precaution [8].

5.2 Pilot Observations and Choice of Travel Parameters

The virtual travel speed and rotation rates of subjects were determined through initial observations of users' performance under different rates, reviewing their feedback, and analyzing data collected in three rounds of pilot studies (each with two subjects). The general strategy employed for this process was to calibrate virtual travel parameters based on the total time tolerated and comfort level between conditions with and without RFs. Table 1 shows parameters used in three rounds of pilot studies with two subjects each.

RFs did not seem to improve the experience at rotation rates of 162°/s and 81°/s. On the third round, we decreased the rotation rate to 27°/s and increased the translation speed to 1.6 m/s, and used these parameters for both studies.

For the first two rounds of pilot experiments, we found subjects intended to stare at the arrows. This intention, to some extent, may have resulted in subjects ignoring the RFs. Thus, we requested that users look around to get a better understanding of the environment at the beginning of each session in the formal experiments, in which case we believe RFs could maximize its benefits to subjects.

Table 1: Parameters tested in 3 rounds of pilot studies. Two subjects in each round (Rd) completed trials with and without RFs each in a different order. Round 3 was decided as the study parameters. V represents translation speed. ω represents rotation speed.

Rd	V	ω	Observations
1	2.0 m/s	162°/s	Low tolerance to the VE and strong VIMS in both conditions. No noticeable differences between conditions.
2	1.0 m/s	81°/s	Translation speed too slow and rotation speed too fast. No noticeable differences between conditions.
3	1.6 m/s	27°/s	Subjects felt a little increase in comfort when rotated, and felt nothing when translated. Rest frames seemed to cause less VIMS.

In addition to optimizing the rotation rates and translation speed, we also explored different types and sizes of the metal net RF during pilot observations.

5.3 Subjects

22 subjects (6 females, ages 18-49, mean±SD 22.4±6.4) were recruited in this study and each attended both sessions. They were randomly and evenly split between two groups based on the order of the condition presentation. We excluded data from two subjects from the study because, according to post-interviews, one subject kept reminding himself that he was in a lab rather than in the virtual world to avoid VIMS, while the other subject indicated she had slight claustrophobia and the RFs made her feel nervous and hot. Thus, the data used in our analysis had a total of 20 subjects.

5.4 Experimental Design

We conducted a two-session study with intervals between sessions being at least two days but no more than 7 days to reduce the influence of the first session [14, 36]. We used a mixed design with two within-subjects independent variables and one between-subjects independent variable. Condition (static RFs–SR, no RFs–NR) and waypoint (1-36) were the within-subjects factors and the order of condition (SR1NR2, NR1SR2) was the between-subjects factor. SR1NR2 subjects experienced static RFs in their first session whereas NR1SR2 subjects experienced static RFs second.

Figure 5 shows the experimental protocol. Each session lasted 30 minutes or less, including up to 15 minutes to experience the application and 15 minutes for questionnaires. Before the first session, all subjects were initially greeted and signed an informed consent form. After that, a background survey about their experience on virtual reality was completed. Then, subjects were shown the equipment and were introduced to the details of the experiment, including what they needed to do, how to use the device and what might happen in the task. Except for signing the informed consent form and answering a background questionnaire, all other procedures were performed again at the beginning of the second session. Each subject was asked to finish up to 6 laps (totalling 3340 meters), which would be completed within 15 minutes, a higher threshold for time in an immersive VE based on previous research [6, 33].

In the first session, odd-numbered subjects experienced the control condition NR, while even-numbered subjects experienced the intervention condition SR. When a subject returned for their second session, they experienced the other condition.

In both sessions, subjects only used an Xbox One Gamepad to control virtual translation (through the left stick Y axis) and virtual rotation (through the right stick X axis), and the Oculus Rift to

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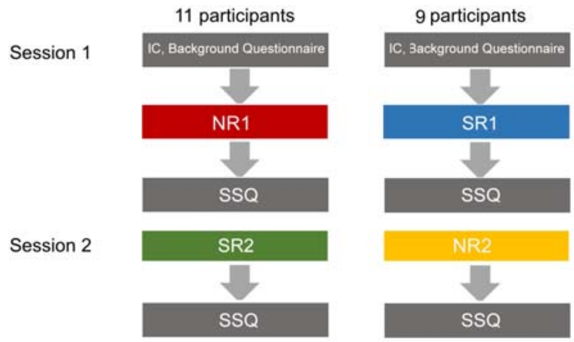

Figure 5: Design of two-session experiment in static RFs.

control pose. When subjects crossed a waypoint, virtual translation and rotation were frozen (although head pose could be changed physically and naturally) and the question was shown. Subjects used the left stick X axis to select the discomfort level and the A button to submit the answer, after which virtual rotation and translation resumed, and the left sticks' X axis was inactivated again. After finishing the session, subjects filled out an SSQ [14], and reported on how prone they were to general MS.

5.5 Results

We analyzed the results of real-time DSs as the primary measure and SSQ as a secondary measure. We have two reasons to make this decision: First, the SSQ does not take the amount of time spent in the VE into account. Second, SSQ, as a post-hoc measurement, unlike real-time DS, only considers users' feelings at the end of their VR experience, which is a single value and cannot tell the evolution of symptoms over the time.

5.5.1 Data Analysis

We based the analysis of our results on Fernandes and Feiner's study [8] and Prothero's experiments on rest frames [25]. Different than Fernandes and Feiner, who only performed t-tests, we performed a mixed-design ANOVA with order (SR1NR2, NR1SR2) as the between-subjects factor and condition (SR, NR) and waypoint (1-36) as the within-subjects factors. Pairwise comparisons (Tukey's HSD) with the Bonferroni correction were used for analysis of multi-level variables as well as interaction effects.

5.5.2 Discomfort Score

Figure 6 shows the self-reported DS over waypoints for each group and Table 2 shows the statistical results. In Figure 6(a), each thin line provides the progression of DSs of a single subject over waypoints in the group of NR1SR2. The thin red dash lines represent NR subjects, and the thin green lines represent SR subjects. The circle or diamond at the end of each line represents the point at which a subject either terminated early or completed all 36 waypoints. Three of eleven subjects finished the first session (NR), seven of them finished the second session (SR). The vertical axis corresponds to DSs where lower scores represent more comfort. The horizontal axis represents waypoints and is progressed over time. The utilization of waypoints can ensure all subjects experience similar visual stimuli before DSs were collected. The DSs of NR1 subjects were averaged over waypoints, which is represented by the thick red dash line. If the subject terminated early, a score of 10 was assigned to the remaining waypoints [8]. This was also done for SR2 subjects which produced the thick green line. The same method was utilized in Figure 6(b) for comparing SR1 and NR2.

Main Effect NR showed significantly higher DSs than SR ($M_{NR} = 5.32, M_{SR} = 4.00, F(1,18) = 9.42, p < 0.01$), which supports H1.

Table 2: Real-time DS from static RFs. Pairwise comparisons are shown for significant interaction effects.

Conditions	**Means**	**F Statistic**	***p* value**
Main Effect		F(1,18) = 9.42	< 0.01**
NR vs. SR	5.32 vs. 4.00		
Interaction Effect		F(1,18) = 15.95	< 0.05*
(Conditions * Order)			
NR1 vs. SR1	6.59 vs. 4.44		0.15
NR2 vs. SR2	4.05 vs. 3.55		0.41
SR1 vs. SR2	4.44 vs. 3.55		0.56
NR1 vs. SR2	6.59 vs. 3.55		< 0.05*
SR1 vs. NR2	4.44 vs. 4.05		0.54

Interaction Effect A significant interaction between condition and order was found for DS ($F(1,18) = 15.95, p < 0.05$). Pairwise comparisons show that NR1 had significantly higher DS than SR2 ($M_{NR1} = 6.59, M_{SR2} = 3.55, p < 0.05$). All other pairwise comparisons did not show significance at $\alpha = .05$.

5.5.3 Number of Waypoints Completed

We looked at the total number of waypoints completed during each trial as a proxy to the total time tolerated in the VE. We measured the number of waypoints finished, rather than using the actual time subjects were in the VE because we did not want to consider moments where subjects were stationary in the VE. Most subjects kept moving during most trials.

Figure 7 shows the number of waypoints completed for each group and Table 3 shows the statistical results.

Main Effect The number of waypoints subjects completed in SR was significantly higher than that of NR ($M_{NR} = 22.70, M_{SR} = 27.11, F(1,18) = 6.36, p < 0.05$).

Interaction Effect A significant interaction effect was found between waypoints finished and order ($F(1,18) = 9.57, p < 0.01$). Pairwise comparisons show that, for group NR1SR2, subjects completed significantly fewer waypoints in condition NR1 than SR2.

Both findings are consistent with H2 that the use of static RFs results in users have longer periods of comfort.

5.5.4 SSQ

We looked into reported simulator sickness at the end of each session. We consider this a secondary result, as it does not capture real-time subject data, and the results are less granular than those of DS.

No main effects of SSQ on RFs condition were found (Overall SS: $p = 0.68$; Oculomotor: $p = 0.84$; Nausea: $p = 0.27$; Disorientation: $p = 0.85$). However, there was a significant interaction effect between order and condition ($F(1,18) = 12.11, p < 0.05$) for overall simulator sickness (SS). Pairwise comparison revealed both groups NR1SR2 and SR1NR2 had significantly higher overall SS in their first sessions ($M_{SR1} = 68.57, M_{NR2} = 39.89, p < 0.05; M_{NR1} = 65.96, M_{SR2} = 43.52, p < 0.04$).

6 User Study 2: Dynamic RFs

For the second study, we used the same opaque metal net as for Study 1 but it faded in and out smoothly once the subjects' rotation rate or translation speed was higher than 30% of the maximum value. We call this technique *dynamic RFs*. The static RF was designed to always be visible, which reduces the visibility of the VE beyond the RF. The chief aim of dynamic RFs was to provide users a fuller view of the VE without interference when not necessary, and to activate RFs to alleviate VIMS when virtual motion surpassed a threshold. Users can perceive more of the environment around them when the RFs are not needed, making dynamic RFs potentially better.

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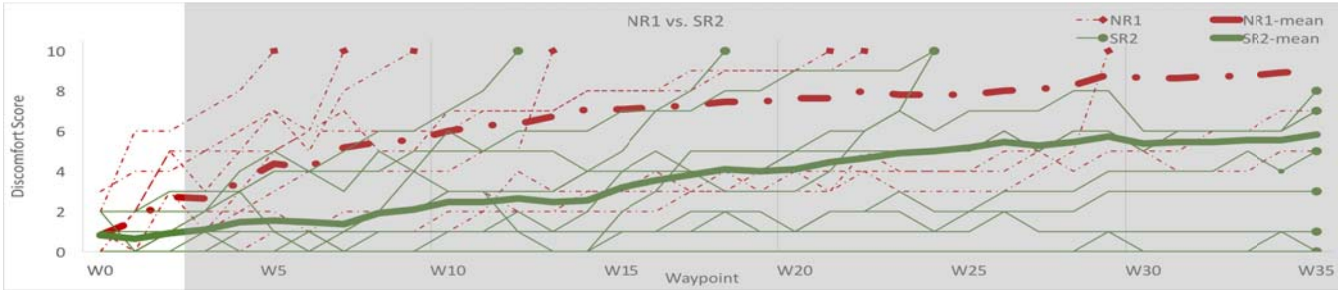

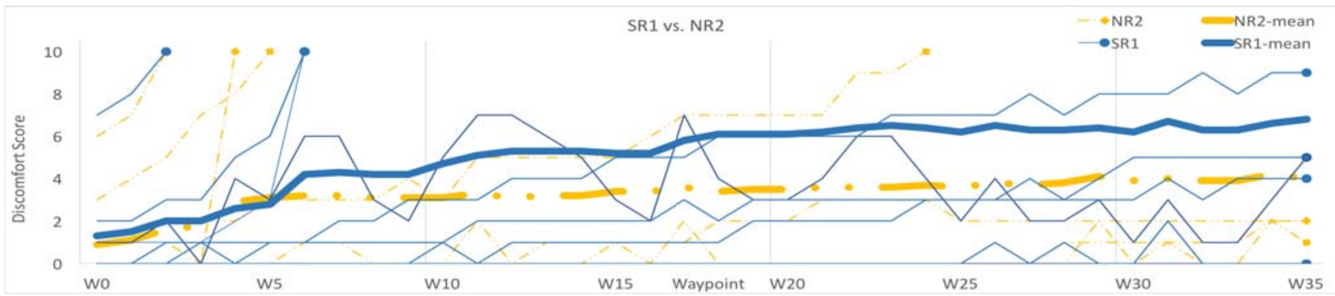

Figure 6: DSs over time for individual subjects and mean DSs over waypoints by session. (a) NR1 vs. SR2. (b) SR1 vs. NR2. The grey shaded region signifies waypoints with statistically significant differences.

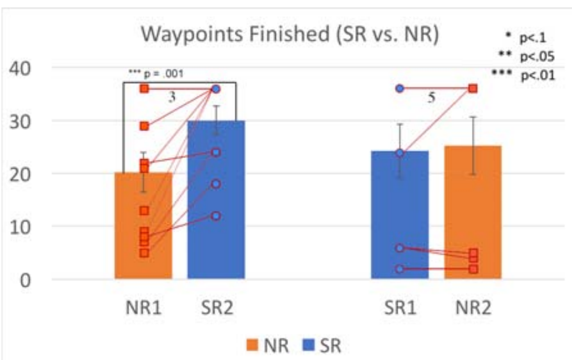

Figure 7: Mean value and individual data of completed waypoints for both groups. The number under the top line represents how many subjects finished all waypoints in both sessions.

Table 3: Number of waypoints finished from static RFs. Pairwise comparisons are shown for significant interaction effects.

Conditions	Means	F Statistic	*p* value
Main Effect		F(1,18) = 6.36	< 0.05*
NR vs. SR	22.70 vs. 27.11		
Interaction Effect		F(1,18) = 9.57	< 0.01**
(Conditions * Order)			
NR1 vs. SR1	20.18 vs. 24.22		0.52
NR2 vs. SR2	25.22 vs. 30.00		0.41
SR1 vs. SR2	24.22 vs. 30.00		0.30
NR1 vs. SR2	20.18 vs. 30.00		< 0.01**
SR1 vs. NR2	24.22 vs. 25.22		0.70

6.1 Apparatus & Experimental Design

The apparatus, VE, procedure and experimental design were the same as the first study. To enable RFs to dynamically appear and disappear, we set a function for the opacity to be completely transparent or completely opaque over a period of less than one second. Based on pilot observations of rotation being more provocative than translation, we set the fading as a result of rotation to be 3x as fast as that of translation.

6.2 Subjects

We recruited 22 subjects (6 females, age: 18-39, mean±SD 22.6±5.2) for this study. No subjects from study 1 participated in study 2. As shown in Figure 8, 11 subjects were arranged in group DR1NR2, and 11 subjects were arranged in group NR1DR2.

6.3 Results

The same methods for data analysis used in the first study was employed for the dynamic RFs study.

6.3.1 Discomfort Score

Figure 9 shows the real-time DSs of 22 subjects from group NR1DR2 and DR1NR2. Figure 9 applied the same method to Fig-

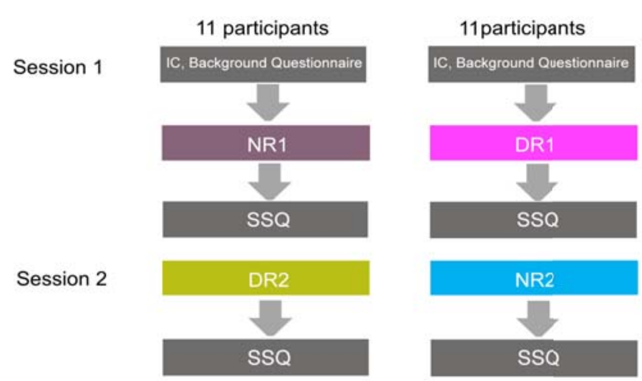

Figure 8: Design of two-session experiment with dynamic RFs. (Divided into two groups, counterbalanced as to condition order).

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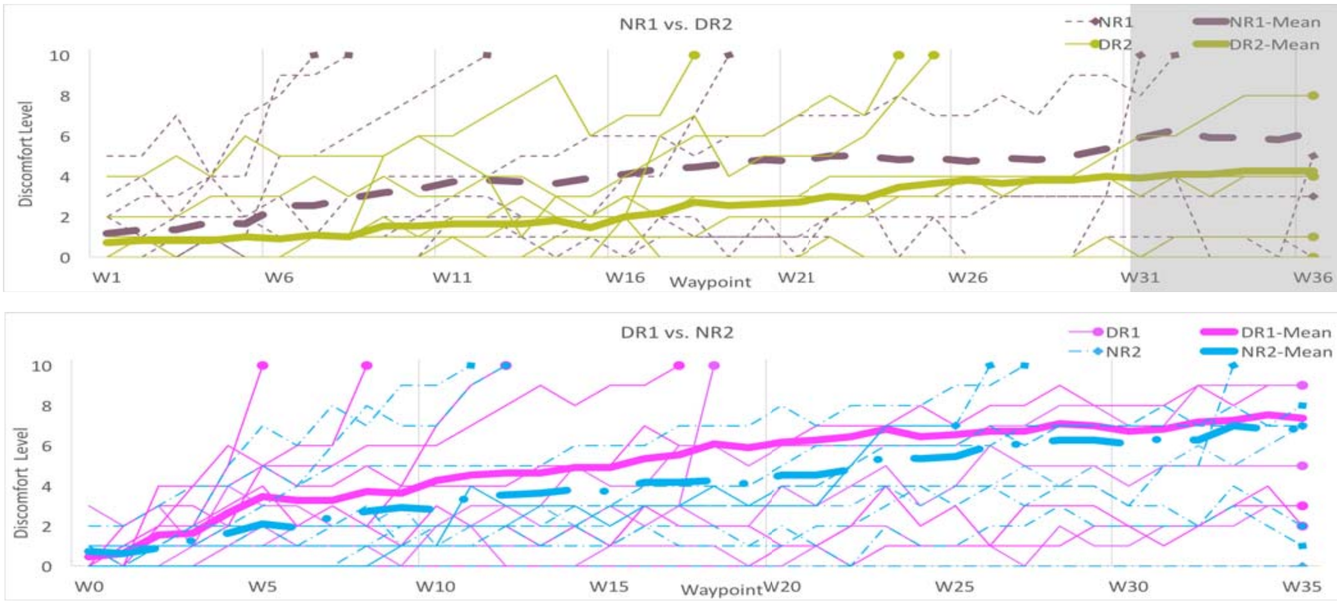

Figure 9: DSs over time for individual subjects and mean DSs over waypoints by session. (a) NR1 vs. DR2. (b) DR1 vs. NR2. The grey shaded region signifies waypoints with statistically significant differences.

Table 4: Real-time DS from dynamic RFs.

Conditions	Means	F Statistic	*p* value
Main Effect		F(1,20) = 0.60	0.45
NR vs. DR	4.13 vs. 3.81		
Interaction Effect		F(1,18) = 0.23	0.06
(Conditions * Order)			

ure 6 in which different colors represented different conditions (see section 5.5.2). Table 4 shows the statistical results.

Main Effects Analysis of DSs across all sessions did not show a significant main effect of condition.

Interaction Effects No significant interaction effect was found between condition and order.

6.3.2 Number of Waypoints Completed

Figure 10 shows the number of waypoints completed for each group and Table 5 shows the statistical results.

Main Effect No significant main effects of condition were found over waypoints finished across all sessions

Interaction Effect A significant interaction effect was found between waypoints finished and order ($F(1,20) = 8.42, p < 0.01$). Pairwise comparisons show that, for group NR1DR2, subjects completed significantly fewer waypoints in condition NR1 than DR2.

The interaction effect is consistent with H4 in that dynamic RFs makes users experience longer periods of comfort.

6.3.3 SSQ

As with static RFs, we looked into SSQ scores as a secondary metric.

No main effects of SSQ on RFs condition were found (Overall SS: $p = 0.43$; Oculomotor: $p = 0.46$; Nausea: $p = 0.48$; Disorientation: $p = 0.48$), neither was an interaction effect between condition and order found ($p = .07$).

7 Between-Subjects Analysis: Static Rest Frames vs. Dynamic Rest Frames

After analyzing static RFs and dynamic RFs individually, we looked whether there were differences between SR and DR, and whether one had a better influence on reducing VIMS. Thus, we performed a between-subjects analysis comparing SR1 to DR1, SR2 to DR2, and NR2 of study 1 ($NR2_{DR}$) to NR2 ($NR2_{SR}$) of study 2. Since we performed both studies with the same protocol, procedure and apparatus, we could perform this analysis without additional experiments.

Data was analyzed using three two-way mixed ANOVAs, with group (DR1 vs. SR1, DR2 vs. SR2 and $NR2_{DR}$ vs. $NR2_{SR}$) as the between-subjects factor and waypoint as the within-subjects factor.

7.1 Results

Real-time DSs of SR1 vs. DR1 and SR2 vs. DR2 did not show any significant main effects. No significant interaction effect between waypoint and group for SR1 vs. DR1 was found ($M_{DR1} = 5.12, M_{SR1} = 4.44, F(1,20) = 1.44, p = 0.05$). Pairwise

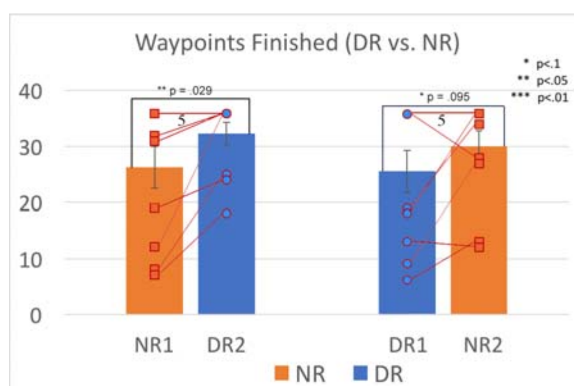

Figure 10: Mean value and individual data of finished waypoints over DR group. Number under the top line represents how many subjects finished all waypoints in both sessions.

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Table 5: Number of waypoints finished from dynamic RFs. Pairwise comparisons are shown for significant interaction effects.

Conditions	Means	F Statistic	*p* value
Main Effect		F(1,20) = 0.18	0.67
NR vs. DR	28.14 vs. 28.91		
Interaction Effect		F(1,20) = 8.42	< 0.01**
(Conditions * Order)			
NR1 vs. DR1	26.27 vs. 25.54		0.89
NR2 vs. DR2	30.00 vs. 32.27		0.52
DR1 vs. DR2	25.54 vs. 32.27		0.13
NR1 vs. DR2	26.27 vs. 32.27		< 0.05*
DR1 vs. NR2	25.54 vs. 30.00		0.09

comparisons indicated that subjects started to have significantly higher DS as compared to waypoint 1 starting at waypoint 23 under DR1, while SR1 had no differences in DS over waypoints.

We also looked at DS for $NR2_{DR}$ vs. $NR2_{SR}$. We found a significant interaction effect between waypoints and group. Pairwise comparisons show that subjects in $NR2_{DR}$ started to have significantly higher DS from waypoint 30, as compared waypoint 1, while group $NR2_{SR}$ did not show significant differences among waypoints.

No significant differences in the number of waypoints completed were found between SR and DR (two-sample *t*-test: df = 15.52, t = 0.84, p = 0.84). SSQ also did not find any significant difference (DR1 vs. SR1: two-sample *t*-Test: $df = 15.57, t = 0.06, p = 0.95$; DR2 vs. SR2: two-sample *t*-Test: $df = 18.84, t = 0.63, p = 0.54$).

8 Discussion

8.1 Static Rest Frames

In the static RFs study, main effects (Table 2) support H1 in that NR had significantly more discomfort than SR. H2 is also supported by the fact that subjects completed more waypoints (as a proxy to time spent in the VE) with RFs than without.

When we break down the results by the order in which RFs were presented, we gain more insights. The interaction effect between condition and order (Table 2) reveals that SR2 caused significantly less discomfort than NR1, whereas no significant differences were found between SR1 and NR2. This ordering effect leads to an interesting interpretation: users, after experiencing a VE initially with static RFs may "adapt" to the VE. This "adaptation" may carry over to a second session, where no RFs are present. Of course, the lack of a significant difference does not imply equivalence. However, if we consider the following facts: (a) NR1SR2 had significantly lower DSs in the second session; (b) the average DS of NR2 was lower than that of SR1 (Figure 6); and (c) the comparisons were done within-subjects (where each subject served as their own control), we posit that it is plausible to assume that a user can "acclimate" to a VE that is designed to reduce discomfort such that future experiences would lead to low discomfort even without the aid. We also point out that this result is consistent with Fernandes and Feiner results [8], where a reduced FOV in an initial session caused no differences in a follow-up session with unrestricted FOV. However, for this interpretation to be statistically proven, more studies are needed.

A similar interaction effect of conditions by order on the number of waypoints finished provides further evidence that users may adapt to the VE after experiencing it with the aid of RFs. Here, a significant difference was only found in the NR1SR2 group, with SR2 having more waypoints finished. Again, the time spent in the VE was not significantly different when RFs were used first, suggesting that the time tolerated in the VE without any aid may approach that of when RFs are present, if these are experienced in an initial session. Together, all these results give us confidence that adaptation may occur when RFs are offered in an initial experience, but further formal testing is needed to verify this hypothesis.

8.2 Dynamic Rest Frames

H3 and H4 were not verified due to the lack of statistical differences between DR and NR on DS (Table 4) and waypoints completed (Table 5). This indicates that dynamic RFs may not provide the same benefit as static RFs on comfort or time tolerated in the VE. However, a significant interaction effect between order and condition on the number of waypoints finished was found. This result partially mimics the one which was found for static RFs. Although only on waypoints completed, we see that the condition which contained RFs led to significantly more waypoints finished when it was performed second. Again, this result may indicate that users could have adapted to the VE if they had dynamic RFs first. However, this conclusion is not as clear as that of static RFs, as this result was not found for DS.

8.3 Static Rest Frames vs. Dynamic Rest Frames

Neither H5 and H6 were verified, as no main effects between static and dynamic RFs were found. The interaction effects found when comparing SR and DR between-subjects indicate that dynamic RFs caused more discomfort over time, either when being performed, or in a follow-up session without RFs. Interestingly, for the majority of waypoints, no significant differences in DS was found. This is counter-intuitive, as the longer someone is in the VE, the more discomfort they will feel. However, we are confident that the lack of significance is due to the small sample size, as much variance is introduced in a between-subjects analysis. More testing is needed to assess the effect of static vs. dynamic rest frames.

8.4 SSQ vs. Discomfort Score

One of the main contributions introduced by Fernandes and Feiner [8] is the real-time capture of comfort feedback. Even if introducing an interruption multiple times along the VE experience may itself affect results, having users report their immediate comfort provides the great benefit of fine-granular data. We used this strategy in our studies and found that our conclusions chiefly rely on DSs as opposed to SS scores. This makes sense, as SSQ is assessed at the end of the experience and several factors can interfere with the data. Because it's reported at the end, SSQ responses are on cumulative effects, and there is no way to capture the progression of symptoms over time. In our studies, this issue was further magnified because subjects finished the experience at different moments, such that a response to the SSQ for someone who stayed longer in the VE was directly compared to that of someone who lasted little time.

However, SSQ asks different questions, and it is unclear whether DS alone is a reliable proxy to VIMS. Further research should be conducted to help determine if SS and DS are measuring the same phenomena, or how they may differ.

9 Limitations and Future Work

The work presented here has several limitations that should be addressed in future studies. One of the main findings of our work was that the combination of our results indicate that there may be a benefit to initiate VR experiences using RFs, and that follow-on sessions could be just as effective without RFs. However, an overarching order effect could not be ruled out due to the design of our studies. In our experiments, the follow-up session was always confounded by the initial session. This makes an independent analysis of the order effects impossible to make, as differences between sessions could be explained either by the condition used, by ordering itself or, more likely, by a combination of both. In order to quantify the real benefit of using RFs in an initial session over order effects, research should be conducted to assess comfort in back-to-back sessions using the same conditions. In other words, data should be gathered for groups experiencing the VE without RFs in both sessions as well as with RFs in both sessions. Alternatively, a between-subjects study could be conducted with a larger number of subjects.

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We found the strongest results on the benefits of using RFs in VEs using static RFs. We hypothesized that dynamic RFs would also show benefits, but this was only partially verified. We realize that our work could have been stronger if a better design process for the dynamic RF were used. The thresholds for fade in and out were anecdotally and arbitrarily set, and we believe that a more systematic approach to its design could have led to more positive results.

Finally, we used the concept of "real time discomfort" as substitute to VIMS, but we have not verified that this is the case. Even though we believe that comfort in an immersive VE correlates strongly with VIMS, further research should be conducted to verify that this is indeed the case. In addition, the evaluation of discomfort score during the immersive experience may cause an interruption in presence. However, we believe this interruption is a necessary trade-off to evaluate discomfort in real-time.

10 Conclusion

We reviewed the concept of rest frames (RFs), iterated upon a design using RFs, and introduced a new concept called dynamic RFs. The results from two studies showed subjects feel more comfortable (as a proxy to VIMS) and tolerate navigating through a scene presented in an HMD longer when an RF is included. We also found evidence that VR, when experienced first with RFs, may lead to more comfort in follow-up experiences with the same environment, although this claim should be tested further. Finally, we were not able to verify that the addition of a dynamic RF is as effective as a static one. Regardless, a dynamic RF might be a better choice than a static RF with the advantage of the VE being entirely visible when the presence of an RF may not be helpful.

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