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Reducing Motion Sickness Resulting From Movement inside Virtual Reality Environments

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Abstract

Motion sickness while using virtual reality (VR) headsets affects 25-40% of users. Motion sickness results from a disconnect between the user's physical movement and their experienced movement in the virtual environment. The problem of how to move and navigate in a virtual environment that is larger than the user's physical environment is a well-studied problem. This project implements the three most common movement methods (teleportation, on-rails and free movement) and implements modifications to two of those methods (a natural acceleration and deceleration motion to on-rails and acceleration/inertia-based movement to free movement). The goal of this project is to find whether the modifications will decrease motion sickness and increase preferability compared to their conventional counterparts when tested in a user study. Users experienced lower nausea with our novel on-rails movement method combined with acceleration/deceleration than with any other method. This method was also preferred evenly with teleportation, the method most commonly used by developers now. This study indicates that on-rails should be given more attention as a viable solution to the virtual reality movement problem.

CCS Concepts

• ***Human-centered computing*** → ***HCI theory, concepts and models; HCI design and evaluation methods; User studies;***

1. Introduction

The problem of moving in a virtual environment larger than the user's physical environment is a well-studied problem but one still looking for a satisfactory solution. In the days before virtual reality (VR), this problem was solved by applications such as Doom forcing the user to use a controller or keyboard to move the user's avatar in the environment while the user's body stayed in one area such as sitting in a chair. VR's appeal lies in providing users a higher level of immersion than simply looking at a screen but the heightened immersion adds problems of its own. Studies show that walking is the preferred navigation method for users in VR because it feels the most natural [MU], [PK17], [FS07]. This is not feasible when the physical tracking space supported by VR headsets is limited to a relatively small area such as the 5 square meter maximum size supported by the HTC Vive. Virtual environments can stretch for many virtual miles, and a user will run out of room very quickly should they try to walk 20 feet in a straight line in their physical environment. While much recent work has focused on redirected walking to alleviate this problem, this is impossible in many environments.

Three possible solutions (teleportation, free movement, and on-rails movement) [EB16] have been generally agreed upon by the research community and entertainment industry but no solution has been accepted as an industry standard at this time. Teleportation (also known as blinking or jumping) involves selecting a destination with some sort of pointer or controller and then initiating an instant transport to that destination as shown in Figure 1.

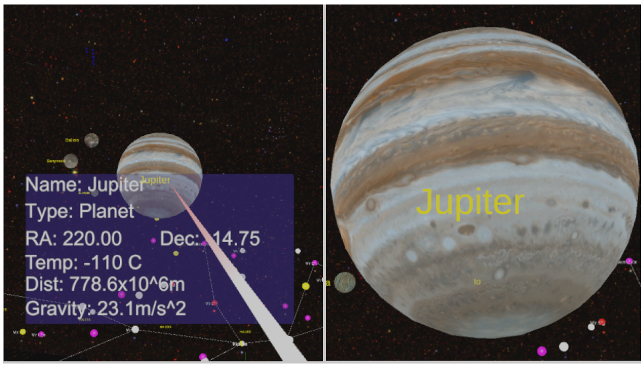

Figure 1: *Teleportation*

Free movement (also known as continuous movement) requires using a controller of some sort to initiate movement in a given direction at a given speed and can change the speed and direction at any time by applying different movements to the controller. As shown in Figure 2, on-rails is a hybrid movement where the user selects a destination as in teleportation. When the transport to the new destination is initiated, the user experiences the entire length of the journey as if they were in a car or train.

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Figure 2: *On-Rails*

All three of these solutions come with some degree of motion sickness that affects users [SD], [TW18], [CKJ18] and motion sickness while using Virtual Reality headsets is an active research area. Motion sickness is caused by the disconnect between actual and perceived motion in the human body and is referred to as sensory conflict theory. Both motion sickness and cybersickness produce similar symptoms [Jr.00] such as nausea, excessive salivation, sweating, vomiting.

Motion sickness has been cited as a negative factor affecting VR not only in research papers but in mainstream media like CNN [LaM20]. Motion sickness in VR is actually something of a misnomer as motion sickness technically results from motion being applied to a person without the person doing anything to cause that movement (e.g. a person subject to g-forces inside a moving car or airplane). Cybersickness refers to a person perceiving motion while their body is not in motion (e.g. a person in VR uses a controller to walk around in an environment while their actual body sits motionless in a chair) and is our focus.

The symptoms of cybersickness and motion sickness are similar enough [Jr.00] that the degrees of these symptoms are commonly measured using the Simulator Sickness questionnaire developed by the United States Navy [RK93]. The SSQ was developed in 1993 and the problem itself dates to the beginning of manned flight so there is a wealth of literature on this issue with a wide variety of suggested cures. Complicating research on this topic is the fact that different people can have very different reactions to the same set of stimuli [TW18]. This leads to research producing contradictory results [EB16], [PK17] so a one-size-fits-all approach to solving this problem has proven elusive.

Complaints of cybersickness in entertainment products with a first person point of view in a three dimensional environment date back to 1994 [Ste94], when the game Doom was the first popular game with free movement using a first person view and helped expose the problem. The problem has persisted through the decades [Mil08].

Industry leading products such as Doom VFR, and Square Enix's Rise of the Tomb Raider promoted teleportation over free movement but were hacked or patched within hours of their release by users dissatisfied with the methods included. Valve's recent Half Life: Alyx started with several different methods [Wha20] and was still patching it months after release [Liv20]. Multiple movement methods are not desirable from a support or consistency of experience perspective.

2. Related Work

Much work has been done using devices such as omnidirectional treadmills to allow realistic walking movement in theoretically infinite directions [Iwa99]. These devices are expensive, complicated to set up and are not included with any of the current generation of consumer VR hardware. Another problem with using devices such as treadmills is fatigue on the part of the user, who for example may want to virtually experience the Pacific Coast trail without the rigor of actually walking the full distance. As mentioned earlier, walking by itself is not sufficient to traverse a fully three-dimensional environment.

Redirected walking is a field of active research but it does not lend itself to sparsely populated environments. Langbehn and Stenicke [EL18] summarized some limitations with redirected walking by mentioning that "a physical space of at least 45 x 45 m would be necessary to enable infinite virtually straight walking...There is still no standard solution for unlimited walking in a restricted tracking space without interruptions." These problems would be accentuated in a sparsely populated environment like those used in this paper.

Williams et al. [BW07] did early work on the problem of the user's physical environment being much smaller than the user's virtual environment. They proposed several different ways for the user to reset their position in the virtual environment when the boundary of the physical environment was reached but found there was a spatial awareness "cost to resetting in terms of a user's orientation to remembered objects."

While it is of course possible to walk through a virtual object, Wilcox et al [WAEG06] showed that objects interfering with the user's perceived personal space causes "significant negative reactions" in users and must be avoided. This has major implications for navigation systems in VR and shows that objects need to be navigated around and cannot simply be passed through. Lopes et al [LYC*17] built upon this concept in adding haptics through muscle stimulation to simulate the feel of real walls and objects while a user moves around a virtual environment to dissuade users from walking through virtual walls and objects.

2.1. Teleportation

Bowman's early 1997 work in VR movement [BKH97] demonstrated that users found teleportation to be "disorienting" and negatively affected users' spatial awareness yet it is still frequently used in entertainment programs now being published. In the following years, different studies have produced contradictory findings about the motion sickness effects of the teleportation method. Bozyegekli [EB16] found that the motion sickness effects of all three movement methods were similar while Weissker [TW18] found that teleportation caused less motion sickness than free movement and did not affect users' spatial awareness.

Bozgeyikli et al [EB16] proposed a pointer based approach to teleportation where the user simply points to a destination and two seconds later is teleported there. The two second delay was to reduce the problem of undesired teleports but was also cited as a major drawback by users. Bozgeyikli acknowledged that two seconds is a long time to wait for users who are accustomed to instant feedback.

2.2. On-Rails Movement

Knodel et al [KHG08] used this method without reporting any motion sickness sensations in users but other papers have reported problems with this method in user studies. Bozgeyikli et al [EB16] investigated further and reported that users disliked on-rails movement regardless of the speed used for the automatic movement. Bowman [BKH97] found users showed increased spatial awareness after on-rails movement and preferred it over teleportation. Bowman also implemented what he called a Slow In Slow Out (SISO) method of on-rails movement with enhancements designed to minimize motion sickness in users. This movement method has been used less frequently in recent years.

2.3. Free Movement

User movement in the virtual environment being completely disconnected from the user's movement in physical space has been cited as a chief cause of motion sickness. [PRS*18] Most research in this area agrees that free movement causes the most motion sickness in users out of all the methods listed, however there is some disagreement on this point.

Steinicke's work tried a fourth approach to the constrained movement problem using scaled movement [FS07], a combination of on-rails and free movement. The user could select a scale to use for their movement, allowing distances greater than the user's physical space to be covered quickly. This method has the advantage of avoiding the disorientation that some experience when using teleportation but has numerous drawbacks, including frequent changing of the scaling level depending on whether the environment has a lot of objects in the user's path, as one cannot walk through objects with this method. Steinicke et al. also created one of the few fully three dimensional VR navigation systems by using two Wii controllers to navigate in all three dimensions. They used a "rocket belt" metaphor for aerial movement but the environment was still ground-based with gravity, so a user could neither remain suspended in mid-air indefinitely nor control their movement while in the air.

In perhaps the most relevant research to this project [TW18], Weissker found that teleportation had lower simulator sickness than free movement and 75% of users had similar spatial awareness to free movement. While this would seem to establish teleportation as the favored movement method to use in virtual environments, Weissker noted that "even some participants with more symptoms of simulator sickness during steering (free movement) seem to prefer this technique." The fact that people would prefer free movement over teleportation despite experiencing more motion sickness implies that teleportation is not a satisfactory answer to the virtual environment movement question. It is also worth noting that 37.5% of participants in this study reported higher simulator sickness with free movement. This is in line with the reported 25-40% of people who are affected by motion sickness in VR [Mas17].

3. Methodology

The above work has focused on navigation in ground-based environments. Moving and looking around in a fully three-dimensional environment by definition must allow the tasks that correspond to the 6DoF (six degrees of freedom, movement in either direction in three dimensions) at any time. Rotation in either direction in all three dimensions will be supported, as well as controls for highlighting an object of interest and initiating transport to that object.

Our program's environment simulated the celestial sphere model of astronomy, which says that stars are so far away from us that they can all be considered to be a constant distance away. While of course inaccurate, this model is helpful for plotting the positions of stars relative to the earth and is commonly used in planetariums and star charts. Astronomical terms Declension and Right Ascension can be thought of as celestial latitude and longitude and have identical degree ranges.

While some research [TW18] differentiates between teleporting in and out of vista space (visible space in the environment), all movement actions here will take place in vista space due to the sparsely populated nature of outer space.

As shown in Figure 3, the X-Y plane is considered the plane of the ecliptic that planets generally fall into when orbiting the sun. The Z plane refers to the third dimension where Polaris would be considered straight up if a viewer was situated on the North Pole. Planetariums and stargazing events typically use some sort of laser

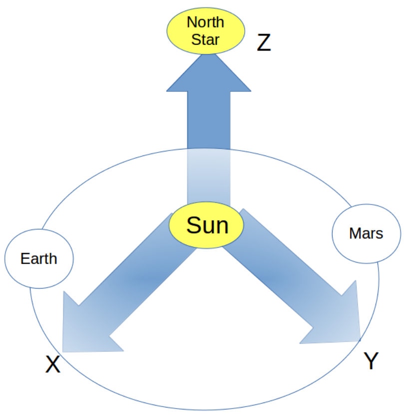

Figure 3: *Plane of the Ecliptic*

pointer to highlight objects in the night sky. In our program, ghostly hands are shown in the user's environment as avatars of the actual location of the controllers so users will be able to see the orientation of the controllers they are holding even if they can't see the actual controllers due to wearing the headset.

Object selection is required for the teleportation and on-rails movement methods. We used pointer-based selection, using the pointer mechanism included in modern VR controllers as shown in Figures 1 and 5. Bowman found this method was preferred by users as a means of interacting with virtual environments [BKH97].

The pointer will function similar to Bozgeyikli's work [EB16] to allow object selection, but movement/transport will be initiated with a controller button press and not use a two second timer. This has the advantage of giving instant response time to the user and also eliminates involuntary teleport (a disadvantage Bozgeyikli noted with their implementation).

4. Novel Movement Techniques

4.1. On-Rails Modification

In recent years, automobile manufacturers have worked on CVTs (continuous variable transmission, a smoother-shifting transmission designed to increase fuel efficiency) where gear shifts were imperceptible to the user. Drivers found this strange and missed the gear shifting motion so the shifting motion was artificially added back to the transmission [Gri15]. This indicated that people were comfortable with the shifting motions of automobiles and it was hoped here that replicating motions people are comfortable with would lead to less nausea.

On-Rails with vehicular motion (ORVM) applied will add acceleration to the beginning stages of the transport and deceleration to the final stages of the transport. This approach is similar to Bowman's SISO (slow in slow out) method [BKH97] but gear shifting more closely duplicates the speeding up and stopping of a vehicle such as a car or subway train in which they have been a passenger. Automatic transmissions are almost universal in most cars and typically have three gears with some cars also having an overdrive setting. This was the method decided on for this project and the gears were set to a constant speed, then after a certain percentage of the journey was complete, to shift up or down to the next gear, and so on. We implemented a scaled acceleration and braking motion at 25% and 75%, repsectively of the user's transit.

4.2. Free Movement Modification

Previous research has shown that people's preferred locomotion method is the one that feels most natural [PK17] [MU]. This is walking for people in a standard two-dimensional ground-based environment with gravity. It is less clear what the natural method would be for a completely three-dimensional environment where there is no natural analog for humans being able to fly. The approach taken here was to add inertia and acceleration to free movement similar to how a real spaceship would fly. The user will select a direction to move and their acceleration will begin in that direction. Their motion continues until they either hit the edge of the celestial sphere or an object (planet or moon) inside the sphere. It is believed this method will be natural to the environment and allow the user to fully explore the environment with less effort than the constant action required by free movement. An "all-stop" mechanic with deceleration motion will be available with the press of a button to allow users to easily and quickly stop in case they feel they are out of control or are unable to exactly reverse their velocities in all three dimensions.

5. Experimental Setup

The PC this experiment used featured an Intel Xeon E5-2603 dual core processor (1.60GHz) with 32GB RAM and an Nvidia GeForce GTX 1060 (6 GB) running Windows 8. An Oculus Rift CV1 with 6 degrees-of-freedom (6DOF) position and orientation tracking was used, with version 1.33.0.0750915 of the Oculus software. The Oculus Touch wireless Controllers (OTC) were used for all movement, viewpoint rotation, user representation display, and transition initiation so these actions were under the full control of the user. Users remained stationary throughout the experiment as shown in Figure 4 since they moved virtually in the environment with the controllers. A large television was connected to the PC and displayed what the viewer saw in their headset.

Figure 4: *Experiment Room*

This display helped the proctor answer any questions from the user that arose during the experiment while they completed their movement tasks. Figure 5 shows what the user field of view looked like while wearing the headset. In Figure 5, the user has highlighted the star Zosma with their pointer.

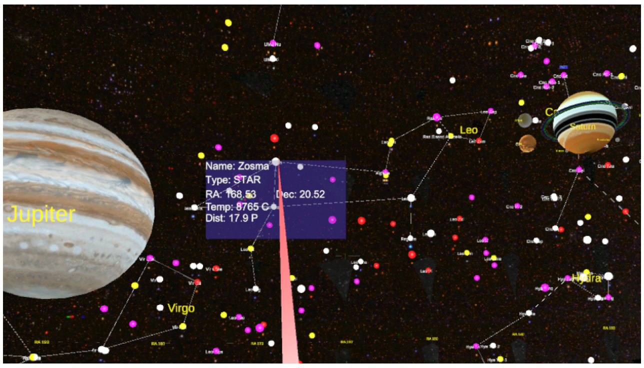

Figure 5: *User Point of View*

The virtual environment was written and implemented in the Unity development engine version 5.6.1. All scripts were written in the C# programming language and planetary textures were obtained from nasa.gov. Outer space pictures to put on the outer edge of the celestial sphere were retrieved from the Sloan Digital Sky Survey (`http://skyserver.sdss.org/dr12/en/home.aspx`) and were placed in their real-life coordinates on the celestial sphere. Proper labelling of stars and constellations came from David Nash's HYG Catalog at https://github.com/astronexus.

6. Hypotheses

Our experiment proceeded with the following hypotheses:

1. Adding vehicle-based acceleration/deceleration to on-rails movement will lower the motion sickness many users have felt with it.
2. Adding acceleration/deceleration to on-rails movement will thereby make it competitive in preferability with the more commonly-used teleportation method.
3. Teleportation will be a more efficient method to accomplish tasks in the user study but will have lower preferability scores than the other methods.
4. Free movement will be preferred to thruster-style spaceship movement (which is arguably more natural to the situation but also has the potential to cause more motion sickness) and teleportation.

Our user study asks which methods users prefer out of the different navigation methods and whether they can easily accomplish simple tasks that might be asked of them in an introductory astronomy assignment. Questions addressing motion sickness will be asked as well. To enable comparison with other work, the often-used SSQ developed by the United States Navy [RK93] will be used for all questions relating to motion sickness.

The user study will obtain preferability and motion sickness scores for five separate movement techniques:

1. Teleportation
2. On-Rails
3. On-Rails with Vehicle-Based Acceleration and Deceleration Applied at the beginning and end of transport (ORVM)
4. Free Movement
5. Free Movement based on Acceleration/Inertia

7. Procedure

User study sessions began with each participant signing an informed consent form and answering questions relating to exclusion criteria. To err on the side of safety, persons who were pregnant or had suffered a concussion within the last 14 days were excluded from this study.

The user session consisted of six separate five minute VR sessions. The first session would always be an introductory session that introduced the participant to the virtual reality environment and controls. Following this introductory session, the participant would take part in five separate five minute VR mini-sessions (one mini-session for each method listed above). The order of the mini-sessions were randomly selected to prevent (or at least even out) any cumulative bias on the part of the participant. Each mini-session featured the same series of tasks travelling long and short distances as well as moving between different types of astronomical bodies (small stars and larger planetary bodies).

Each task was given to the user as a signpost inside the virtual environment relative to the user's location and each destination object the user was supposed to travel to was highlighted by a translucent white sphere as shown in Figure 6. Upon touching the sphere, the user would be given a virtual signpost telling them their next destination (e.g. Travel to Jupiter) and the highlighted sphere would then highlight the next destination object.

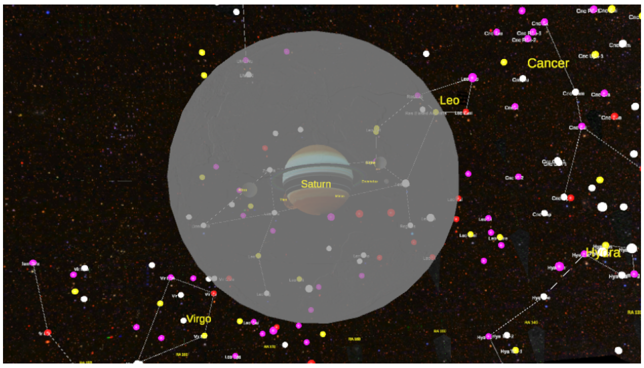

Figure 6: *Destination Highlighting*

Each five-minute mini-session was followed by a five-ten minute break to evaluate the participant's well-being and ask if they felt comfortable continuing with the study. During this break, the participant would fill out a quick motion sickness questionnaire about the movement technique they just finished. At the conclusion of the mini-sessions, the user would answer questions about user preferability between the different techniques.

In total, 19 participants (12 males, 7 females) participated in the user study. Sevety-nine percent of participants were university students or staff.

7.1. Nausea Metric

The SSQ (Simulator Sickness Questionnaire) [RK93] is a widely used questionnaire used to measure simulator and motion sickness so it was selected for use in this study. The SSQ places common motion sickness symptoms into one of three different categories (Oculomotor, Disorientation and Nausea) and measures each on a scale of zero - three, with zero meaning the user did not experience this symptom at all while three indicates severe symptoms. The Oculomotor and Disorientation categories are only relevant to simulators where users are subject to significant g-forces and were deemed not relevant to this study. Eliminating these two categories also significantly reduced the burden on participants, requiring them to only answer eight questions after every method.

This study uses the Nausea (N score) component from the SSQ with their eight symptoms: General Discomfort, Increased Salivation, Sweating, Nausea, Difficulty Concentrating, Stomach Awareness, Burping, and Disorientation. The original SSQ formula summed the symptom score scores and multiplied the total by a weighting factor of 9.54 when the N score was incorporated into the complete SSQ. This weighting factor is not necessary when there is only one category so raw counts will be used in this study without the weighting factor.

Two participants were not able to finish all movement methods due to intense nausea, resulting in an inconsistent number of questionnaires for each movement method. To account for this and allow for proper inter-method comparisons, the average N score per user for each method will be computed and referred to as N_{user}. This score, while helpful, is not enough to properly measure people's nausea level as one of the problems with people's nausea in VR is it varies widely from person to person [TW18] so an average score does not reflect the depth of nausea felt by those susceptible to it.

Previous work has not attempted to answer the "How much nausea is too much?" question. While that is undeniably subjective, we will introduce two metrics here to hopefully start a conversation about how to answer this in the future. If the user's N score was greater than 7, this would indicate the user averaged feeling at least a 1 in every area, a sign that the user was feeling nauseous and reacting negatively to the method. This metric will be labeled $N_{adverse}$ will be expressed as a percentage of the whole. Conversely, the metric $N_{NoEffect}$ will be expressed as the percentage of participants whose N_{user} was a 0 or 1 for the method, indicating that the user showed virtually no nausea symptoms while using a given method.

7.2. Preferability Metric

The six point Likert [Lik32] scale will be used (0 - 5) for user preferability ratings regarding the different movement techniques studied in this project. Three questions were asked separately per movement technique to enable comparisons between different techniques resulting in 15 total questions. The three basic questions were:

1. (Movement method) is my preferred method of travel.
2. (Movement method) is the most efficient method of travel.
3. (Movement method) is the easiest method to understand.

The Likert scale is commonly used in questions relating to opinion and preferability. Previous work [TW18] has typically focused on comparing two methods against each other where only one question would be necessary to elicit a response favoring one method or the other. Because five methods are being compared in this project, the methods must be queried separately in order to properly compare preferability scores.

When computing preferability using the Likert scale, there will be three different methods used here. $Pref_5$ refers to the number of times a user selected that method as being worthy of the maximum grade. $Pref_{top2}$ refers to the number of times the user selected the method as scoring a 4 or 5. $Pref_{total}$ is the total number of preferability points each method got if you added them all up across users. These are different ways to measure preferability and all should be fairly similar. Because there are five methods in this survey, the top2 method is intended to show methods that users responded favorably to but that were not their top choice.

8. Results

Applying the Friedman test to the Nausea score results indicated statistically significant differences between the movement methods so pairwise Wilcoxon tests were then applied. Figure 7 displays the results of this analysis and shows that ORVM was significantly different from the two methods that had the highest mean nausea scores (both free movement varieties). ORVM's highest nausea score was 5, less than half of any other method.

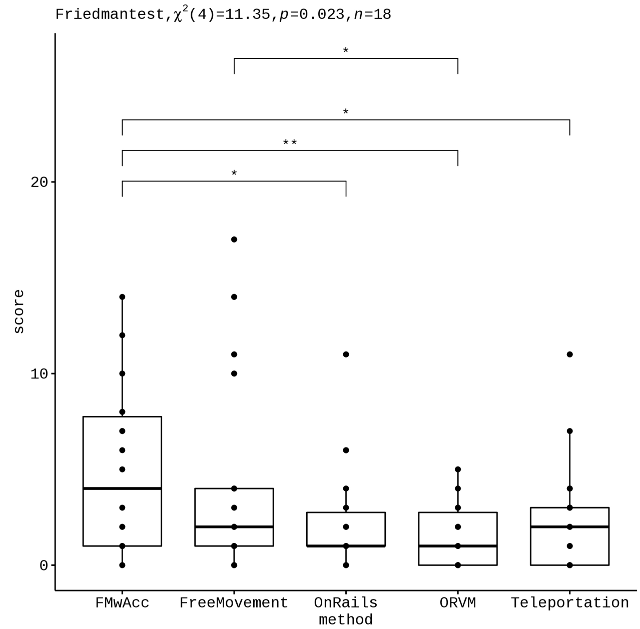

Figure 7: *Pairwise Comparison plot*

Figure 8 also shows that the Free Movement (Inertia) method was significantly different from all other methods. This method's high nausea scores demonstrate that this method was negatively viewed by participants, much more so than any other method. The large iqr range shows it affected participants in very different ways, making it undesirable for general use. The pairwise test was inconclusive when comparing other methods.

Table 1: *Nausea scores per Movement.*

Method	N_{User}	$N_{Adverse}$	$N_{NoEffect}$
On-Rails (ORVM)	1.61	0%	55.5%
On-Rails	2.2	5%	60%
Teleportation	2.37	5.2%	42.1%
Free Movement	3.89	21%	47.3%
Free Movement (Inertia)	6.00	31.6%	31.6%

Table 1 shows user's nausea scores (lower indicates less nausea) and allows evaluation of the first hypotheses of this experiment. Hypotheses 1 stated that "Adding acceleration/deceleration to on-rails movement will lower the motion sickness many users have felt with it." This was shown to be true as ORVM had the lowest average N_{User} of any method in the survey, surprisingly even beating teleportation which has typically earned the lowest nausea scores. The modification was also successful with those participants susceptible to nausea, with no users' nausea scores rising high enough to qualify as adverse.

Several users had issues with teleportation, calling it "weird" and consistently rating it as disorienting, one of the components going into the original nausea score. Our user study indicates ORVM feels very natural to people, as almost everyone has been in a vehicle of some sort where acceleration and deceleration are frequently experienced. As cited above [MU], [PK17], [FS07], motion feeling natural is crucial in lowering nausea scores and users felt less nausea with the ORVM introduced in this experiment than with every other method.

ORVM scored similarly to the standard on-rails method that only runs at a constant speed and has abrupt starts and stops. While on-rails' $N_{NoEffect}$ score was slightly higher, it is suggested that the lower nausea scores of ORVM shows that it should be considered in future studies.

Table 2: *Preferability scores per Movement*

Method	5MAX	4 or 5 (top 2)	TOTAL
On-Rails (ORVM)	4	9	53
Teleportation	5	8	52
On-Rails	5	6	44
Free Movement	3	4	36
Free Movement (Inertia)	2	5	30

Hypotheses 2 also dealt with our novel ORVM method, stating that "Adding acceleration/deceleration to on-rails movement will thereby make it competitive in preferability with the more commonly-used teleportation method." This was true as Table 2 shows Teleportation and ORVM had scores within one user of each other and even within one point of each other in the Total Points category. These results are competitive enough to make ORVM worthy of future study in fully three-dimensional environments.

Hypotheses 3 stated that "Free movement will be preferred to inertia-style spaceship movement (which is arguably more natural to the situation but also has the potential to cause more motion sickness) and teleportation." As shown above, the fear of this method causing motion sickness was well-founded. Hypotheses 3 turned out to be half correct, as free movement was preferred to free movement with inertia as stated in the hypotheses. The second half of the hypotheses was incorrect as free movement scored below both teleporation and on-rails. This is an important result because in two dimensional ground based environments, free movement has generally been preferred to teleportation. User's complaints about free movement mentioned the vast distances and generally uncluttered environment of space, factors which would also be present in an underwater environment. Space and underwater are the two most common types of fully three-dimensional environments, and their sparse nature makes free movement less appealing as there are vast distances to be traveled which require more effort from the user to traverse than either on-rails or teleportation.

Table 3: *Efficiency scores per Movement.*

Method	5MAX	4 or 5 (top 2)	TOTAL
Teleportation	12	13	65
Free Movement	2	2	29
Free Movement (Inertia)	2	3	25
On-Rails (ORVM)	2	8	51
On-Rails	3	6	45

Hypotheses 4 said "Teleportation will be a more efficient method to accomplish tasks in the user study but will have lower preferability scores than the other methods." The first half of this was true as teleportation was rated as most efficient by a wide margin as shown in Table 3, no doubt due to its taking far less time than the other methods due to its instantaneous transporting of people. The second half of this hypotheses was false as teleportation was virtually tied with ORVM in overall preferability.

9. Conclusion

If the experimental free movement with inertia method is omitted (exclusive to this paper), 21% of users studied here felt significant sickness effects with the free movement method and only 5% with other movement methods. Converting Weissker's SSQ scores to work with these metrics, we found 25% of users in that study qualified as feeling $N_{Adverse}$, which is a similar number and shows that the nausea figures in three dimensional environments are consistent with those in two dimensions.

While $N_{Adverse}$ is a new attempt to answer the question of "How much nausea is too much?, " the 25% in these studies is within the bounds of the commonly cited sciencenews.org range of 25-40% of users feeling nausea in VR. This corroborates previously cited studies that nausea in VR affects a minority of users but it is a significant percentage and these users can be severely affected.

The most surprising thing about this experiment was the strong performance of the on-rails method, especially with the modification introduced in this paper to add a realistic acceleration and deceleration to the start and end of the transition. This is surprising because most virtual reality products in recent years have used either teleportation or free movement (with and without field of view narrowing). Despite market trends, it is shown here that for fully three dimensional (6DoF) environments, our ORVM method scored better than teleportation in nausea metrics and was virtually tied with it in preferability.

ORVM causing overall less nausea than free movement was unexpected given that ORVM has an acceleration/deceleration component and free movement was at a constant rate. This is surprising because human vestibular systems are typically more sensitive to acceleration. One potential cause of this finding is that the constant linear rate of free movement was not actually constant if the user stopped all motion and then started again. Repeated occurrences of starting and stopping may have increased the nausea here.

Another potential cause is the unnatural motion involved with going from a full stop to a constant movement speed or the reverse. Other studies have shown that making movement seem natural is vital to reducing motion sickness so acceleration going from 0 to 20km/h with all speeds in between feels more natural than going 0 one microsecond and 20 km/h the next.

Free movement's poor showing in both nausea and preferability was surprising. Free movement gave people significantly more nausea than either on-rails or teleportation, something which previous studies had corroborated for the most part. Free movement in other studies scored high in preferability even though it caused some people nausea, something not seen here as both variants of free movement were significantly less preferred than the other methods seen here. Free movement has not been well studied in fully three-dimensional environments as most software written in such environments has users taking control of spaceships or airplanes and not doing 1:1 movement. This experiment shows that on-rails should be considered as an alternative or addition to teleportation in such environments and that free movement be tested thoroughly before being used.

The inertia variant of free movement should not be used again as it was statistically significantly different, the least preferred and the most nausea inducing of any method. Users had difficulty controlling it and the sensation of moving without any input was cited by users as causing significant nausea. Interestingly on-rails also has movement without input as the user doesn't do anything once the transition is triggered. Users said they found it easier to focus on other objects during on-rails than free movement with inertia which may help explain this result.

10. Future work

There are many opportunities for future work in movement methods for virtual reality. On-Rails with Vehicular Motion can be done many different ways using the general idea proposed here, that is simulating the motion of an automobile with gear shifting. Transition durations and speeds can be altered an infinite number of ways and future work could explore which settings would most accurately simulate vehicular motion. The settings used here were developed in informal testing but could benefit from further refinement.

Similarly, there are a near infinite number of ways to modify free movement. Adding vehicular motion to free movement when the user is stopped and starting to move or moving and wanting to stop is something that should be attempted as discussed in the conclusion. The constant speed can be altered as well. Results here show that using inertia to allow continued movement without user inputs is not worthy of future study.

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