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# Exploration of comfort factors for virtual reality environments

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## Abstract

*The democratization of virtual reality with head-mounted displays has brought a tremendous number of possible applications. However, depending on the used content and device, the user's quality of experience (QoE) and comfort may be significantly altered. It is thus very important to understand and model the factors involved in this process. Many authors investigated the potential aspects leading to sickness or discomfort in immersive environments, each of them targeting a set of specific factors (often a single one). Our goal in this paper is to understand how QoE and comfort are impacted by the virtual environment, observer's motion, scene complexity and rendering quality, based on psychophysical experiments. Our study starts by identifying a set of factors potentially affecting QoE. A reliable and reproducible experimental protocol is proposed to characterize their impact on the user. Base on a statistical study of the results, a better understanding of the nature of impact is achieved.*

***Keywords:*** *Discomfort, Virtual reality (VR), Quality of Experience (QoE), Psychophysics, Unreal Engine*

## Introduction

Even though virtual reality (VR) tools are becoming mainstream, with head mounted displays (HMDs) made available for the general public to an affordable price, long sessions in VR are still problematic for various reasons (motion sickness, eye fatigue, screen door effect, etc.). Yet, industrial applications target VR technology (gaming industry among others) where the user is given visual stimuli that may deteriorate rapidly the user experience, possibly even leading to sickness. One should then tread carefully when creating VR content to avoid such complications. In that regard, being able to know at the production stage the amount of discomfort VR content is likely to produce seems like a must-have.

In this study, we stand in the context of 3D virtual environments generation for virtual reality, which brings up other potential problems to tackle compared to 360-degree content, namely the compromise between rendering quality and performance. Being able to create one's own virtual environment that can be explored in real-time $360^o$ has become more accessible, with the emergence of video game engines such as Unity, Unreal Engine or CryEngine to name a few. The rendered visual quality has also greatly improved with such displays. However, HMDs are very demanding in terms of performance compared to more traditional displays, seeing as they require to compute a $360^o$ view for each eye. Hence, a good trade-off must be found between virtual environment visual quality and performance to provide a viable experience, especially with these immersive displays.

In that context, our study looks at understanding what drives the perceived quality of experience (QoE) on a general scale, with a focus on parameters that lead to sickness, and on the impact of the rendered scene quality. This study should heighten content creators awareness on which visual element is most important in VR real-time rendering to ensure comfortable experience to users. More precisely, the main contributions of this paper are the following:

- Study of the main factors that may be identified as having an influence on QoE;
- Design of a psychophysical experiment for evaluating the impact of each factor on the user in terms of various items ranging from discomfort to perceived scene quality, with a wide variety of virtual environments;
- Statistical analysis of the gathered user assessments, driving several important conclusions and advice that could improve QoE.

This paper starts with a review of the work most related to this topic, it then describes the experimental protocol and the study we conducted. An analysis of the obtained results is followed by discussions for further developments.

## Related work

Since we are talking about QoE in general when exploring real-time rendered virtual environments, we will not only focus on simulator sickness, an inherent problem of immersive displays, but also on the virtual environment rendered quality.

### *Simulator Sickness*

Several authors have conducted experiments for studying sickness with HMDs [1], including various aspects:

- **Content-related**: Rotational speed [2, 3, 4, 5], translational speed [6, 4, 7], content FoV [8], depth [4], oscillations [9, 10], peripheral movement [11, 12];
- **User-related**: Head movements [13], eye movements [14], postural stability [15, 16], human factors [17];
- **Hardware-related**: Latency [18, 19], Headset FoV [20], vergence-accommodation conflict [21].

Each of them has an impact on user-experience individually, but it could potentially get worse when combined.

Amongst the aforementioned factors, studies investigated the impact of translational or rotational speed, providing insights on the navigation parameter thresholds. Nevertheless, one cannot build a predictive model on top of these conclusions because they may *(i)* be outdated [6, 22], *(ii)* use other equipment than HMDs [7], *(iii)* not decorrelate the parameters [6] or *(iv)* use abstract visual stimuli [3, 5]. Although previous works investigated numerous factors, separately in most of them, it is still difficult to quantify quality of experience for immersive applications, especially at the content production stage. To the best of our knowledge, no general metric or measure exists for this purpose.

### *Virtual Environment Quality*

The quality of a virtual environment depends on several aspects:

- The intrinsic scene quality (geometric models, textures, lighting, etc.)
- The rendering quality (display methods, aliasing, shadows, light computation, etc.)

Each of these aspects being demanding in terms of computational power, it can become quite cumbersome to find a good compromise between visual quality and performance for VR.

Improving the overall visual quality of virtual environments is something people typically strive on when trying to fully immerse the user with such immersive displays [23]. When it comes to VR, a lot of work is still to be done to try and find ways to improve visual quality within what is possible with current technologies [24, 25]. Seeing the state of things now, we can say that the quality of virtual environments has greatly improved over the years, making it sometimes almost photo-realistic experiences [26] with current video game engines. Such tools are constantly being improved over the years to achieve better visuals all the while keeping it viable in terms of performance [27].

Some studies even have tried to look at the impact of graphical realism on cybersickness [28, 29], showing that visual quality of rendered environments is something worth looking into as potentially either improving or deteriorating the user's overall QoE.

Based on existing studies, we identified important parameters to assess the overall quality of a VR experience using an HMD. We did not only select known factors (translational and rotational speed) to evaluate and avoid motion sickness, we also studied visual quality and thus decided to also take into account parameters regarding rendering quality of the virtual environment (textures, shadows, draw distance, antialiasing).

An important contribution of this work lies in setting up a thorough protocol to evaluate the impact of each of these factors on user's comfort and QoE. Based on experiments following the said protocol, we were able to assess each factor's impact separately and combined with one another.

## Method

Our method aims at determining the main factors that may impact the user experience. Therefore, we have defined several types of scenes, including user motion, and various types of rendering quality. The experimental protocol relies on the following.

### *Stimuli*

We based our work on two statements: (i) factors have been identified in the literature as leading to user discomfort, and (ii) they can be measured in real time inside the game engine. Out of this, two important categories of factors have to be considered as influential on the overall quality of a VR experience [6, 30, 3, 26, 29]:

- **User's motion**: Translational speed (m/s) and rotational speed (°/s);
- **Rendered quality**: Textures, shadows, antialiasing, draw distance, etc.

We measured the impact of these factors based on an experimental protocol aiming to obtain mean opinion scores from users.

For that purpose, a total of 6 different virtual environments were created, as scene-independent as possible (see Figure 1). In the next sections, we will refer to them as Australia, Bridge, Downtown, Factory, Forest and House.

Figure 1: Virtual environments built for the study. Top: Australia, Bridge, Downtown; Bottom: Factory, Forest, House.

For each virtual environment, we set up two locomotion scenarios (with a variety of speeds, for both translation and rotation), avoiding critical values identified in the literature [6, 30, 3, 5] as creating irreversible motion sickness, for preventing premature abort of the experiment. A stimulus consists of 4 parameters: (i) the chosen scene, (ii) a rotation or translation, (iii) its associated speed, (iv) a rendering quality. Translational and rotational speeds are chosen amongst 4 possible values (respectively 3, 6, 10, 15 m/s, and 10, 15, 20, 25 °/s). The rendering quality is chosen amongst Epic, High, Medium or Low. All the possible configurations lead to a total of 160 stimuli.

We have chosen to avoid motion configurations that surely lead to observers sickness (*e.g.* going faster than 6 m/s in small closed environments), but the selected values have been managed to still get close to the limits in order to evaluate the observer quality of experience variations. More precisely, with translations the user is virtually placed on a straight rail at one of the four studied translational speeds. With rotations, the user is placed on a rail that follows 90-deg turns moving at a constant translational speed of 6 m/s (the default speed in the engine). The targeted rotational speed determines in this case the curvature of the turn. Each stimulus, both for translation and rotation, lasts for 20 seconds. See figure 2 for a visual representation of such motion paths inside the game engine.

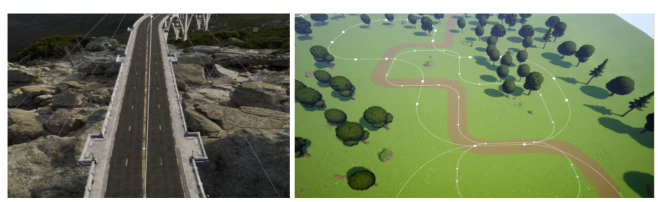

Figure 2: Examples of motion paths followed for the two types of stimuli, respectively translation (left) and rotation (right).

3D engines propose a wide variety of parameters that can be combined in order to find the best compromise between performance and visual quality (textures resolution, resolution scale, shadows, depth management, antialiasing, post-processing, etc.). General quality levels are also provided, setting all of these parameters values at once. Although it would be interesting to look into each of them individually, the number of virtual environments and stimuli already provide a considerable number of experiences.


(a)

(b)

Figure 3: (a) Available options inside the game engine to tweak quality parameters ranging from resolution scale to shading. (b) Comparison of two quality levels inside a virtual environment (Australia), namely Epic (left) versus Medium (right).

We thus decided to use these general quality levels to have a manageable combination between speed and rendered quality levels. Note that low quality rendering tends to produce flickering effects, low resolution textures, aliasing, or missing shadows, while high quality rendering requires computation time potentially inducing jerkiness and display lag. A visual representation of said quality levels is provided in figure 3.

The observers are proposed two types of sessions: those with translations only and those with rotations only, each session requiring about 20 minutes to complete. In total, a set of 16 stimuli is provided for a session (4 speeds, 4 rendering quality levels). For a typical experiment, candidates go through two sessions, one for translation, and one for rotation. The whole procedure also includes a training session and other tasks (visual acuity test, filling questionnaires, etc.), which can take up to one hour per participant in total. The next sections detail the whole procedure.

## Questionnaire

To evaluate the global QoE, we have chosen several types of recurrent questions to ask after each stimulus: (i) General questions to have the user's overall opinion on the stimulus or the scene, (ii) questions regarding the user's comfort and (iii) questions regarding the rendered scene quality. The following questions were asked to the candidates:

- Rate the quality of experience.
- Rate the quality of the scene details.

Both of these questions were answered using a 5 items Likert scale: Poor/bad/Fair/Good/Excellent.

- Have you experienced discomfort?
- Have you experienced fatigue?
- Have you experienced dizziness?

These questions were answered using the following 5 items Likert scale: Not at all/slightly/Moderately/Strongly/Severely.

A sixth question was asked to discriminate which quality parameters stood out as being more annoying to the user:

- Which scene element(s) was(were) annoying?

Standing as multiple choice questions, the candidate could chose one or several answers among these: Flickering, Shadows, Textures, Draw distance, Jerkiness, Motion speed, None of them, All of them. If the candidate had chosen one of the first 6 items, he had then to define a level of annoyance ranging from 1 (slightly annoying) to 5 (extremely annoying) associated to the chosen element to really assess what element stood out.

In order to avoid having users focusing too much on their discomfort, a random general knowledge question could be added with the rest of the series, although not after each stimulus to keep it a random event.

All the aforementioned parameters and questionnaires were implemented using the game engine so that the user could keep the HMD for the whole duration of the experiment. They used a controller to answer all of these questions inside a virtual environment made for that purpose in between each stimulus.

Aside from these questions during the experiment, candidates filled out a Simulator Sickness Questionnaire [31] before and after each translation or rotation session.

## Procedure

Subjects began the experiment by going through the Freiburg Visual Acuity Test [32], their score indicating if they could participate in the experiment (a minimum score of 1 was required). They would then go through the Ishihara test [33] to check their possible color blindness.

We then had them fill out a general information form about various items, ranging from gender to having previous experience with VR, followed by a pre-experiment Simulator Sickness Questionnaire (SSQ).

This was followed by a training session of about 15 minutes where they got used to the quality degradation and motion scenarios they would witness during the experiment. We also took the time during this training session to explain the questions they would have to answer after each stimulus while they learned how to do so with the controller.

After the training session was done, candidates went through a translation session of roughly 20 minutes where they would witness 16 stimuli (8 if they were in the House or Downtown scene, deemed too small to run the whole set of translational stimuli) while having each time to answer the 6 questions described above.

After this first session, they had to fill out another SSQ followed by a 10 minutes break.

After the break, they went through a second session implying rotational motion (again, for about 20 minutes). We ended the experiment by letting them fill out a third SSQ.

### *Apparatus*

We used Unreal Engine to run our experiments, creating 3D environments based on freely available assets at our disposal, obtained either from the unreal engine marketplace or from partners in the project. For both experiments, the user was seated on a chair while wearing the HMD (an HTC Vive Pro), with a controller in his hand used to answer questions. Data processing and statistical analysis were performed in python using libraries such as numpy, pandas or statsmodels.

## Subjects

Because of the high number of configurations, each candidate could not go through all of them. When participating in the experiment, each candidate typically went through 2 configurations. Across all of them, we managed to get a minimum of 12 full evaluations. Candidates age ranged from 19 to 55 with an overall mean of 27. All subjects had normal or corrected-to-normal vision according to the Freiburg Visual Acuity Test. Only one candidate turned out to be color blind after passing the Ishihara test. Subjects were free to terminate the experiment at any moment in case of severe sickness. None of them had to quit the experiment prematurely.

## Results

Seeing as our questions were likert items ranging from 0 (Not at all/Very bad) to 4 (Severely/Excellent), we ran Kruskal-Wallis tests for non-parametric data with each question results as dependent variables against the aforementioned factors. These tests were followed by post-hoc analysis using Mann-Whitney U tests with the Holm–Bonferroni method to identify significantly different factor levels.
The same reasoning applies to the multiple choice question discriminating which scene elements were annoying as it translates, for each element, to a Likert item ranging from 0 (the element was not selected) to 5 (the element was selected and defined as extremely annoying).
For SSQ results, one-way ANOVAs were run on the scores difference between the questionnaires obtained before and after each session.

### Speed

Focusing on the impact of speed, Kruskal-Wallis tests revealed that it had a significant impact on dizziness [$H(3) = 12,4457$, $P = 0,006$] for rotational stimuli and on both discomfort [$H(3) = 10.221$, $P = 0.01$] and dizziness [$H(3) = 24.81$, $P = 1.e^{-05}$] for translational stimuli. Post-hoc analysis with Mann-Whitney U test revealed for rotation that both 25°/s *vs.* 10°/s [$P = 0,03$] and 25°/s *vs.* 15°/s [$P = 0,03$] were significantly different when looking at Dizziness. As for translation, both 15 m/s *vs.* 3 m/s [$P = 5.e^{-06}$] and 15 m/s *vs.* 6 m/s [$P = 0.008$] were deemed significantly different when it came to dizziness while only 15 m/s *vs.* 3 m/s stood out for discomfort [$P = 0.01$]. Overall, the highest speed value happened to lead to either more dizziness or more discomfort in comparison to lower values.
Having a look at figure 4, we can see an overall trend occurring for translation stimuli where increasing speed seems, to increase overall discomfort and dizziness for all quality levels except low. Although the effect is fairly limited due to experimental design, we can see such a tendency occurring, with the highest speed standing out as being more problematic.

### Quality level

Looking now at quality level, Kruskal-wallis tests revealed that it had a significant impact on most question results, namely: Discomfort [$H(3) = 196$, $P = 2.e^{-42}$], Dizziness [$H(3) = 8.47$, $P = 0.03$], Fatigue [$H(3) = 39.4$, $P = 1.e^{-08}$], Experience quality [$H(3) = 434$, $P = 8.e^{-94}$] and Scene quality [$H(3) = 616$, $P = 2.e^{-133}$]. Overall, post-hoc analysis revealed that Low and Medium stood out in comparison to High and Epic (typically for Low *vs.* Epic on discomfort [$P = 6.e^{-28}$]). Visually speaking, we can see on figure 4 that a clear tendency can be drawn where lowering quality level increases discomfort quite significantly.

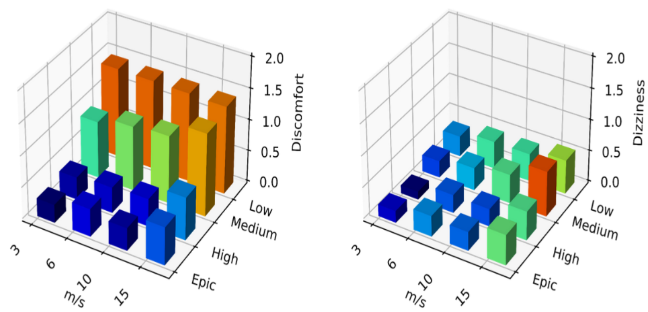


Figure 4: 3D bar plots evaluating the impact of speed and quality level on both discomfort and dizziness.

Focusing on content related parameters ranging from flickering to motion speed, quality level was significantly impactful on: Flickering, shadows, textures and draw distance (with a particularly important impact on flickering [$H(3) = 684$, $P = 5.e^{-148}$]). For most of them, post hoc analysis revealed that Low and Medium stood out against High and Epic.
The impact on jerkiness is less consistent though, as rotational stimuli implied that higher quality levels lead to jerkiness being more often selected as annoying (Post hoc analysis on Low *vs.* Epic [$P = 0.002$]) while it was less clear for translational stimuli (not significant both in general with Kruskal-Wallis and in post hoc analysis).

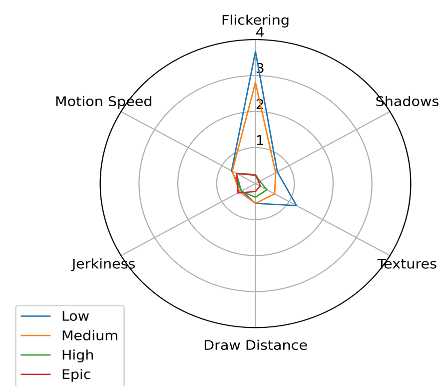


Figure 5: radar chart analyzing the impact of quality level on various content parameters.

Looking at figure 5, one can see which scene element was deemed more annoying depending on the quality level. As it turns out, flickering stood out as being the most prevalent effect, although others were still worth taking into account (for example jerkiness or motion speed with higher quality levels).

### Scene

Depending on the scene candidates were in for the session, a comparable speed or quality level did not have the same impact on question results. We split up translation scenes and rotation scenes to compare them individually. For rotation scenes, it seems like the scene component had a significant impact overall on all question results (typically for discomfort [$H(4) = 42$, $P = 3.e^{-09}$]). Post hoc analysis revealed that Australia stood out as being more

problematic on all aspects (typically for Australia *vs.* House on discomfort [$P = 7.e^{-10}$]).
For translation scenes, the scene component had a significant impact on all question results except motion speed (typically for discomfort [$H(5) = 39$, $P = 1.e^{-08}$]). Post hoc analysis revealed that Forest and Downtown were overall less problematic against other scenes (typically for Downtown *vs.* Bridge on discomfort [$P = 3.e^{-09}$]).
However, SSQ results did not reveal strong statistical significance based on the scene component.
One can see for example the difference between translation scenes on figure 6 where Australia, Bridge or House stand out as leading to higher discomfort for an equivalent speed or quality level in comparison to other scenes.

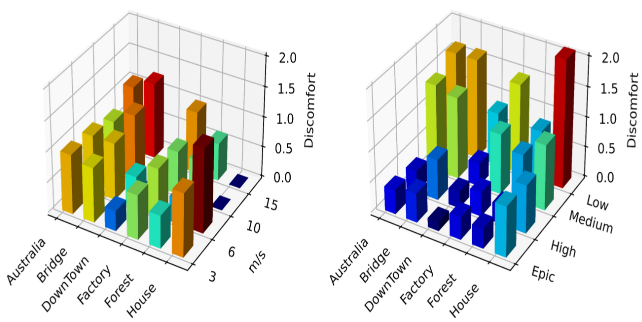


Figure 6: 3D bar plots evaluating the difference in discomfort scores between scenes per speed (left) and quality level (right)

Figure 7 illustrates the difference in chosen annoying elements depending on the scene when quality level is set to Low. Looking at it, although flickering is consistently deemed most annoying across scenes, one can see that other parameters are more or less prevalent based on the virtual environment. For example, we can outline the fact that motion speed was annoying in House, a small indoor scene, whereas shadows and textures were more of an issue with Australia, a wide open natural area populated with trees.

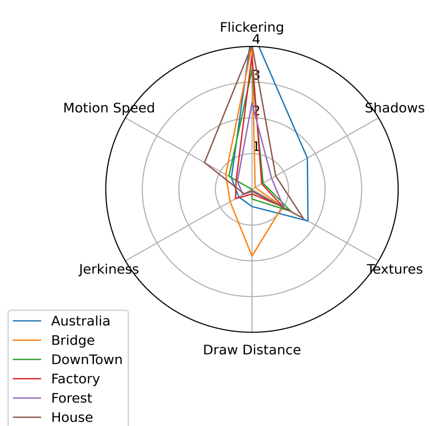


Figure 7: radar chart analyzing the impact of the scene component on various content parameters when quality level is set to Low.

## *Type of motion*

Comparisons were done between rotation and translation session results. Doing so, it revealed that the type of motion was indeed significantly impactful in this study on most question results: Discomfort, Dizziness, Fatigue, Experience quality and Scene quality (typically, Mann-Whitney for discomfort [$P = 0.002$]). In our case, Translational stimuli happened to be a bit more problematic than rotational stimuli.
Looking at SSQ results especially, we were able to identify the same trend where overall scores were higher after translation sessions on both sub-scores (nausea [$F(1,144) = 5.4$, $P = 0.02$], oculomotor [$F(1,144) = 7.5$, $P = 0.006$], disorientation [$F(1,144) = 7.8$, $P = 0.005$]) and total scores [$F(1,144) = 9.2$, $P = 0.002$] with Figure 8 illustrating this phenomenon.
However, even if translation sessions were more provocative, overall sickness scores were still reasonable.

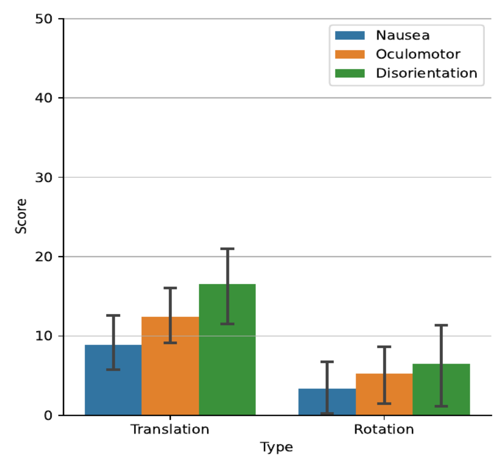


Figure 8: Comparison of SSQ sub-scores results after a translation or a rotation session.

## *Duration effect*

A duration effect of the experiment on candidates results was also assessed. Knowing that candidates had to go through 16 stimuli per session, they watched each speed and each quality level 4 times in total. We thus took into account for each stimulus the number of expositions to the said speed or quality level.
Doing so, we found that the number of expositions was mostly significant on Fatigue, both for speed [$H(3) = 31$, $P = 5.e^{-07}$] and quality levels [$H(3) = 39$, $P = 1.e^{-08}$]. Setting aside a natural tendency of increasing fatigue with the number of expositions, this increase was steeper with more problematic stimuli (namely high speed or low quality level). This phenomenon can clearly be outlined in figure 9. It implies that problematic stimuli of our study did have an impact on the user's overall fatigue accumulation.

# Discussion

The results of the current study suggest a lot of different remarks: First of all, speed, although being fairly limited in this study due to experimental design, revealed to lead to an increase in dizziness and discomfort. The highest speed value stood out in particular. It is fair to notice that this effect is less clear once one gets to the lowest quality level, surely because the discomfort

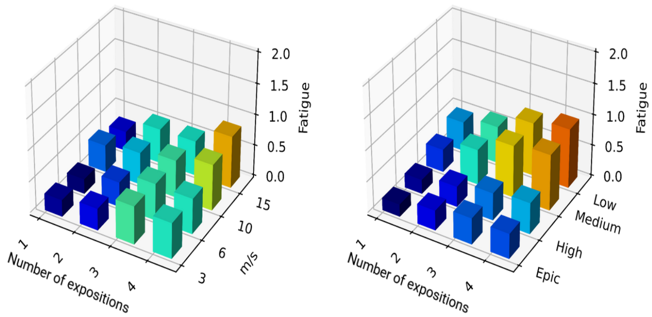


Figure 9: 3D bar plots evaluating the difference in fatigue scores based on the number of expositions to speeds (left) and quality levels (right).

brought by lowering rendering quality becomes stronger than the one brought by navigation speed. It means that, under a certain quality threshold, navigation speed loses part of its provocative effect.

Rendering quality seems to have a strong impact on user's overall QoE, meaning that one should be careful when lowering overall quality as it could make the simulation almost unbearable in VR. This is not surprising considering how strong the quality degradation is when one gets to levels such as Medium or Low. Seeing as flickering stood out as being the most annoying parameter in all cases, one should then be careful when lowering anti-aliasing quality in a simulation intended for VR. However, it would be interesting to see if other quality parameters become more problematic once you remove the aliasing issues, since it might have hidden other effects by being the most prevalent one.

Scene composition is also worth taking into account. Both the arrangement of assets in the scene and the atmosphere or type of environment (outdoor with wide open spaces, indoor with deem lights, etc.) can explain that effect. The former can lead to increased effects of navigation speed due to the relative distance to objects when moving. The latter can change the overall effects of quality degradation (e.g. having to render far away objects in open areas can lead to higher flickering effects when lowering rendering quality whereas small indoor scenes would present more aliasing issues on straight structures). The next step of this study would be to measure this effect to assess what quality parameter could alter user's QoE based on the current environment.

Lastly, rotation was deemed less problematic than translation, something a bit counter intuitive as we would have expected the opposite phenomenon. This difference should be taken cautiously since we chose rotational speed values a bit further away from identified problematic values from the literature in comparison to translation. This design choice was motivated by fear that rotational stimuli would be more likely to provoke simulator sickness. It could be interesting to do a similar study by pushing rotational speed values up to see if this difference still stands then. Candidates also noted a more prevalent vection effect (sensation of self-movement) with translational stimuli during the deceleration phase at the end of each stimulus, being more noticeable in those sessions in comparison to rotational stimuli where translational speed was constant and reasonable.

## Conclusions and future work

Based on the results of this study, some interesting conclusions can be drawn:

- Navigation speed, even though having a limited effect, leads to an increase in discomfort and dizziness;
- Translational stimuli were deemed a bit more problematic in our case, potentially due to the acceleration and deceleration phases being more noticeable in the former;
- Rendering quality had a significant impact on user's comfort, with flickering being the most prevalent effect;
- Scene composition is a factor worth taking into account when assessing user's QoE.

We thus plan to further study these parameters, with the goal to propose a predictive model, that could be interactively employed during a VR experience. Our final goal is to get upstream of the content production workflow and propose a solution to predict the Quality of experience that could be generated by such VR contents.

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- Automotive Bridge by Epic Games
- Downtown West by PurePolygons
- Factory Environment Collection by Denys Rutkovskyi
- Stylized Forest by TomkaGS

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