Velocity-Based LOD Reduction in Virtual Reality: A Psychophysical Approach

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Abstract

Virtual Reality headsets enable users to explore the environment by performing self-induced movements. The retinal velocity produced by such motion reduces the visual system's ability to resolve fine detail. We measured the impact of self-induced head rotations on the ability to detect quality changes of a realistic 3D model in an immersive virtual reality environment. We varied the Level of Detail (LOD) as a function of rotational head velocity with different degrees of severity. Using a psychophysical method, we asked 17 participants to identify which of the two presented intervals contained the higher quality model under two different maximum velocity conditions. After fitting psychometric functions to data relating the percentage of correct responses to the aggressiveness of LOD manipulations, we identified the threshold severity for which participants could reliably (75%) detect the lower LOD model. Participants accepted an approximately four-fold LOD reduction even in the low maximum velocity condition without a significant impact on perceived quality, suggesting that there is considerable potential for optimisation when users are moving (increased range of perceptual uncertainty). Moreover, LOD could be degraded significantly more (around 84%) in the maximum head velocity condition, suggesting these effects are indeed speed-dependent.

CCS Concepts

• ***Computing methodologies*** → ***Perception;*** *Virtual reality;*

1. Introduction

Real-time rendering in Virtual Reality Head Mounted Displays (VR HMDs) requires extensive computational resources. One approach to ameliorate this focuses on exploiting the characteristics and limitations of the Human Visual System (HVS). Here we focus on changes in sensitivity that relate to the self-induced movement of the observer and lead to global patterns of motion on the retina.

Most HMDs allow tracking of user movement with 6 Degrees of Freedom (6DOF) and present the visual stimuli that would accompany such movement. Users often produce fast head movements when interacting with the environment which create movement on the retina. The relationship between movement and sensitivity to the visual consequences of that movement is complex, depending on visual features in the display as well as the types of movement and task undertaken. However, there is evidence of reduced temporal and spatial sensitivity during movement [Mur78] and that the HVS's sensitivity is altered when there is global motion on the retina resulting from observer eye/head movements [BSG17]. The extent to which the complexity of a scene can be reduced, based directly on the velocity of the self-induced movement, as well as the perceptual methods required to address this question have not been explored before. In this paper, we propose a method and experimental framework for exploring the feasibility of a velocity-dependent scene-complexity reduction algorithm in a commercial VR HMD. In order to achieve this, we degrade the geometrical LOD of a stimulus as a direct function of self-induced velocity independent of any other properties of the HVS. The contributions of this paper are:

- We test the feasibility of a lightweight method that only uses velocity as a metric for guiding LOD degradation (i.e. agnostic to other properties of the HVS). Thus, pre-generated LOD levels attached to most virtual objects can be used in more ways than just based on distance from the viewplane.
- Using psychophysical methods, we clearly demonstrate that self-induced horizontal head rotations allow a significant (approximately four-fold) degradation in LOD for a well-lit model.
- We provide evidence that the level of degradation tolerated by users increases even further for faster movements, suggesting these effects are speed-dependent.

2. Related Work

Previous research has investigated how the limitations of the HVS can be used to guide algorithms by detecting potential rendering ar-

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tifacts. Yee et al. proposed a model exploiting properties of the human spatio-temporal sensitivity function using motion estimation [YPG01]. Models that predict the quality of motion in a velocity-dependent way account for movement artifacts [DJMM20], and others that use variable shading to model masking of degradation artifacts due to motion [YZK*19] were also implemented. Velocity-driven LOD methods have received less attention in recent years. Reddy et al. [Red01] studied the sensitivity to LOD degradation by taking into account the eccentricity and velocity of the object in simple stimuli. Similar models with LOD selection algorithms based on kinetic vision were studied by Oshima et al. before[OYT96]. Parkhurst and Niebur [PN04] also explored the impact of LOD degradation in search task when rotational movement is present. Although these methods study the impact of velocity of objects, they do not explore the independent effect of velocity generated by ego-movement.

3. Methods

In our experiment, participants were asked to track a fixation point by performing yaw rotations of the head while simultaneously judging the quality of two models presented sequentially in different intervals. One of the intervals always contained the reference (maximum LOD) model for the duration of the interval and the other contained the same model, but with LOD degradation (varying in severity from trial to trial) applied whenever rotational head velocity exceeded a fixed threshold. The participant's task was to identify the interval containing the degraded model. This is referred to as a 'two-interval forced choice' (2-IFC) procedure, which is used to investigate perceptual characteristics [KP16]. We used a HTC Vive HMD with a wireless receiver to display tethered content from the PC (Intel i7-7700K CPU and NVIDIA RTX 3080 Ti GPU). The HMD and receiver have a refresh rate of 90 Hz. The resolution is 1080 x 1200 pixels and the experiment ran at 90 FPS.

3.1. Design and Stimuli

To measure the impact of head speed on a participant's ability to perceive LOD changes we manipulated maximum user head *speed* as an independent variable with two levels (*Fast* and *Slow*). We used a fully within-participants design, meaning all participants took part in both conditions. For each of the two speed conditions, participants undertook 280 trials for which the severity of the LOD degradation applied (here termed 'aggressiveness') was varied over a range of seven pre-determined values. For each aggressiveness level participants repeated the same number of trials. This approach is commonly referred to *as the Method of Constant Stimuli* [KP16].

A moving fixation cross, which participants were asked to track, was presented on each trial (illustrated in the top left panel of Figure 1). The cross occupied around 2x2 degrees of the visual field. The fixation point moved in the virtual environment on a fixed radius circular trajectory centred on the participant's head and with a range of 100°(i.e. 50°to the left and right of straight ahead). The radius was given by the distance between the participant and the statue, which was 5m in virtual space. The angular velocity of the fixation cross (relative to the head) was sinusoidal (Figure 2). In the *Fast* condition, the velocity peaked at approximately 157°/sec and in the *Slow* condition at around 52°/sec. The *Slow* condition velocity was chosen to be in the range used by Jindal et al. [JWMM21]. We chose the considerably higher *Fast* condition velocity because other studies report rotational velocities of up to 300°/sec [HCZX10].

The primary stimulus was an environment-stationary model of a statue. The model was presented in the default Unity scene in a well-lit environment (Figure 1).

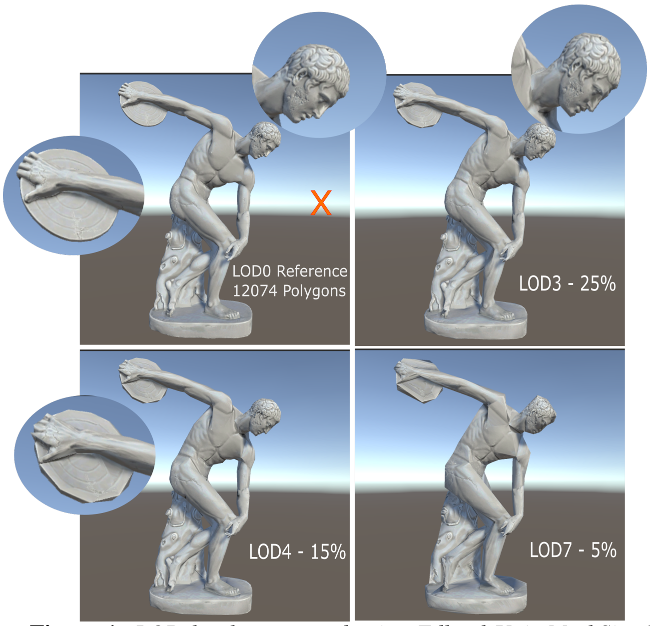

Figure 1: *LOD levels generated using Edlund UnityMeshSimplifier.*

The LOD degradation process applied to the statue model was an adjusted version of the quadric metric mesh simplification. The algorithm acts to reduce the number of polygons of the mesh and was adapted to enable speed-dependent application such that the LOD degradation is implemented once a minimum threshold user head speed was crossed (50% of maximum velocity for fixation). Degradation was applied at one of the seven levels of aggressiveness (50%, 25%, 20%, 15%, 12.5%, 10%, 5%) detailed in Figure 1. These represent the percentage out of the initial number of polygons. The reference model was composed of 12074 polygons and in the most aggressive LOD condition, this was reduced by a factor of 20 to around 600 polygons (see supplement). When the rotational velocity of the head reached 50% of the peak velocity of the fixation point, the quality degraded. This meant that the quality of the statue was reduced for around half of the number of frames when the participant moved their head. Therefore, the participants saw the stimulus in both intervals (reduced and reference) in their peripheral and foveal vision. As the motion was the same in both intervals, the quality judgement could occur based on either input. This also minimised the effect of eccentricity on judgements.

As seen in Figure 2, by plotting the horizontal angular displacement of a participant during a trial, the sinusoidal velocity trend of the fixation point is matched, which gave us confidence that the intended head rotational velocity was achieved in the trials.

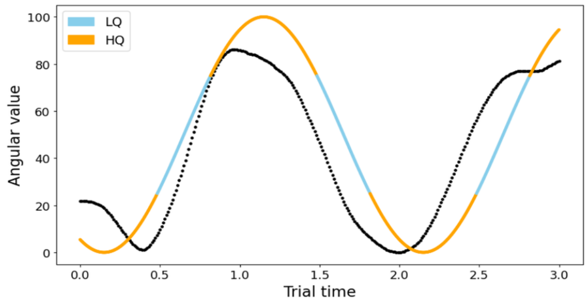

Figure 2: *The angular position of a participant's head sampled during the trial (black) mapped against the angular position of the fixation target. Points at which the stimulus changed LOD are highlighted in orange and blue.*

3.2. Procedure

Seventeen participants were recruited; 15 were naive to the purpose of the study whereas 2 had expertise in using VR. The study was approved by institutional ethics and written consent was gathered. Participants were given time to acclimatise to the VR environment and monitored for dizziness or nausea. Practice trials were conducted before starting the experiment to maximise data quality. The participant's position was then aligned with the mid-sagittal plane of the statue. Two participants were excluded because their data appeared random across aggressiveness levels and could not be fit reliably with the psychophysical model.

Each trial contained of two intervals (each 2.5s) in which the participant tracked the fixation point by rotating their head. The intervals contained either the reference or the LOD reduction condition and the order was randomised. Their task was to identify whether the reference was in the first or second interval.

Over the course of the experiment, each participant provided 40 responses for each of the 7 possible pairs of reference and LOD models. In addition, we interleaved trials for the fast and slow maximum head velocity conditions. Participants provided 280 responses in total. In order to prevent fatigue and nausea, data collection was separated into two blocks in different days and participants were allowed to take breaks whenever they needed.

Psychometric Function Fitting To analyse the data we used a psychometric function (PF) [KP16] approach for each participant and condition (Figure 3). We plotted the LOD values against the proportion of correctly identified intervals (out of 40 repeated trials). The proportions obtained should vary between around 50% correct (chance performance) for a small LOD degradation and 100% correct for large levels of degradation, and follow an ogive shape reflecting the accrual of more evidence as LOD degradation severity increases. A PF represents a model of how observer perception changes as a function of some physical parameter (here the LOD manipulation). We used a cumulative Gaussian with two free parameters (mean and standard deviation) as the psychometric function model. Fits to the data using this model were obtained using the *quickpsy* package [LL16]. From these fits (Figure 3), we recovered the threshold LOD value which resulted in 75% performance [KP16]. This threshold parameter reflects the LOD value for which participants can reliably distinguish the reference from the degraded stimulus. Our hypotheses would be confirmed if the thresholds observed are high and increase as a function of maximum head velocity.

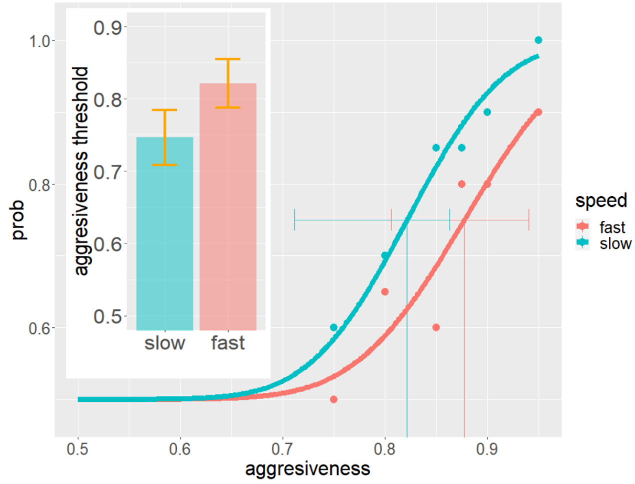

Figure 3: *Bar plot showing the mean threshold values at the 75% point (Left - Embedded). Example psychometric functions recovered from one Participant. Fast - in red; Slow - in blue*

4. Results

Based on the function fitting, we recovered PF statistics for each participant in each condition. The embedded plot in Figure 3 (left) illustrates the mean thresholds calculated over the 15 participants in this experiment for the *Slow* and *Fast* maximum head velocity conditions. Note that even in the *Slow* condition the LOD degradation tolerated by participants before they can reliably identify the interval containing the degraded model is 74.6% (s.d. 14.8). This corresponds to almost a 4-fold reduction in the number of polygons (note the LOD% metric tends to be qualitative). Importantly, this threshold appears to be higher for the high maximum head velocity condition. The threshold in the *Fast* condition was 82.2% (s.d. 13.1). We ran a 1-tailed paired t-test on these data and found that the threshold obtained in the *Fast* condition was significantly higher than in the *Slow* condition ($t = 2.71$, $p = 0.008$), consistent with our hypothesis that the effects observed are user speed-dependent.

Taken together these data are consistent with our hypotheses in suggesting that: i) Humans are markedly insensitive to large degradation in geometrical detail (i.e. polygon count in our experiments) during head movements; and ii) They become more insensitive as the speed of head movement increases. These findings suggest there is potential for a simple optimisation approach if the quality of rendering is made dependent on head (and/or eye) movement speed.

5. Discussion

Our method provides a different approach to switching between LOD levels that does not use distance from the camera (the standard approach in most commercial game engines). We have shown that even with very aggressive quality degradation, participants cannot reliably perceive these changes.

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There is clearly scope to achieve even greater degradation in LOD without a perceptual consequence if we consider additional higher-level cognitive processes (e.g. attention, decision-making, etc.). These results are consistent with the findings of Parkhurst and Niebur [PN04], in which a model was degraded by a factor of more than 3 without an impact on task performance in a search task. This suggests that perceptual LOD degradation is still to explore and that this is the case even when participants are actively looking for a degradation. In related work, Jindal et al. [JWMM21] did explore the impact of different velocities in VR, but did not find a significant effect. Note, however, that they simulated two LCD screens in VR to mimic their real-life experiment and did not consider user-generated movement.

It is possible that different causes of retinal motion might change the pattern of results observed here. We investigated the case in which head movement causes the retinal motion, but the same effect could arise for a stationary observer and moving object in the environment. However, Murphy [Mur78] suggested that retinal motion, irrespective of its cause, is the primary driver of reduced visual performance. Similarly, we anticipate that the same effects would occur irrespective of the cause of movement, and this will form the basis of our future work.This research speaks to the need for more in-depth analysis of different causes of observer movement and, potentially, across a wider range of velocities. Metrics recovered from such analyses could be useful for inclusion in vision models such as those presented in [MAC22].

Limitations and Future Work. We used a discrete LOD change method resulting in occasionally noticeable stimulus flickering, which could have been used by participants to indicate the degradation. We mitigated that by only showing the model after the participant initiated the movement. Note, however, that this should have improved performance and suggests the LOD degradation tolerated by users could have been even more severe if using a progressive mesh technique. A second issue is that we did not track the eyes and so could not be sure that participants were following instructions perfectly. Although eye-tracking is becoming more common on commercial headsets, most do not have it so using cues such as head velocity is useful in those cases. Nonetheless, the head movement observed was generally close to the instructed movement (see Figure 2). Irrespective, even if the participants were not perfectly tracking the target the effects observed were large and in line with our hypotheses. Third, we examined only one type of observer movement. Clearly, we might find subtly different effects for different directions of movement, different combinations of eye, head and model movement or other factors such as eccentricity, distance, or type of pursuit that can modulate visual acuity. Testing all these was not feasible in our study, but represents an interesting avenue for future research.

6. Conclusion

In this paper we examine the idea of velocity-based rendering using a psychophysical approach to measure precisely the extent to which users can reliably detect degradation of a model in the scene in the presence of retinal motion. Our method differs from previous approaches because: i) model degradation rests directly upon information about the self-induced velocity of movement (and ignores distance in the scene or information about object velocities in the scene); ii) it examines sensitivity to quality degradation when users are directly instructed to detect such changes; iii) it uses well-established psychophysical methods to provide precise estimates of the parameters in question. Our data suggest that even in slow head rotations a degradation of up to 75% relative to the original model is accepted by participants, even when they are asked to pay attention to it directly and these effects are amplified further at higher.

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