Evaluating Gaze-Contingent Level of Detail Rendering of Virtual Environments using Visual Search

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Abstract

Level of detail rendering reduces the geometric complexity of objects in virtual reality in order to reduce the computational load on the rendering system. Although the resultant increase in rendering speed is desirable, the behavioral consequences of these techniques for humans performing realistic tasks in complex virtual environments are not well understood. The current study examines the behavior of human observers in virtual environments rendered using a gaze-contingent level of detail criterion. This method takes advantage of the fact that the visual sensitivity of the human visual system is greater at the point of gaze than in the periphery by rendering objects in the periphery with less detail than objects at the point of gaze. In the experiment, participants performed a "virtual search" task, i.e. a visual search task where participants are required to pan the viewport to find a target object among distractors in a virtual environment. Gaze-contingent rendering was employed where the level of detail dropped continuously from the point of gaze. The time to detect and localize the target was measured as a function of the rate of decline in visual detail. Frame rates were allowed to increase with decreasing detail, thus keeping computational load approximately constant. Reaction times to detect the target increased with decreasing detail while reaction times to localize the target decreased with decreasing detail. These results suggest that reduced detail impedes target identification while the increased frame rates due to the reduction in detail faciliates interaction with virtual environments. Overall, these results indicate that the behavioral performance costs of gaze-contingent level of detail techniques can be offset by the behavioral performance gains due to increased rendering speed.

CR Categories: I.3.6 [Computer Graphics]: Methodology and Techniques—Interaction Techniques;

Keywords: Level of Detail, Visual Search, Virtual Reality, Variable Resolution

1 Introduction

Much effort has been focused on the development of efficient methods suitable for reducing the complexity of geometric models used in virtual reality applications. These methods reduce the geometric complexity, or level of detail (LOD), of models in order to reduce the computational resources required to render the virtual environment. The saved resources can be utilized to increase rendering frame rates or can be shifted to other computationally intensive tasks.

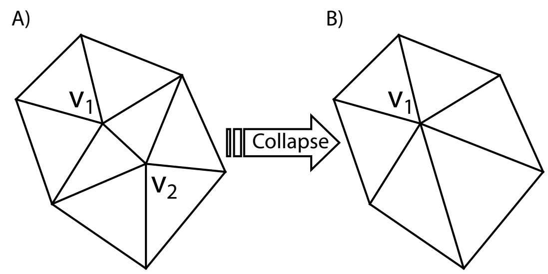

Figure 1: The edge in mesh A that spans from vertex v_1 to v_2 is the smallest edge in the mesh and is therefore collapsed to a single vertex v_1 in mesh B.

Level of detail rendering techniques take advantage of the fact that much of a three dimensional model's geometric detail is unnecessary under certain circumstances. For example, distance-based level of detail manipulations reduce model complexity when the model is distant from the viewer and therefore only visible in a small portion of the visual field. Distance-based level of detail rendering has been successfully implemented in flight simulators since originally conceived [2]. Similarly, real-time viewpoint dependent simplification methods have been developed that reduce model complexity in parts of the model that are hidden when rendered from a particular vantage point [7, 10, 24]. Common to both of these methods is that they take advantage of the specific geometry of the virtual environment to determine the rendered level of detail.

Recently, another class of level of detail rendering techniques has been developed that takes advantage of the way the human visual system processes information. These techniques exploit the fact that the sensitivity of the visual system to detail can vary in different situations. For example, the visual system has a reduced sensitivity to the details of moving stimuli [12, 1]. Velocity-based

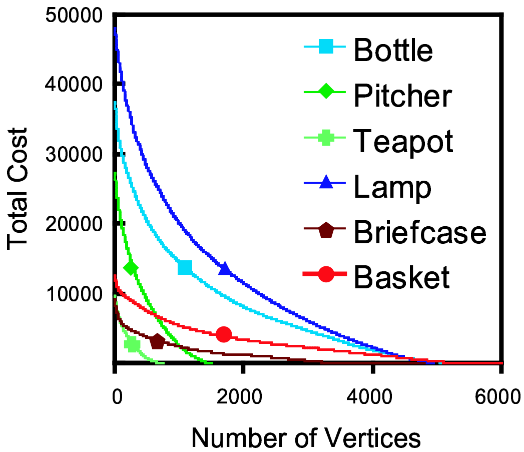

Figure 2: The relationship between the number of vertices and the total cost of rendering a mesh. Note that the cost is a non-linear function of the number of vertices in the model, which varies from object to object.

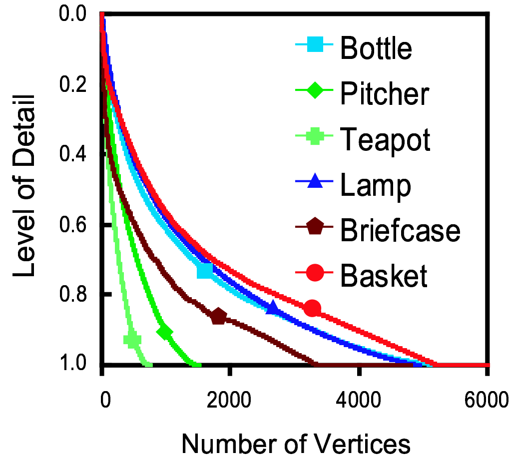

Figure 3: The relationship between the number of vertices and the normalized level of detail of the object. Note that the relationship is non-linear and for some models the level of detail remains high until a large number of vertices have been removed fromthe model. This is especially true for models with large numbers of vertices.

level of detail techniques take advantage of this fact by rendering moving objects in less detail than stationary objects [5, 16, 17]. It is also well known that visual sensitivity to detail falls off rapidly in the visual periphery [21]. Gaze-contingent level of detail techniques take advantage of this fact by rendering models using less detail in the periphery than at the point of gaze [14, 11, 13]. This technique requires that the point of gaze be tracked in real-time, but the potential computational savings using such a technique is one order of magnitude, or greater, depending on display parameters such as size and resolution [15].

The development of level of detail reduction techniques that rely on perceptual criteria promises to further reduce the computational requirements for virtual reality systems. Unfortunately, little research has been conducted to examine the behavioral consequences of such manipulations with realistic tasks and in complex virtual environments. The human visual system is a complex, non-linear system and therefore detailed behavioral evaluations of these display techniques must be conducted. The current study is the first of which we are aware to examine the behavioral consequences of a gaze-contingent level of detail rendering technique with realistic, interactive virtual enviroments and natural behavioral tasks.

We examine behavioral performance in a “virtual search” task, a paradigm similar to the traditional visual search paradigm where participants are required to search for a specified target item in a display. The virtual component of the task requires that participants search a complex three dimensional virtual environment for a target object. The virtual environments used in the experiment are a series of single-room home interiors (see Figure 5). Participants are always centered in the room and allowed to rotate (pan) the viewport using a mouse in order to find the target object.

The experiment examines behavioral performance across a range of level of details conditions. In all conditions, the instantaneous level of detail of an entire object is determined by the distance from the objects center of mass to the point of gaze. The decline in detail from the point of gaze is continuous, and the rate of decline was experimentally varied. The time to detect a target object and subsequently localize the target was measured as a function of the rate of decline in visual detail.

Level of detail techniques free up computational resources otherwise used in traditional uniform resolution displays. The most immediate use one can make of these resources is to increase frame rendering rates. In the present experiment we allow frame rates to vary and therefore keep the computational resources required to render each condition approximately constant. The behavioral effects of this combined reduction of peripheral visual detail and increase of temporal resolution will be examined. Because slow system responsiveness has been shown to be detrimental when interacting with virtual environments [23], it is predicted that the increased frame rates associated with low levels of detail will ameliorate performance that requires such interaction.

2 Level of Detail

Level of detail manipulations were implemented using a simple vertex decimation algorithm that collapses two vertices connected by an edge into one single vertex (see Figure 1). Vertex decimation is a widely used technique [18, 20, 8] and can be used to produce a progressive mesh representation [6]. A progressive mesh is essentially a linked list of vertices that indicates the successive order of edge collapses from the highest to the lowest level of detail. This linked list can be precomputed prior to run time and therefore affords rapid selection of many levels of detail at render time. A progressive mesh representation is used for all models in this study. All mesh collapse sequences are precomputed prior to runtime.

Typically, vertex decimation proceeds by selecting the edges of lowest cost to collapse first. Edge cost depends on a cost function. A wide variety of parameters can be used to determine the cost of collapsing an edge including the edge length, local curvature, local color or texture differences. In general, these parameters can greatly affect the visual quality of a simplified mesh. As to now, there is no unambiguous measure that captures all aspects of the visual quality of a simplified mesh (although see [17, 9] for candidate measures). Rather, most techniques focus on some aspect of geometric fidelity. For the purposes of simplicity and generality, we use a cost function where the cost to collapse an edge is solely determined by the length of that edge. Therefore, the total cost associated with a simplified model is the sum of the costs of each collapsed edge, or in other words the sum length of all collapsed edges.

One requirement for using level of detail based techniques in complex virtual environments is that model complexity must be varied consistently across all objects. Using the progressive mesh representation, it might be appealing to use a fixed percentage of vertices to represent a given level of detail. Unfortunately, this has undesirable consequences. For example, removing 50 percent of the vertices from an over-tesselated mesh with 10,000 vertices may not be visually disturbing, but on the other hand, removing 50 percent of the vertices from a model with only 100 vertices would be very visually disturbing.

An alternative is to use a given cost to represent a level of detail. Unfortunately again, this has unappealing consequences. Shown in Figure 2 is the relationship between the number of vertices and the total cost for six objects used in the experiment. As can be seen, the objects vary greatly in their total number of vertices and consequently, the total cost associated with each object also varies greatly. Additionally, the total cost is a function of the relative size of the object, with larger objects incurring a greater cost. Choosing an absolute cost level to represent level of detail still results in a greater visual disturbance for complex objects.

The solution we devised to this problem (i.e. to produce a perceptually constant simplification across objects that vary incomplexity, size and geometric construction) is to normalize the total cost of a mesh at a given level of detail by the cost associated with the lowest level of detail (a mesh of three vertices). For instance, Figure 2 shows that the cost of reducing the“Pitcher” object from its maximal number of vertices (about 1500) to the lowest level of detail of approximately 28,000 length units. Thus, we define the level of detail of a reduced version of this object as the sum of the length of all its edges divided by 28,000. It is clear that this number is between 0 (lowest level of detail) and 1 (highest level).

As can be seen in Figure 3, this normalization procedure serves to equate models of different complexity. This can also be seen in Figure 6 where four levels of detail are shown for a set of objects. As expected, low levels of detail tend to have few vertices and high levels of detail tend to have more vertices. Note that at any given level of detail, the number of vertices rendered varies across objects. High complexity objects can withstand the elimination of many more vertices than low complexity objects.

This transformation is not perfect and it could be improved by using more perceptually valid cost measures. Doing this would most likely increase the number of vertices that could be eliminated for a given perceptual quality. Such efforts may further increase the computational efficiency of level of detail techniques.

3 Gaze-Contingent Level of Detail

Gaze-continent level of detail reduction was implemented by relating the rendered level of detail of each object to the distance of that object to the instantaneous point of gaze. As shown in Figure 4, level of detail decreases linearly as the distance from the rendered object to the point of gaze increases. A minimum level of detail of 0.10 was maintained in each condition.

Six experimental conditions were examined corresponding to six different rates of LOD decline. Detail dropped as the distance from the point of gaze increased at a rate of 0.00, 0.02, 0.04, 0.06, 0.10 or 0.20 LOD units per degree of visual angle.

Pilot studies indicated that noise in the measurement of the point of gaze, typically less than 1 degree of visual angle, in combination with the gaze-contingent level of detail rendering caused a visually disturbing effect. This effect can be characterised as shimmering and was most likely a motion signal that was strong in the peripheral visual field. Random fluctions in the measured point of gaze due to noise caused the number of vertices in each object to fluctuate

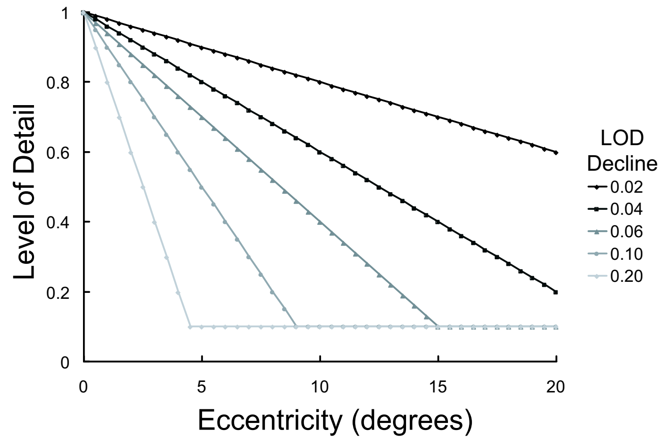

Figure 4: The relationship between the rendered level of detail and the distance from the point of gaze in each of the experimental conditions.

rapidly. This fluctuation resulted in vertices “popping” in and out of the mesh.

To reduce this visually disturbing effect a threshold was imposed on the point of gaze. The point of gaze, as relevant to the gaze-contingent rendering, was considered to have moved only if it had surpassed a criterion distance of 1.5 degrees of visual angle. This threshold for the most part eliminated the disturbing effects due to noise. “Popping” in or out of vertices still occured when the observer fixated a location and panned the display at the same time, causing the distance from each object to the point of gaze to change. This effect was less visually disturbing than that caused by the noise, and this fact is most likely due to the reduced visual sensitivity to the details of moving objects. Note that when participants panned the display and continued to fixate an object (rather than a location) using smooth pursuit eye movements, the distance to each object and the point of gaze was constant and therefore no visual disturbances were present. Tracking objects using smooth pursuit eye movements while the display was panned was a common strategy adopted by participants.

4 Methods

4.1 Participants

Six Johns Hopkins students were paid for participation in the experiment. All participants had normal or corrected-to-normal vision and all were naive with respect to the purpose of the study.

4.2 Apparatus

Virtual environments were rendered using the Unreal^{TM} rendering engine on an 1Ghz Intel Pentium III based personal computer using an Elsa Gladiac Graphics Adapter with 32MByte of video memory. All environments were presented full-screen on a standard 17 inch computer screen at a resolution of 800 by 600 pixels at a video refresh rate of 60hz. Participants were seated at normal viewing distance ($60cm$) from the computer screen, the viewable portion of which subtended 30.0° of visual angle horizontally and 22.4° vertically. Participants interacted with the environment using a standard right-handed, three-button mouse. The viewport of the virtual environment could be rotated by moving the mouse left or right, controlling yaw, as well as by moving the mouse forward or

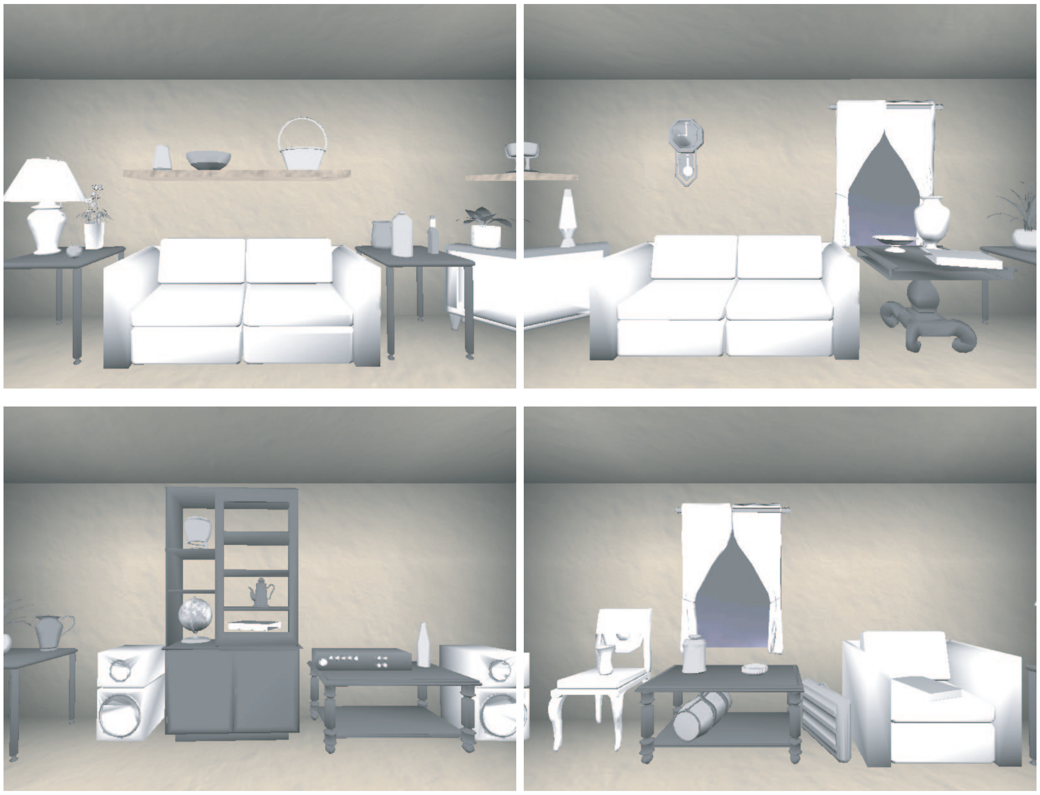

Figure 5: Four different viewpoints of one virtual home interior used in the experiment. These four views of 90° each span the whole room (360°). Each view is drawn using the highest level of detail (1.0).

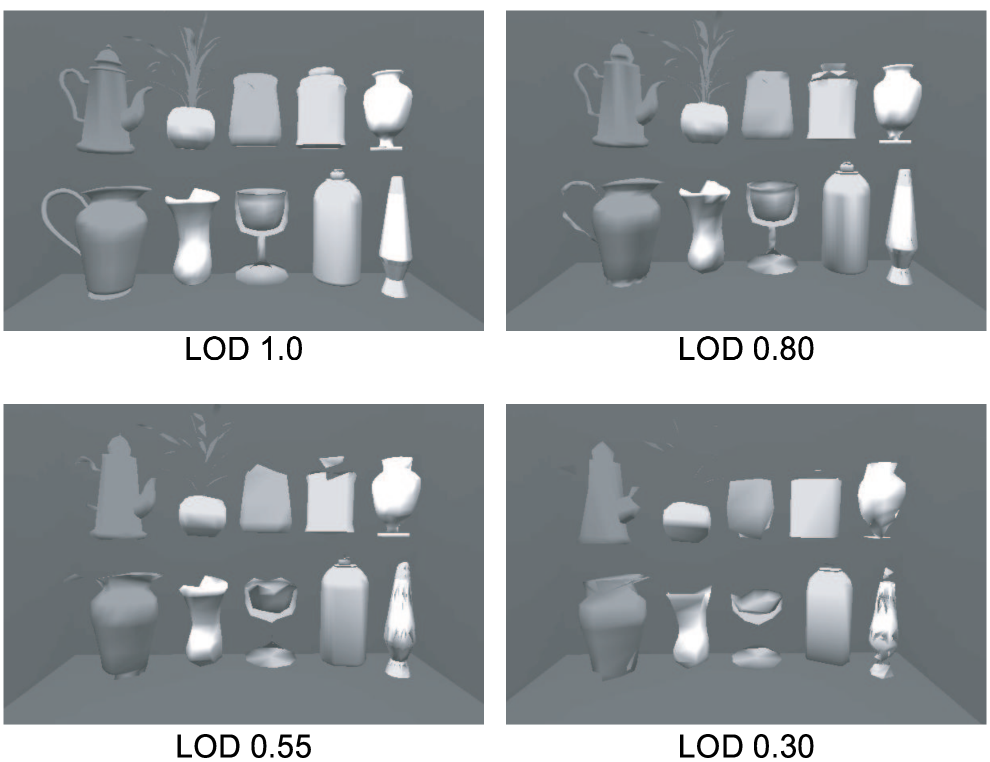

Figure 6: The 10 target objects are shown at 4 levels of detail.

backward, controlling pitch. The rendered field of view spanned 90° of visual angle in the virtual environment.

4.3 Eye Tracking

An ISCAN model RK-416 eye tracker was used to monitor eye position. This model is a real time digital image processor that tracks the center of the participant's pupil and measures its size from an infrared video image of the participant's eye. The unit automatically computes the position of the pupil over the two-dimensional matrix of the eye imaging camera. Pupil coordinates and diameter are computed at a rate of 60Hz. A bi-cubic nonlinear interpolation (cubic in both horizontal and vertical dimensions) between a grid of nine calibration points was used to calibrate the eye tracker [19]. This procedure helped to minimize errors from non-linearities due to infrared source reflections. Additionally, the calibration was adjusted using a procedure where an eye sample from the fixation point at the beginning of each trial, just after viewing the target object and just prior to entering each virtual room, was used to re-align the original nine point interpolation. A custom chin rest was used to minimize eye tracking artifacts due to head movements.

4.4 Stimuli

The virtual environments were constructed by using polygonal mesh objects from a wide range of sources on the Internet, presumably generated using different methods and/or software. To that point, the complexity of the models differs greatly. The number of vertices in the models range from 100 to 6005 with a mean of 1730 vertices (SD=1617). In addition, the topology of the meshes varied. Some meshes were a singular piece with no holes (e.g. the vase in figure 6) while others had a number of disconnected parts (e.g. the leaves of the plant). One consequence of this fact is that heavily reduced meshes sometimes appeared to have two disconnected parts (e.g. the teapot and its handle in Figure 6).

A total of five different home interiors were created for this experiment. Each home interior contained the same set of objects, but arranged differently. All home interiors were of the same physical dimensions and the participant's virtual position was always in the exact center ofthe room. Participants could control the viewport rotation but not their virtual position. Objects were placed along each of the walls in a way that gave as near as possible a normal home interior appearance. No objects were placed in the center of the room. Because the complexity, and therefore the rendering time, of each object varied widely, some effort was made to distribute the objects uniformly across the room when they were created so as to maintain an approximately constant frame rate from any view. The distribution of objects can be seen in figure 5 where four different viewpoints of the same home interior are shown.

4.5 Task

The virtual search task requires participants to search for a target object in a virtual environment. Our virtual search task differs from traditional visual search paradigms because it involves not only a sensory component, i.e. detecting a visual stimulus, but also a motor component, i.e. controlling the viewport. Ten target objects of similar visual appearance were selected from the objects that were contained in each home interior. All targets are shown in Figure 6. Note that the visual similarity of the targets increases as the level of detail decreases. This is primarily due to the loss of small defining features, for example, the loss of the handle on the pitcher or the teapot.

Psychophysical evidence indicates that color can be efficiently used to guide attention in visual search paradigms [4]. If the task examined does not critically depend on the visual form of the target but rather on the color of that target, little or no effects of varying the level of detail should be found. By removing the ability of color to guide the search, the task becomes more dependent on form, and more likely to be sensitive to level of detail manipulations. To limit the ability of participants to use color information rather than form information, all objects in the environments were rendered in shades of gray. Although the range of object shades varies from target to target, no target was uniquely defined by its shade of gray. The potential for task demands to interact with the behavioral effects of level of detail manipulations is itself interesting and will be examined in future studies.

4.6 Procedure

At the beginning of each trial, a nine point eye tracker calibration was conducted. Then, a target object was randomly selected from 10 possible target objects (see Figure 6) and presented to the participant on a blank screen. The object was continually rotated about all three axes such that participants had a chance to view the object from all directions. The target object was presented until the participant pressed the left mouse button at which time the target disappeared and was replaced by a centrally located fixation cross. Participants were instructed to fixate the cross and press the left mouse button to begin the trial.

Once the trial began, the virtual environment was displayed. Participants were instructed to find the target as quickly as possible and respond that they had detected the object by clicking the left mouse button. After this first response a green crosshair appeared at the center of the display. Participants were required to localize the target by panning the display so that the crosshair was aligned with the target object and subsequently pressing the left mouse button. Participants were told that accuracy was important for the localization response.

4.7 Experimental Design

A total of six experimental conditions were examined, each with a different rate of LOD decline. Framerates were allowed to vary and increased with increasing rates of LOD decline (see Results). Each participant completed a total of 180 trials. Each of the 5 different home interiors was presented in each of the 6 different experimental conditions a total of 6 times. Experimental conditions were selected for each trial in a random order.

5 Results

Mean reaction time to detect the target objects was calculated based only on those trials where the subsequent localization response was accurate within plus or minus 2 degrees of visual angle. In addition, any trials where participants required greater than 5 seconds to localize the target after signaling detection were excluded. This eliminated any trials where participants may have false alarmed on the detection response but tried to localize the correct target. Using these criteria, accuracy was, on average, 97 percent and did not significantly differ as a function of the rate of LOD decline ($F(5, 25) = 1.32, p > 0.10$).

Mean reaction time to detect the target object was calculated for each participant. The detection times increased with increasing rates of LOD decline ($F(5, 25) = 4.07, p < 0.05$). This is shown in Figure 7 as the mean across participants plus or minus one standard error of that mean. A regresssion analysis was conducted and a line of best fit was calculated for reaction times as a function of the rate of LOD decline. A significant slope of 71 ms per 0.01 units of LOD decline was obtained ($F(1, 34) = 6.55, p < 0.05$).

Mean reaction time to localize the target object was calculated for each participant. Time to localize the target was measured

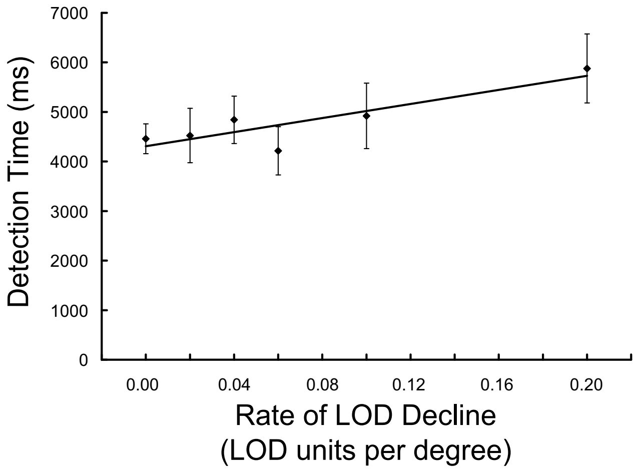

Figure 7: Mean reaction times to detect the target. Reaction times increase with greater rates of LOD decline. (Errorbars=±1SE)

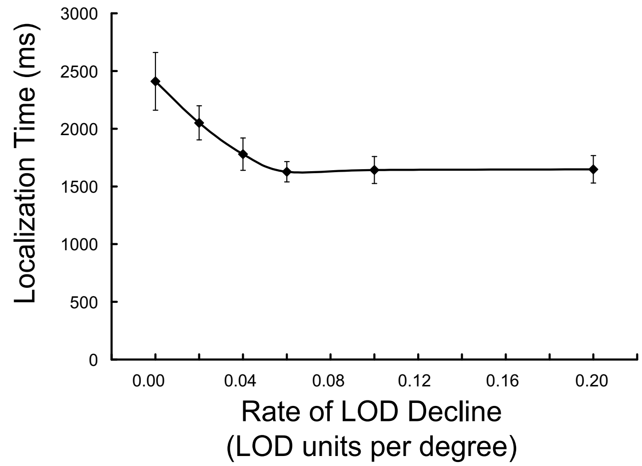

Figure 8: Mean reaction times to localize the target. Reaction times decrease with greater rates of LOD decline. (Errorbars=±1SE)

from the time of detection to the time which participants placed a crosshair on top of the target and responded using the mouse. Localization times decrease with increasing rates of LOD decline $(F(5,25) = 8.67, p < 0.05)$. This is shown in Figure 8 as the mean across participants plus or minus one standard error of that mean.

Mean frame rendering times were recorded in each condition and the results are shown in Figure 9. Render times decreased with increasing rates of LOD decline $(F(5,25) = 1238, p < 0.05)$.

6 Discussion

The aim of this study was to examine gaze-contingent level of detail rendering techniques using realistic, interactive virtual environments and natural behavioral tasks. Detection and localization times were measured while participants performed visual search of interactive virtual environments rendered using a gaze-contingent level of detail technique.

A significant slowing of target detection times was observed as a function of the rendered level of detail. Targets were harder to detect when the peripheral level of detail was low. This effect can potentially be attributed to three aspects of the reduced level of detail manipulation. First, reduction of the rendered level of detail reduces the visual distinctiveness of objects. As can be seen in Figure 6, target similarity increases with decreasing detail. As target-distractor similarity increases, so does visual search difficulty [3]. Along similar lines, the reduced level of detail may affect object recognition in general. This interpretation is supported by the results of Watson, Friedman, and McGaffey (2000) that indicate that object naming time is sensitive to model simplificaton. Lastly, dynamic level of detail techniques introduce a visible flicker due to the appearance or disappearance of vertices as level of detail changes. This flicker may be stronger when the level of detail in the periphery is low and cause slowing.

A significant decrease of target localization times was observed as a function of the rendered level of detail. Targets were easiler to localize when the peripheral level of detail was low. This effect is most likely due to the increase in frame rates that accompanied the low level of detail. The time to render a frame in the full detail condition was 108 ms (i.e. 9.2 fps) whereas in the condition with the most significant reduction, the time to render each frame was only 18 ms (i.e., 56 fps). This significant increase in frame rates lead to a decrease in localization times of approximately 800 ms.

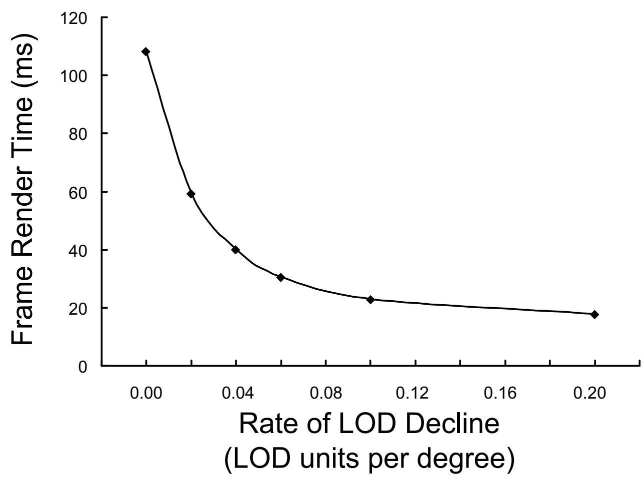

Figure 9: Mean frame rendering time as a function of the rate of level of detail decline. (Errorbars=±1SE and are smaller than symbols)

The results of this study are restricted in that only one level of detail reduction technique was examined. A simple vertex decimation technique was utilized where the cost function was soley a function of edge length. The ability of this reduction technique to maintain a high degree of perceptual quality for heavily reduced models is limited. Edge decimation is a widely used technique and serves as the basis for many more sophisticated reduction algorithms. Thus, the overall results, which indicate a slowing in detection times and a speeding of localization times with more drastic levels of reduction, likely generalize to many other reduction techniques, while the magnitudes of the reaction time costs may be smaller for more sophisticated reduction techniques. It is expected that the use of other reduction techniques, both view independent and view dependent, will increase the benefits while limiting the costs associated with level of detail rendering techniques.

The goal of this study was to examine the behavioral consequences of using gaze-contingent level of detail rendering techniques. The primary finding is that virtual search performance is impaired as the rendered level of detail decreases but that the gains in localization performance due to the increased rendering rate can offset the detection costs associated with the reduced visual detail.

These results suggest that gaze-contingent level of detail rendering techniques represent a viable future technology.

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