#### **Purdue University** Purdue e-Pubs

**Open Access Theses** 

Theses and Dissertations

Spring 2014

## JUST NOTICEABLE DIFFERENCE SURVEY OF COMPUTER GENERATED IMAGERY USING NORMAL MAPS

Michael Edward Hoerter Purdue University

Follow this and additional works at: https://docs.lib.purdue.edu/open\_access\_theses



Part of the Computer Sciences Commons

#### Recommended Citation

Hoerter, Michael Edward, "JUST NOTICEABLE DIFFERENCE SURVEY OF COMPUTER GENERATED IMAGERY USING NORMAL MAPS" (2014). Open Access Theses. 191.

https://docs.lib.purdue.edu/open\_access\_theses/191

This document has been made available through Purdue e-Pubs, a service of the Purdue University Libraries. Please contact epubs@purdue.edu for additional information.

# PURDUE UNIVERSITY GRADUATE SCHOOL Thesis/Dissertation Acceptance

This is to certify that the thesis/dissertation prepared

r ·r···	
By Hoerter, Michael Edward	
Entitled JUST NOTICEABLE DIFFERENCE SURVEY OF COMPUT NORMAL MAPS	TER GENERATED IMAGERY USING
For the degree ofMaster of Science	
Is approved by the final examining committee:	
David Whittinghill	
Nicoletta Adamo-Villani	
Ray Hassan	
To the best of my knowledge and as understood by the stud <i>Publication Delay, and Certification/Disclaimer (Graduate</i> adheres to the provisions of Purdue University's "Policy on copyrighted material.	School Form 32), this thesis/dissertation
David Whittinghill	
Approved by Major Professor(s):	
Approved by: Mihaela Vorvoreanu	4/21/2014
Head of the Department Graduate Program	Date

### JUST NOTICEABLE DIFFERENCE SURVEY OF COMPUTER GENERATED IMAGERY USING NORMAL MAPS

A Thesis

Submitted to the Faculty

of

Purdue University

by

Michael Edward Hoerter

In Partial Fulfillment of the

Requirements for the Degree

of

Master of Science

May 2014

Purdue University

West Lafayette, Indiana

#### ACKNOWLEDGEMENTS

I would like to thank Dr. David Whittinghill, my committee chair, for his invaluable guidance and mentorship.

Thanks also to Luke Policinski for his work on the survey web platform, without which this study could not have been possible, and to Mary Spalla for providing the bases for two of the character models used in this study.

Finally, I thank my parents, who have been so understanding and supportive throughout this whole process.

#### TABLE OF CONTENTS

	Page
LIST OF TABLES LIST OF FIGURES	
ABSTRACT	vii
CHAPTER 1 INTRODUCTION	1
1.1 Research Question	1
1.2 Scope	3
1.3 Significance	6
1.4 Statement of Purpose	8
1.5 Assumptions	9
1.6 Limitations	10
1.7 Delimitations	10
1.8 Definitions	11
1.9 Summary	12
CHAPTER 2 REVIEW OF LITERATURE2.1 An Explanation of Normal Mapping	
2.2 History of Bump and Normal Mapping	16
2.3 Summary	22
CHAPTER 3 METHODLOGY	23
3.1 Design	23
3.2 Participants	26
3.3 Variables	26
3.4 Measures	27
3.5 Materials	27
3.6 Procedure	29
3.7 Analysis	33
3.8 Summary	34
CHAPTER 4 RESULTS	35

	Page
4.1 Survey of Just Noticeable Difference Threshold	35
4.2 Demographic Survey	38
4.3 Summary	38
CHAPTER 5 CONCLUSIONS	40
5.1 Significance of the Testing Group	40
5.2 Significance of Demographics	41
5.3 Future Research	42
5.4 Summary	43
REFERENCES	44
APPENDIX	47

#### LIST OF TABLES

Table	Page
Table 3.1. Basic subject demographics	26
Table 4.1. Estimated marginal means of JND set threshold per group	36
Table 4.2. Total mean JND threshold per group, and per character	36
Table 4.3. ANOVA Type III Tests of Fixed Effects	36
Table 4.4. ANOVA Type III Tests of Fixed Effects of Demographics	38
Appendix Table	
Table A-1. JND thresholds per character	47
Table A-2. Subject demographic data	49

#### LIST OF FIGURES

Figure	
Figure 1.1. Example of "blocky" silhouette despite modified surface normal	4
Figure 3.1. The character models used, shown at maximum polygonal density	28
Figure 3.2. Example model comparison for control group	30
Figure 3.3. Example model comparison for experimental group	31
Figure 3.4. Example set progression flowchart	32
Figure 3.5. Set five of character three within control group (non-textured)	33
Figure 4.1. Modes for each detail set for all characters within the Control group	37
Figure 4.2. Modes for each detail set for all characters within the Experimental grou	ир 37

#### **ABSTRACT**

Hoerter, Michael E. M.S., Purdue University, May, 2014. Just Noticeable Difference Survey of Computer Generated Imagery Using Normal Maps. Major Professor: David Whittinghill.

Normal maps are widely used as a resource-efficient means of simulating detailed topology on 3D surfaces in the gaming, simulation, and film industries. However, as surface mesh density increases, it is unknown at what level of density these increases become no longer perceivable, and whether normal maps significantly affect this threshold. This study examined at what point participants were unable to discern differences between one level of mesh density and another using an adapted staircase model. Participants identified this threshold for five different organic character models. The averages of each of these thresholds were taken and compared against the results of a control group, which observed the same models without normal maps. The study found that the average threshold for discerning differences in level of detail occurred in the 3,000 to 14,000 polygon range for normal mapped models, and the 240,000 to 950,000 range for the control group. This analysis suggested that normal maps have a significant impact on the viewer's ability to discern differences in detail, and that developing graphics beyond the range of 3,000 to 14,000 polygons is unnecessary for organic character models when normal maps are used.

#### CHAPTER 1 INTRODUCTION

This chapter presents a basic overview of this research project, and will explain the research question, the scope and significance of the research, and a statement of purpose, as well as listing several limitations, delimitations, and assumptions.

#### 1.1 Research Question

In rendered three-dimensional models, as surface mesh density increases, at what level of density are these increases no longer perceivable? Is this threshold of perceptibility different for three-dimensional models that are rendered using normal mapping?

Computer Graphics Imagery (CGI), especially in gaming and animation, makes frequent use of polygons to simulate objects and surfaces. A surface generated from many polygons is referred to as a *mesh*. As a mesh's surface complexity increases, greater numbers of smaller polygons are needed to define the shape and surface of the virtual object.

It seems intuitive then that as greater numbers of polygons allow a greater amount of surface detail, the relationship between "detail" and the number of polygons in a mesh is linear, i.e., increasing polygons naturally increases detail by the same degree.

There must, however, be some point at which increasing the number of polygons, or *actual detail* no longer noticeably impacts the *perceived detail* of a surface. As an example, while a pane of glass may appear perfectly smooth, it is revealed to be rough and uneven when seen under magnification. The actual detail of the surface – or any other natural surface – is extremely high, but is of such a miniscule nature that the human eye cannot detect it, so there is little *perceived* detail.

In graphics applications, there is the additional issue of a more steep level of resource consumption for increased detail: more processing time, more rendering time, and more development time. This phenomenon has been observed consistently throughout most advances in graphics technology; that the increase in detail entails an increase in the resources needed to produce that detail. Given that actual polygonal detail cannot increase ad infinitum, an alternate method of creating meaningful detail must be used.

Bump mapping, and variants thereof, is used almost universally in high-level graphics applications, such as films and computer gaming, to improve the viewer's perception of surface detail without increasing the complexity of that surface's geometry. This allows system resources to be more efficiently managed and utilized. There are several variants of bump mapping that produce different effects. One of the most highly utilized variations is "normal-mapping" (also known as Dot3 bump mapping), as it produces more predictable results than basic bump mapping due to its containing surface normal information within the texture map itself, rather than relying on an algorithm to interpret it. A surface normal is defined as a vector perpendicular to the plane formed by three points or vertices. This is useful for determining which direction the plane is

"facing", and are commonly used for lighting and shading calculations. Normal maps adjust this surface normal data in order to produce more "bumpy" surfaces.

While the widespread use of normal mapping is indicative of its effectiveness, there is an apparent lack of research into how this technology affects a viewer's perception of fine detail. This study seeks to determine at what point increasing polygonal detail no longer has an impact on the perceived quality of the surface, and to what degree the use of normal mapping confounds the ability to distinguish between different levels of surface detail.

#### <u>1.2 Scope</u>

Normal mapping techniques are used in a wide range of visual media, so a similarly wide range of people has seen it in use, whether they realize it or not. In a broad sense, this overall audience can be considered to fit into two distinct groups: those who are familiar with graphics techniques such as normal mapping, and those who are not. It is suspected that these two groups may produce different results, as more savvy viewers may be able to pick out particular tell-tale signs of normal maps and low-detail geometry.

One of the primary visible signs on low-detail normal mapped geometry is the silhouette of the model, which is not altered by the normal map. Also, in surface meshes with sufficiently few polygons, normal map detail can, in effect, be overridden by the polygonal surface of the model. Both of these phenomena are demonstrated in Figure 1.1 below.

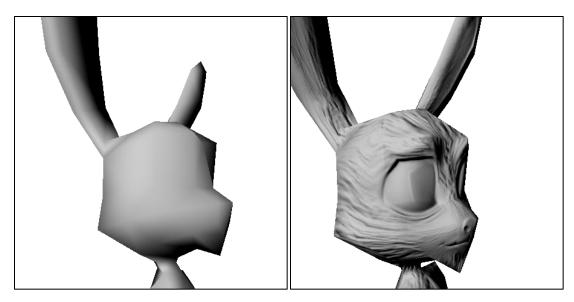


Figure 1.1. Example of how the "blocky" silhouette remains despite modified surface normals

This study does not attempt to divide knowledgeable participants into groups at the outset, but instead included a pre-test to determine a participant's general level of graphics knowledge, and examined the resulting data *post hoc*. The pre-test also helped identify whether a participant is a gamer, an avid movie-goer, and so on. Each of these may have some impact on test results for each individual, as a pre-existing familiarity with normal mapping technology may theoretically lead to the participant being better able to identify them. The main question of this study is to determine the degree to which the implementation of normal maps will "trick" the average viewer into being unable to tell the difference between various differently detailed models of the same object.

Two versions of a computer-generated character were displayed side by side in the study, each with separate "turn-table" animations so that viewers were able to see the depth-queues given by shadows and highlights. Animated sequences were selected for this study, as normal mapping is generally most beneficial in animation and real-time rendering rather than static images.

A wide range of participants were used for this study. The scope of the test is mostly college-aged individuals from Purdue University, but roughly 1/3 of the participants were either graduated from college or had not attended college. The participant's area of study, if applicable, was included in the pre-test along with participant familiarity with computer graphics techniques and media. Participants were also asked to include their age and gender. No other identifying information was collected.

The reason no other age-range demographics were included is because it is suspected that the overall results may differ based on age, as a common belief is that younger generations are more familiar with current computer technology than previous generations. (Karavidas, Lim, & Katsikas, 2005) The reasoning being that, having grown up with this technology, younger generations are able to interact more easily with said technology than older generations who have had to adapt over time. Though it would be interesting to examine exactly how large a gap there might be between the results for younger and older participants, that question is outside the scope of this study. Future work in this area should seek to address this question.

There are also two main areas of computer graphics that this study could focus upon: animation and gaming. There is often overlap between these media, but the basic difference is that animation typically employs more highly-detailed geometry and renders a specific sequence of images ahead of time (a.k.a. "pre-rendering"). Gaming, on the other hand, tends toward simpler geometry, rendering in real time for the purpose of interactivity. It is this real-time rendering that typically necessitates simpler geometry, as

greater complexity requires greater processing power; power that may not necessarily be immediately available.

For the purposes of the study, the character models were pre-rendered, with basic lighting and shading that is typically found in present-day interactive games. The MentalRay<sup>TM</sup> rendering software was used for this purpose. The use of this rendering platform was for the sake of convenience only, and does not employ any unique rendering styles that might not be found in other engines, in order to be as generalized as possible.

Participants were simultaneously shown two versions of a single character model, one version having four times the number of surface polygons (or "faces") as the other. Participants then indicate whether they can or cannot detect any differences between the two models. Using the forced staircase method, each time a participant noticed a difference, they were shown a set of more detailed models, and each time they failed to notice a difference, they were shown a set of less detailed models. This process was repeated *K* times, and the last "reversal" was taken as the threshold value for that set.

#### 1.3 Significance

It is impractical to scale up detail indefinitely. There must come a point where a computer will lack the resources to render sufficiently highly detailed models in real-time. Especially in gaming and real-time simulations, the goal is to produce exactly as much perceived detail as is necessary to achieve the desired effect, rather than to maximize the amount of actual detail. To avoid transgressing that point where there is *too much* actual detail, but still give the impression of extremely detailed surfaces, normal maps and

variants thereof are used to produce details that would otherwise require many millions more polygons.

As mentioned earlier, bump mapping technology has been used extensively in nearly all fields within the graphics industry. Bump maps – and, more recently, normal maps – are used to improve surface detail while minimizing the computer resources needed to generate and display that detail. It can be used for purely aesthetic purposes, such as adding realistic wood-grain to a door, as well as for more functional purposes, such as in scientific or medical simulations to increase the amount of visual information for a given surface, such as a heart or blood vessel.

The significance of bump- and normal-mapping as a tool seems obvious. However, while this technology is used extensively in media, there seems to be a lack of empirical data detailing the parameters on exactly how bump- and normal mapping affect a viewer's perception of quality in images that implement it. As a common challenge seen in many areas of computer graphics is using the available hardware capabilities with the maximum possible efficiency, understanding the capabilities of this bump- and normal-mapping should provide a significant benefit to the field of computer graphics as a whole. It is hoped that the ultimate result of this study will help developers and designers find a more optimal medium between hardware capabilities and the maximal level of quality.

For instance, if a computer game is being developed for a specific gaming platform, the developers would better understand the capabilities of the hardware for which they are developing. The results of this study would help them to target development toward using more or less normal-mapping technology as opposed to fully-

detailed models in order to achieve the maximum level of perceived detail possible. By the same token, if a certain level of quality is desired from the outset, these same results should help pinpoint exactly how extensively normal-mapping technology should be used, and what kind of hardware capabilities would be necessary to achieve the desired effect.

The ultimate goal of this and similar future studies is to optimize the graphics development pipeline and make it easier for developers to pinpoint the exact level of detail and quality they want to achieve.

#### 1.4 Statement of Purpose

The aim of this study is to reveal the threshold point where the addition of actual surface detail no longer significantly impacts perceived detail, and to examine how this phenomenon is changed by the use of normal maps. This is in order to identify a humanoid character model's theoretical maximum actual detail M. This is not to say that M can be applied universally to all computer-generated surfaces objects, such as buildings or vehicles. It is, however, believed that since character models tend to represent the most densely-detailed entities in a game or virtual environment, M is greater than the theoretical maximum for most other surface objects. Additionally, because the models in this study are pre-rendered, processing power is not a variable. Even if there exists a computer that can render a character with detail >M, the perceived detail of that character will be identical to a character with detail M.

This, it is hoped, will prove to be useful to industry professionals for use in designing and planning products that use computer graphic imagery. The results from this study would ideally allow these professionals to determine with greater accuracy

where and how to focus the efforts of their teams to maximize efficiency and quality in their products. Knowing at what point the average viewer is unable to tell the difference between the next highest levels of surface detail, developers could shift production to approach M in order to produce objects with the appearance of M detail as costeffectively as possible.

In other cases, it may be used by developers who have a specific pool of resources to determine exactly how those resources would be used to produce high-quality imagery most efficiently. This would allow those saved resources that to be used elsewhere to further improve the product, instead of potentially using more than necessary while achieving diminishing returns.

The overall goal of this study is to help developers both speed up production and increase the quality of their products while minimizing the required computational and labor resources to produce them.

#### 1.5 Assumptions

This study assumes the following to be true:

- Test participants will answer questions as accurately and honestly as possible.
- Test participants will be able to view the presented animations.
- Test participants are able to read, write, and understand English; specifically
  the questions and instructions given throughout testing.

#### 1.6 Limitations

This study had the following limitations:

- Participant reaction data was not collected, as the survey website was
  distributed via email and social media, and the study was therefore not
  conducted in a controlled environment.
- Participants were limited to viewing the survey website only through computer web browsers, and not through mobile or other means.
- The study was limited to a three week period from March 10, 2014 to March 28, 2014.
- As the study was taken online outside a controlled testing environment, the study did not control for the participant's screen size, resolution, or 2dimensional screen rendering ability.

#### 1.7 Delimitations

This study is *not* concerned with determining the following:

- The theoretical maximum necessary detail for any type of model or surface
   *other* than basic character models.
- The effects of animation versus static imagery on perception of visual quality.
- The existence or magnitude of the correlation between race and/or culture and the perception of visual quality in normal maps.
- Whether the perception of detail in normal maps is affected by varying mental states.

- Whether the perception of surface detail in normal maps is affected differently by different rendering engines, styles, or algorithms.
- The effects of light levels and shadow density on the perception of surface detail in normal maps.
- The effects of displacement, parallax, or bump maps versus normal maps in the perception of surface detail.
- The development time of varying implementations of normal map (only render time is taken into consideration, as development time is highly variant and dependent on other factors.)
- The real-time rendering framerate of the models.

#### 1.8 Definitions

- Normal Map or Dot3 Bump Map a technique in computer graphics that uses an image to generate bumps and wrinkles on a simulated surface, allowing greater detail to be displayed without needlessly increasing surface tessellation. (Krishnamurthy & Levoy, 1996)
- Bump Map an older, lower-fidelity variation of normal maps that uses grayscale rather than RGB image maps to simulate height details. (Blinn, 1978).
- CGI [computer generated imagery] computer graphics as applied to the animation, art, simulation, and gaming fields, among others.

- Polygon a multi-sided shape, in this case used as the basic building blocks of a computer generated surface. In graphics, polygons typically have three sides (triangles).
- Mesh the surface shape formed by multiple polygons; essentially the "skin" of any computer generated object.
- Surface Normal the vector perpendicular to the surface of a polygon generated from three points. This is in essence the direction the face is pointing.
- Tessellation a mathematical term referring in this case to the level of polygon-mesh subdivisions. Greater tessellation equals more polygons, which allows for finer details to be generated. In most cases, the level of tessellation is intended to be only as great as it needs to be.
- Pseudorandom Number a number which, though designed to appear random, is not. A pseudorandom number is typically produced separately from a testing model, and used to emulate statistical randomness. This method of creating the appearance of randomness allows for the same number to be used repeatedly. (Vadhan, 2012)

#### 1.9 Summary

This chapter was intended to give a basic overview of the research project, as well as the scope, significance, and purpose, as well as limitations, delimitations, assumptions, and important definitions. The next chapter will examine the background of normal mapping technology in an effort to identify any gaps in the research, and to demonstrate how far the technology has progressed.

#### CHAPTER 2 REVIEW OF LITERATURE

This chapter will cover the relevant literature in the areas of normal-mapping technique and the effects of shadow quality on perception. This is in an effort to both illustrate the importance and constant improvement of normal mapping technology, and the importance that shadows (an integral part of what makes normal mapping such an effective technique for simulating detail) contribute to shape recognition and perception of depth. There is very little in the way of research directly relating to this study; that is, no studies seeking to identify the effects normal mapping has on the perception of visual quality have been found.

This review of the literature will examine the growing utility and various uses of normal mapping techniques, help to illustrate how and why it is such a robust technology, and hopefully show that a deeper understanding of how it affects perception of quality is important for both optimizing its use and possibly even further improvements to the technique itself.

#### 2.1 An Explanation of Normal Mapping

Before explaining normal mapping, it is necessary to give an explanation of the techniques on which it is based: bump mapping. Bump mapping is a rendering technique that simulates surface detail in computer generated imagery (CGI) by means of a simple

grayscale image being applied as a texture to a virtual surface. Depending on the value of each pixel in this texture, the corresponding spot on the surface is either raised or lowered. This topology is then shaded based on existing light sources to effectively create a texture that reacts to the changing angles and levels of light (Blinn, 1978). This thereby allows the rendering engine to produce the illusion of greater surface detail without actually computing that detail; the simulated topology is not being fully rendered, and is meant only to fool the viewer into seeing more detail than is actually present.

The bump mapping algorithm interpolates surface normal values from a grayscale height map, where lighter pixels are represented as being "higher", or more pronounced than darker pixels. Surface normals are calculated from this height map and then rendered, very closely emulating actual polygonal details. However, at areas of the model that are not sufficiently parallel with the viewing plane, the weaknesses of bump mapping becomes clear; while this technique can approximate surface details reliably, it cannot modify the actual topology of the surface. As such, the silhouette of the polygonal surface remains unaffected.

A more recent variant of bump mapping is normal mapping. Normal maps, or Dot3 bump maps, are so named because explicit surface normal information is stored in the RGB image map, allowing the algorithm to accurately produce surface normals more reliably than grayscale bump maps, where they must be interpolated (Cignoni & Montani, 1998). This increased density of information offered by RGB normal maps leads to more predictable results and therefore greater creative control on the part of the artists generating these maps.

Displacement maps are an even more recent application of the bump mapping technique, except that instead of merely simulating these surface details, the model itself is subdivided and deformed by the map, producing real geometry to match the displacement map. This produces a surface that is effectively identical to a fully tessellated surface, and unlike bump and normal maps is able to produce self-occluding and self-shadowing details, and an accurate silhouette. However, this type of bump mapping is by far the most costly, as it requires a great deal of extra geometry to recreate these details. More advanced algorithms exist to intelligently determine what areas of a mesh need to be subdivided into multiple polygons to achieve the desired surface detail, and where to reduce polygons on areas with little detail or variation in surface normals.

The last major variant of bump mapping is parallax mapping, also known as offset mapping or virtual displacement mapping. This algorithm functions in much the same way as normal maps, producing height and surface normal details from an RGB map; however, the difference lies in how surface texture coordinates are displaced based not only the viewer's position, but the viewing angle. Steeper surface angles are rendered with greater texture displacement than surfaces that are more in-line with the viewing plane. This addresses the primary weakness of bump and normal mapping, which is that steep surface angles are rendered the same as direct surfaces, which can break the illusion of detail. In its basic form, parallax mapping shares the limitation of bump and normal maps in that it cannot modify a surface's silhouette or create self-occluding details.

However, in the last decade, a series of enhancements to the parallax mapping algorithm that produced self-occluding details and silhouette modification were published: dynamic parallax occlusion mapping (Tatarchuk, 2006). This appears to be the

culmination of non-intensive surface detail simulation, as it accounts for all of the weaknesses of the original bump mapping algorithm.

While these techniques exist, this study will focus on the basic implementation of normal maps, examining the effects of surface detail simulation and silhouette recognition.

What follows is a review of the literature chronicling the development history of bump mapping and several of the variants thereof.

#### 2.2 History of Bump and Normal Mapping

Bump mapping was first introduced by James Blinn in 1978 as a means to increase the realism of CGI without using the tremendous processing resources needed to generate fully detailed topology. Blinn recognized that while the computer graphics of the day were indeed impressive, they were nonetheless unable to fool anyone into thinking it was "real". He developed bump mapping, the earlier variant of normal mapping, as a solution to this problem.

While bump mapping was an extremely effective technique, it was nonetheless more computationally demanding than basic Phong shading (a highly simplistic shading algorithm widely used both then and now) and texture mapping. It was not until later, when computer technology was advanced enough to allow the meaningful use of bump mapping, that it came into widespread use.

It seems that after the invention of this rendering technique, little work was done on improving it until the early 1990's, when a new algorithm was proposed that allowed smooth transitions between different bump rendering methods without having to

recompile the scene (Becker & Max, 1993). This was a form of level of detail (LOD) that allowed finer and finer levels of detail to be used dynamically based on how close the viewer was to the surface in question.

It was around this time that bump mapping started entering mainstream use, as 3D computer gaming was beginning to emerge as a large and influential industry. There was a certain point in the cycle of improving real-time graphics where current hardware was not sufficiently powerful to render highly-detailed geometry at reasonable speeds. It was then that bump mapping entered the mainstream, as it was an economical and effective way of increasing detail without sacrificing space or performance.

Bump mapping, and variants thereof, rely on producing dynamic shadows and highlights on a surface. Testing by Wanger in 1992 showed that shadow quality in CGI had a significant impact on viewers' perceptions of size, position, and shape. This may serve to explain the effectiveness of bump mapping, because it provides many visual cues that humans use to discern what they are seeing.

It is important to note at this point that while bump mapping made excellent use of shadows, it was not perfect. Older bump mapping techniques would produce simulated bumps that reacted to light, but not to the shadows of other objects. This is a significant limitation, as cast shadows are an important indicator of height and shape. To help solve this problem, researchers Tsukasa Noma and Koichi Sumi (1994) developed a bump mapping algorithm that perturbed the edges of cast shadows on the bump surface.

Two years later, bump maps would be used for another purpose: simplifying highly tessellated geometry while retaining the same level of visible detail (Krishnamurthy & Levoy, 1996). This approach to model simplification allowed a highly

"messy" object surface to be "fitted" with a smooth surface, using bump maps to simulate the original surface details. In this way, a model could be simplified for animation or real-time rendering and still appear as highly-detailed as the original, highly-complex model.

While there were limitations to this technology, such as it being incapable of generating surfaces with holes or highly variable surface topology such as draped cloth, the fact that bump maps can be used to reliably and unobtrusively mimic real-world details with such accuracy sheds some light on why it has become an industry standard.

A couple years after this, another similar algorithm was proposed for "appearance-preserving simplification" that was able to produce multiple levels of detail (Cohen, Olano, & Manocha, 1998). All of which, though they each had progressively fewer polygons, looked nearly identical to the original model. This particular algorithm has a more logical application in gaming and real-time simulations, as level of detail is an extremely important technique for reducing the complexity of objects that are too far off for the viewer to see clearly, thereby freeing up computer resources.

Even later, in 2000, yet another variation of this is developed, known as "normal meshing" (as opposed to normal *mapping*). This works in much the same way as the previous two instances, except that the generated surface is intended to mimic the original mesh as closely as possible without involving bump maps. The important aspect of this study is that even without using bump maps to simulate details, this algorithm is able to create highly detailed surfaces *without* overtaxing the processor. This article is included in the literature review mainly as an illustration of a good testing method for measuring the effectiveness of mesh simplification. It is also an intriguing area of further study, to

see whether this method is necessary to achieve a similar level of perceived visual quality. In this case, it is likely meshes of this type would be used for simulations in which exact detail is needed, such as in medical applications.

Several years later, this concept would be brought into the field of real-time rendering, with the presentation of "a technique for mapping relief textures onto arbitrary polygonal models in real time" (Policarpo, Oliveira, & Comba, 2005). This technique involves the use of dual-depth relief textures, which are two relief textures (i.e., texture maps that modify mesh topology not by building up bumps, but by making indentations) projected from opposite sides of a model to create a separate, completely relief-map-defined object, all while avoiding the creation of erroneous self-occlusions or interpenetrations. This impressive technology may one day replace bump- and normal-mapping, but despite its being available for use in real-time rendering, it is unlikely this will be utilized in gaming engines to any great extent.

To return specifically to advances in bump mapping, in 1997, they would be further optimized to require even less computational power to run effectively. As mentioned previously, bump mapped objects historically took a significantly longer time to render than objects using a basic Phong shader. This did not at the time seem like much of a limitation, as Phong shaders were some of the least taxing to run on any platform. This did not stop some researchers from attempting – and succeeding – in improving the underlying algorithms for bump mapping to such a degree that they could run efficiently on any hardware that could generate Phong shaders (Peercy, Airey, & Cabral, 1997).

In that same year, bump maps would be named as an integral part of generating photorealistic computer generated images, but not without solving one of its lingering shortcomings (Schilling, 1997). This issue was with anti-aliasing the bump map to produce smoother images; that is, the simple fact of smoothing the bump map ended up smoothing out the bumps themselves. Schilling sums this up rather succinctly by saying "filtering bump maps means to remove the bumps." (p. 8).

Schilling solved this rather glaring problem by adding a second layer of detail called a "roughness map" over the existing smoothed bump map. This allowed for a smoothed and gentle bumped surface to be generated with proper anti-aliasing, while also retaining the shaper, finer details that were not intended to be lost. This novel solution certainly fixed the problem, as the presented output images proved, but it is difficult to know whether it was widely implemented. Certainly, bump mapping technology of today does not have the glaring problem of over-smoothing bump maps, so it is reasonable to assume that if this specific solution was not implemented, a similar one likely was.

In any case, this again illustrates that the limitations of bump and normal mapping as a technology are gradually being overcome. One such limitation, the fact that the simulated bumps on a surface, while they each reacted to light levels, did not themselves cast shadows on the rest of the surface, was solved in 1998 by Dr. Nelson Max of the Lawrence Livermore National Laboratory, using a complex combination of generated surface patches, scaled curved patches, and light vector transformations to calculate light rays, as well as taking into account the curvature of the overall surface. The result is a staggeringly realistic looking array of shadows that simulate surface topology so well, it

is nearly undetectable. What remains unclear from the article, however, is whether this is capable of being rendered effectively in real time.

Moving ever forward, bump mapping technology was optimized for more powerful graphics processing units (GPUs) and improves greatly upon the original model presented by James Blinn (Kilgard, 2000). Kilgard goes into extreme detail in describing exactly why and how his proposed algorithm is more suitable for the GPUs of the day, saying:

First, the technique . . . substantially reduces the need to tessellate the rendered polygon model as a fine mesh to avoid linear interpolation artifacts. Second, the normal map can encode completely arbitrary perturbations. . . . Third, by filtering the normal map properly and through the use of linear-mipmap-linear filtering, temporal aliasing artifacts when animating are minimal. Fourth, the technique reasonably accounts of [sic] local surface self-shadowing effects. Fifth, the technique is not limited to directional lights so objects are free to move around and interact with the light source. (p. 22)

Mentioned in this quote are normal maps, which for the purpose of this literature review, are essentially the same thing as bump maps, just with a higher level of detail. In many cases, "bump map" is used to refer to the concept of using texture height maps to simulate topology.

To close out this review of literature, it must be stressed that one of the overriding trends has been to attempt to perfect the lighting algorithms for bump maps in order to produce the highest quality results possible through improved shadowing. This is

because, as discussed above, shadows play an integral part in perception of detail and depth. For example, a shading and lighting method using hardware-acceleration with the aim of being as close to photorealism as possible was presented in 1999, using global illumination and multipass methods combined with normal mapping to produce images with greater realism (Heidrich & Seidel, 1999).

Much later, shadow accuracy and detail was improved further by combining normal maps (higher-detail variation of bump mapping technology) with Precomputed Radiance Transfer methods (Sloan, 2006). Precomputed Radiance Transfer (PRT) is a means by which complex lighting effects are able to be rendered in real time by computing these lighting interactions ahead of time.

Lastly, in 2007, an employee of Valve Studios further improved shadowing of normal maps by using radiosity normal mapping to increase shadow softness, which gave an increased sense of depth and detail (Green, 2007). This same technique is used to great effect in several Valve games, such as *Half-Life 2* and *Team Fortress 2*.

#### 2.3 Summary

This chapter has provided a brief explanation and historical account of bump mapping techniques, as well as evidence for the importance of shadows and shading in discerning detail and depth. This chapter also illustrates the widespread use of bump mapping techniques, and their importance in real-time rendering applications. There is however very little research into finding how normal maps affect the difference threshold for level-of-detail models. This is the gap that this study seeks to fill.

#### **CHAPTER 3 METHODLOGY**

This chapter will outline the research design, population, and variables involved in this study.

#### 3.1 Design

This study sought to identify the effects of normal maps on the just-noticeable-difference of level-of-detail in CG character models. In order to determine this relationship, a quantitative testing procedure was employed. Test participants were also first asked to fill out a preliminary survey that identified past experience with computer graphics, college major/degree, gender, and age. No further identifying information will was collected. The purpose of this pre-test was to identify any causes for different results between certain demographics, but these were not used to draw any definitive conclusions.

After this pre-test, participants were presented with an animation displaying two computer-modeled objects with different levels of surface detail side by side. Each increasing level of detail is composed of four times the number of polygons as the last, in a process known as *subdivision*, wherein a polygonal face is divided into four smaller faces, and so on.

As there is some precedence for testing applying Weber's Law of Just Noticeable Difference to visual stimuli, participants were asked to indicate whether they perceive any difference in detail between the two models (Tao, Li, Lu, & Gao, 2009). A variant of the Bruceton analysis, or "staircase" method of testing was used for this study due to its combined efficiency and relative accuracy for determining stimulus thresholds (Cornsweet, 1962). In this variant, the first set j in the test displays the two lowest levels of detail for the model. If the participant was able to identify any differences between the two animations, the test proceeds to the next set j+1, which displays the highest-detail model from the last set, and the next highest detailed model. This continues as long as the participant is able to discern differences, or until the last set is reached. If the participant is *unable* to discern any differences, the next set will decrement j-1. This is repeated K=3 times (Dixon & Mood, 1948).

After the test has gone through three reversals, or the participant manages to discern differences in the final detail set, the test randomly progressed to the next of five characters. After all five characters were completed the final answer which triggered the end of each character set was taken as that participant's threshold value.

Because of the high level of predictability in this testing method, it is possible that participants may have discovered this pattern and were able to "cheat" by giving false data, assuming that if they continue to say "yes", the set *j* will continue to increment. This is offset, however, by the equal likelihood that the participant was "honest", but it does pose a confounding element to the data. A double staircase-method is sometimes utilized to offset this limitation (Cornsweet, 1962). However, this method was not used due to the discreet nature of the stimulus being judged by the participant, owing to each

subsequent level of detail being four times as dense as the last due to the nature of mesh subdivision. Had there been a greater number of possible displayed levels of detail, a double staircase method might have been appropriate. This study compensated in part for this predictability by randomly including false positive sets in which the compared models were identical, and also by randomly reversing the order that the models were displayed within the set (i.e., the higher-detail model may be displayed to the left in one set, and to the right in another.)

The displayed models made two full rotations over the course of 20 seconds, with a 20 second timer. If the 20 seconds elapsed before participants could decide if a difference existed, it would automatically be counted as an incorrect answer and load the next set accordingly. The 20 second time limit was implemented because, in addition to the model being animated to make a full rotation once every ten seconds, and it was judged that participants would need at least two full rotations in order to give participants ample opportunity to study the object in full (Rock, Wheeler, & Tudor, 1989).

Participants were not informed that normal mapping techniques were being used, as the effect of pointing this out may have skewed the results. Participants needed only to identify whether there was any difference between the two animations in each set. The test employed animations as opposed to static images because of the importance of shadow movement in determining surface details (Wanger, 1992). The control group was shown the same series of animations, but without any normal-mapping or detail-simulating effects to determine significance.

The average value of each reversal for each participant was taken as that participant's JND value. The mode of each JND value for each participant were then plotted against the polygon count (displayed as the character "set").

#### 3.2 Participants

The study population was open to any participants. The sample population consisted of 74 participants from a range of backgrounds. A convenience sample was collected via email and social media, with ages ranging from under 20 years to over 35, with a roughly even split between male and female. A majority of participants were college students in the Computer Graphics Technology major at Purdue University, with 24 participants falling into that category.

Table 3.1. Basic subject demographics (See Appendix A for full listing of each participant)

Group	Male	Female	Student	Non Student
Experimental	19	16	24	11
Control	21	18	30	9

#### 3.3 Variables

The variables in this study were as follows:

- Independent Variables:
  - o Polygonal detail of non-textured humanoid character models
  - o Polygonal detail of normal-mapped humanoid character models
- Dependent Variables:
  - o Just Noticeable Difference threshold

#### 3.4 Measures

Data was collected through a PHP website which recorded the participant's age, gender, and college background. Previous familiarity with computer generated media and technical graphics techniques were collected using a Likert scale. A rough estimate of the average amount of time spent per week consuming digital media was also collected. Having entered these data, the participant would then enter the study proper, where he or she was presented with a series of videos comparing two different versions of computer generated character models side by side. Participants would then be asked to report whether they could perceive any visual differences between the objects being displayed at each step. Each step in this test was recorded as a "yes" or a "no". The final answer to each character set was taken as the "threshold" value, or the point at which they could no longer tell any visual differences. This process was repeated with five character models.

#### 3.5 Materials

Materials used in this study included the invitation email and the PHP website survey, which was composed of a pre-test survey and the primary study survey. In the primary survey, participants were presented with a series of videos and were asked to answer whether they could detect any differences between the models displayed. There were five characters that participants observed, and each character had six sets of animations. Each side-by-side comparison of the character models was in a single video clip. In addition to the comparison sets, there was a reversed version of each set where the higher-detail model was displayed on the left as opposed to the right, and there were seven sets where the models displayed were identical.

The models used in the study were chosen to represent a reasonably wide range of organic bipedal characters in various styles and with various textures. Certain models had rough scales, folded clothing, wrinkled skin, or fur, while also incorporated additional extremities such as long ears, tails, horns, and so on. Realistic human models were not used because it was judged that there might be additional confounding elements at work, where the human mind is finely tuned to recognize human features, and might serve to increase the sensitivity to differences in detail over those of the other characters (Mori, 1970).

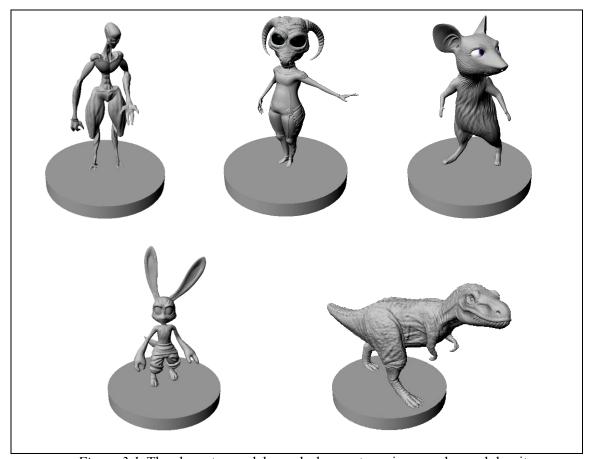


Figure 3.1. The character models used, shown at maximum polygonal density

Participants were divided into two groups, one in which the displayed models were textured with normal maps, and one in which the models were not textured. In total, including both groups, 190 video clips were used in the study, though each participant may have at most seen only half of them.

#### 3.6 Procedure

This quantitative study sought to determine whether normal mapping had a statistically significant effect on participants' ability to discern visual differences between differing levels of detail. Demographic data was also collected prior to the study in order to identify age, gender, college background, and previous familiarity and exposure to computer generated imagery.

At the start of the test, participants were placed into one of two groups, the Experimental group, in which normal mapped models were displayed, and the Control group, which showed identical models to the experimental group, but without normal maps. In order to ensure a roughly equal split between experimental and control groups, participants were placed alternately in each group based on the order in which they started the test.

The test consisted of a series of video clips showing side-by-side comparisons of 3D character models. There were a total of five characters shown throughout the study in pseudo-random order. The seed number that determined the pseudo-random display of characters and sets was the same for all participants, so while it would appear random to a single participant, the order was not truly random.

Each character was modeled in seven different levels of polygonal detail, ranging from one thousand polygons up to three million. Each increasing level of detail is composed of four times the number of polygons as the last level. This is because each square polygon was divided into four more polygons at each stage of increasing detail (a process known as subdividing).

These seven levels of detail were then animated to rotate, then rendered side by side in a series of comparison videos, known as "sets". Each of the five characters had six total comparison sets, with the first set comparing the first and second levels of detail, the second set comparing the second and third, and so on. In addition to these six sets, there were six additional sets with the compared models reversed, so that the higher-polygon model was on the left as opposed to the right. Finally, there were seven more comparison sets that displayed the same detail models side by side, known as "false positive" sets. These additional reversed and false positive sets were included randomly in the test to help prevent participants from identifying the testing pattern.

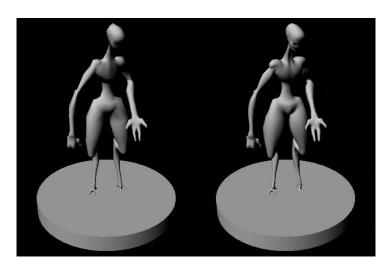


Figure 3.2. Example model comparison for control group.

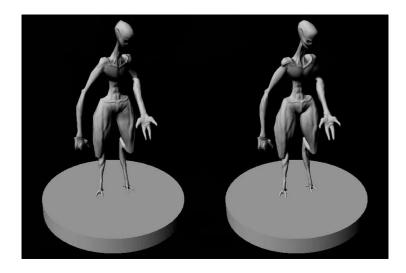


Figure 3.3. Example model comparison for experimental group.

Upon being presented with the first set of one of the five characters, participants were asked to identify whether they could make out any visual differences between the models. No further instructions were given that might bias the participant into specifically attempting to identify polygon silhouettes or texture stretching. A twenty-second time limit was imposed at each stage both to keep participants from spending too long on the test, which might cause them to exit the survey prematurely.

Once participants answered whether they could see any differences, the testing program would then either progress to the next set in the sequence, displaying higher level of detail models, or would reverse in the other direction to show a lower detail comparison, depending on whether the participant was correct in identifying differences within the set. This would repeat multiple times until the participant reached a point where they were unable to reliably discern differences within a set.

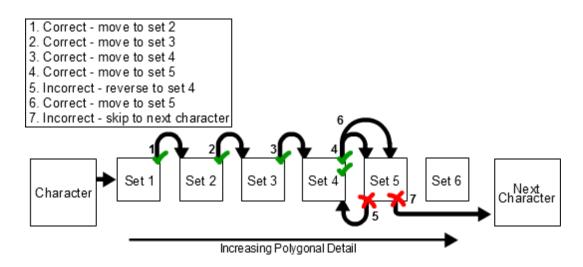


Figure 3.4. Example set progression flowchart.

This "threshold" point occurred when a specific set of circumstances were met.

The participant had to first report they could not see any differences in a set, which would then reverse them to the next lowest set. If they claimed to see differences within this set, they would then return to the higher set. If they once again reported to not see any differences in this higher set, this could be counted as the threshold point. An example of a set where the average participant was unable to reliably discern visual differences is shown in Figure 3.5. The participant would then be moved randomly to another character model, and the process would repeat until another threshold was found, and so on. Once the participant found his or her threshold set for each of the five characters, that individual's test was concluded.

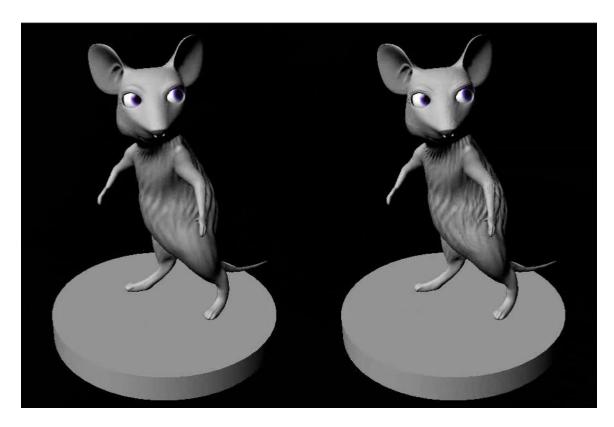


Figure 3.5. Set five of character three within the control group (non-textured).

# 3.7 Analysis

The analysis for the data gathered from this survey compares the average JND threshold to determine whether there was a statistically significant difference between the average responses of the experimental and control groups. The data was first divided into these two groups, and then again for each of the five characters. The JND threshold for each character within each group is averaged, and a separate average is calculated for each overall group's responses. These averages would then be compared to determine statistical significance and standard error. The character averages would also be compared to determine whether the differences between them had a significant impact on the overall averages for each group.

The pre-test survey data was collected in order to be compared to the results from the primary test survey in order to identify any effects different demographics might have on the results, and whether those effects are significant.

## 3.8 Summary

This chapter outlined this study's design, population, variables and measures, and the procedure used. The test is intended to determine whether the use of normal maps has a significant effect on the perception of differences between different levels of polygonal detail. The collected data will be presented in the next chapter.

#### **CHAPTER 4 RESULTS**

This chapter presents the results of the experiment survey without attempting to draw any conclusions. The next chapter will go into greater depth in analyzing the collected data.

Results from this study fall into two categories. The first is the response data gathered during the study and how the two experiment groups relate to each other, and the second involves demographic data used to investigate the existence of any interactions with the test results.

### 4.1 Survey of Just Noticeable Difference Threshold

Data from 74 participants were collected. Participants were divided into two groups; the experimental group with 35 participants, and a control group with 39. Not all participants completed the full run of five character sets, but since the characters were presented in pseudo-random order, the data from those characters they did complete is still useable. Participants' data was discarded if they did not complete at least one character set.

The threshold for each group was averaged, as shown in Table 4.1. The mean JND threshold for the control group was 4.891 with a standard error of 0.156 and 61.086 degrees of freedom, and the mean for the experimental group was 1.933 with a standard

error of 0.172 and 63.609 degrees of freedom. Averages were also taken for each character within the two groups, as shown in Table 4.2.

Table 4.1. Estimated marginal means of JND set threshold per group

				95% Confidence Interval		
Group	Mean	Std. Error	df	Lower Bound	Upper Bound	
Control	4.891	.156	61.086	4.579	5.203	
Experimental	1.933	.172	63.609	1.589	2.277	

Table 4.2. *Total mean JND threshold per group, and per character* 

Group	Total	Char. 1	Char. 2	Char. 3	Char. 4	Char. 5
Control	4.97	4.97	4.91	4.82	5.28	4.86
Experimental	1.93	1.90	1.78	1.93	2.11	1.96

An analysis of variance (ANOVA) shown in Table 4.3 was used to determine the significance interval of the two groups' results. The participant's experimental group was shown to have a p-value of 0.000. The individual character set across both groups showed a p-value of 0.623. The interaction between the participant group and the individual character was 0.950.

Table 4.3. ANOVA Type III Tests of Fixed Effects

Source	Numerator df	Denominator df	F	Significance
Intercept	1	62.455	862.424	0.000
Group	1	62.455	162.018	0.000
Character	4	242.888	0.656	0.623
Group * Character	4	242.888	0.177	0.950

The mode threshold data for each group was also organized into two graphs showing the amount of times each set was taken as a participant's JND threshold. These are shown in Figure 4.1 and 4.2.

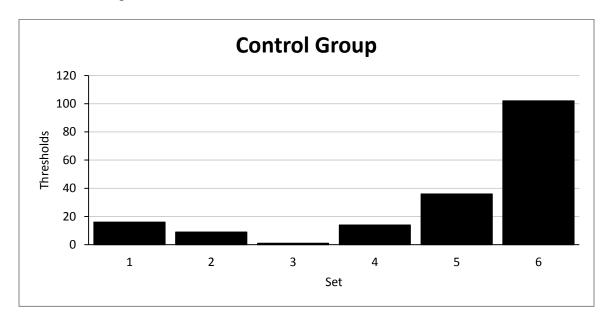


Figure 4.1. Modes for each detail set for all characters within the Control group.

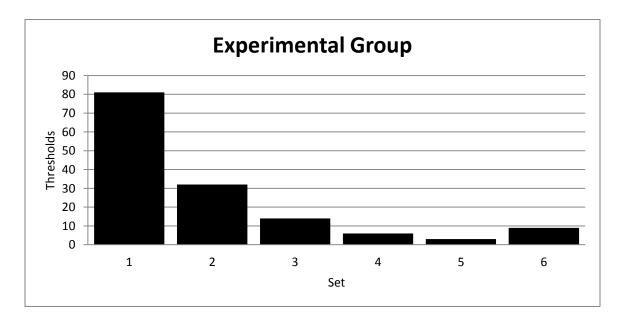


Figure 4.2. Modes for each detail set for all characters within the Experimental group.

## 4.2 Demographic Survey

Demographic data from 74 participants were collected in order to investigate the existence of any correlations with the results of the just noticeable difference (JND) survey. The recorded demographic data includes participants' age, gender, college major, and familiarity with computer generated media and computer graphics development techniques, as well as the average hours per week spent viewing or otherwise consuming computer generated media. Additionally, the participant's screen resolution was recorded. The results of the ANOVA test of fixed effects for demographics are shown in Table 4.4.

Table 4.4. ANOVA Type III Tests of Fixed Effects of Demographics

Source	Numerator df	Denominator df	F	Significance
Intercept	1	21	36.133	0.000006
Group	1	21	32.074	0.000013
Age	4	21	0.249	0.907
Gender	1	21	1.272	0.272
College Major	20	21	0.925	0.568
Media Familiarity	4	21	0.200	0.936
Technical Familiarity	4	21	1.184	0.347
Media Consumption	5	21	0.272	0.923
Screen Resolution	10	21	2.715	0.026

# 4.3 Summary

This chapter presented the experiment and demographic data resulting from the study. The significance of the results suggests that the null hypothesis, that normal maps do not have a significant impact on discerning differences between levels of detail in the presented character models, can be safely dismissed. It also showed that additional

factors such as age, gender, college major, and previous familiarity with computer graphics media does not significantly impact the participant's ability to discern differences between levels of detail in the character models presented. The next chapter will discuss these results in greater detail, and will attempt to draw conclusions from the data presented in this chapter.

## **CHAPTER 5 CONCLUSIONS**

This chapter explores the conclusions that can be drawn from the earlier presented data. These include reasons for the slight variance in means between characters, thoughts on the impact demographics have on the viewer's perceptions of detail, and possible avenues for future research.

### 5.1 Significance of the Testing Group

Firstly, this study attempted to identify the point at which the level of polygonal density in a three-dimensional model becomes indistinguishable from previous levels of detail. This threshold was found to be closest to the fifth set, which corresponds to a range of roughly 240,000 to 950,000 polygons. Secondly, the study attempted to examine whether and to what degree normal maps alter this threshold. It was found that normal maps do indeed alter the threshold by a statistically significant degree, reducing the range to the second set, corresponding roughly to between 3,000 and 14,000 polygons, with a p-value of 0.000013.

Since differences within sets beyond that point could not be reliably discerned by the average participant, it follows that this is the point beyond which increasing polygonal surface detail is unnecessary to achieve the same effect. This is the

fundamental purpose of normal mapping; to make a low-detail model appear as similar to a high-detail model as possible while requiring the fewer system resources to render.

Though differences between the displayed characters were obvious, they did not have a statistically significant impact on the total average response. This suggests that the results found here are applicable to a wider range of character models than just those used in the study itself.

However, it was found that the participant's screen resolution did have a statistically significant effect on the outcome. Unfortunately, this study could not fully control for the participants' screen resolution, as the test was conducted online and outside any controlled testing environment. This result is not surprising, in that on-screen details will naturally be easier to distinguish when there is a greater amount of information displayed on screen, as is the case with higher resolution screens.

These results compare favorably to the current standard in the gaming industry of designing character models to be around 10,000 polygons, augmented with normal maps in order to simulate additional details.

This study suggests that increasing detail beyond the 14,000 polygon point begins to yield diminishing returns in the area of perceived detail. Development of dense polygonal meshes for organic characters is therefore provided with a specific level of detail to develop toward, but which is not advantageous to exceed.

# 5.2 Significance of Demographics

Of the categories of demographic data collected, none were found to have a statistically significant impact on the outcome of the study. Of these, the reported

familiarity with computer graphics development seemed to have the greatest impact on the results, but not enough to be significant. Students in Computer Graphics Technology tended to have higher thresholds in both the control and experimental groups, but this was not found to be statistically significant. Age, gender, familiarity with computer-based media, and hours per week spent consuming CGI media were shown to be the least significant. It was not anticipated that gender would have a significant impact, but this result does help refute any existing stereotypes that imply older generations (with 35% of the test participants over the age of 35) are less adept at judging details in computer graphics.

#### 5.3 Future Research

This study has successfully indicated that normal maps have a significant effect on judging details between different levels of detail when comparing models within the same group, either normal mapped or not, rather than a direct comparison between the two. Taking this research a step further, the testing model could be adapted to include a third group, which, instead of comparing only normal mapped or untextured models to each other, compared the two different groups directly. While this study does suggest that normal maps are a viable means of simulating details, a study such as the one suggested would help solidify whether low-detail normal mapped models are really comparable to high-detail untextured models.

While uncolored character models were the subject of this study, there are many more areas of computer graphics imagery that benefit from surface detail simulation, and the results of this study are not necessarily directly applicable to these other areas. Future

studies may additionally seek to account for the effects of normal mapping on inorganic models such as architecture or inanimate objects, and on high-detail facial animation.

The effectiveness of normal mapping as a detail simulation technique may be compared to more modern styles of detail simulation, such as displacement mapping and dynamic tessellation. Such a study might also compare the system resources needed to process each of these methods.

Finally, future studies would benefit from being conducted within an environment that controls for potential confounders of the results, such having a standardized screen resolution.

#### 5.4 Summary

This chapter explored the conclusions and implications of the gathered data. The results suggest that normal maps are an effective means of simulating detail and obfuscating the differences between levels of detail in the same model. These results are further supported by the frequent and continuing use of normal maps in modern computer generated media as a means of simulating details.

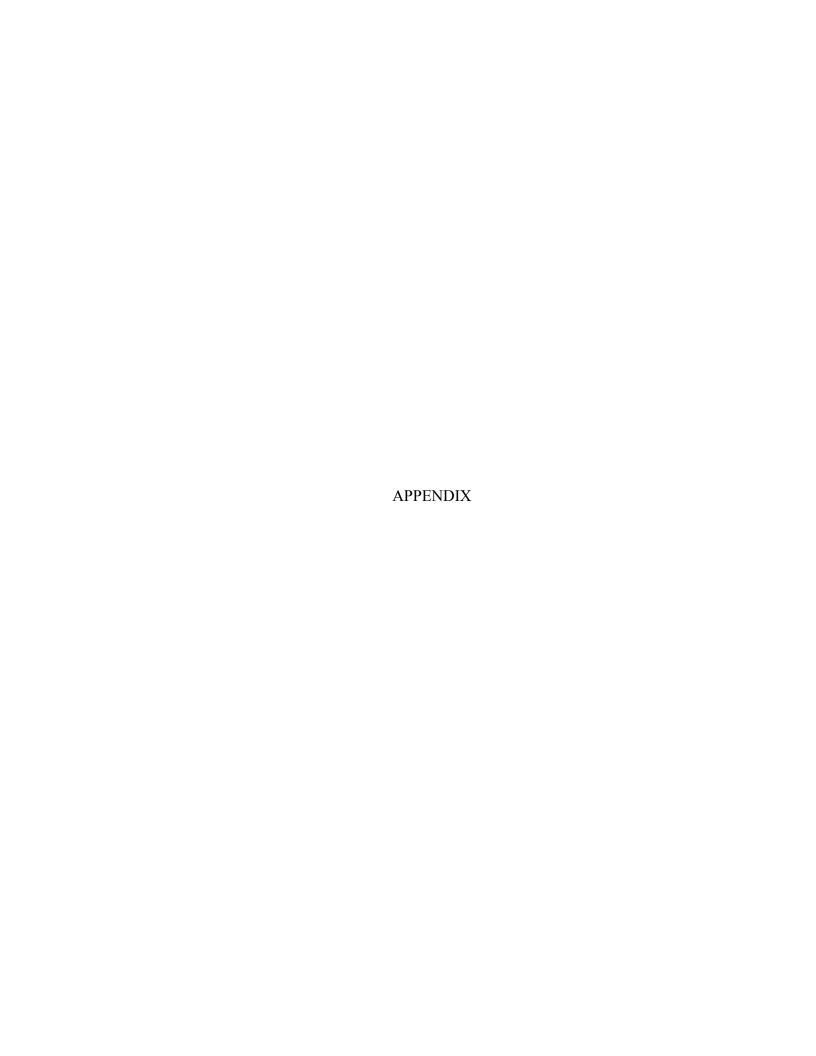


#### REFERENCES

- Becker, B. G., & Max, N. L. (1993). Smooth transitions between bump rendering algorithms. *Proceedings of the 20th annual conference on Computer graphics and interactive techniques SIGGRAPH '93*, 183–190. doi:10.1145/166117.166141
- Blinn, J. F. (1978). Simulation of wrinkled surfaces. *ACM SIGGRAPH Computer Graphics*, 12(3), 286–292. doi:10.1145/965139.507101
- Cignoni, P., & Montani, C. (1998). A general method for preserving attribute values on simplified meshes. *Visualization'98*. ..., 59–66,. doi:10.1109/VISUAL.1998.745285
- Cohen, J., Olano, M., & Manocha, D. (1998). Appearance-preserving simplification. Proceedings of the 25th annual conference on Computer graphics and interactive techniques - SIGGRAPH '98, 115–122. doi:10.1145/280814.280832
- Cornsweet, T. (1962). The staircase-method in psychophysics. *The American journal of psychology*, 75(3), 485–491. Retrieved from http://www.jstor.org/stable/10.2307/1419876
- Dixon, W., & Mood, A. (1948). A method for obtaining and analyzing sensitivity data. *Journal of the American Statistical* ..., 43(241), 109–126. Retrieved from http://www.tandfonline.com/doi/full/10.1080/01621459.1948.10483254
- Green, C. (2007). Efficient self-shadowed radiosity normal mapping. *ACM SIGGRAPH* 2007 courses on SIGGRAPH '07, 1. doi:10.1145/1281500.1281664
- Heidrich, W., & Seidel, H.-P. (1999). Realistic, hardware-accelerated shading and lighting. Proceedings of the 26th annual conference on Computer graphics and interactive techniques - SIGGRAPH '99, 171–178. doi:10.1145/311535.311554
- Karavidas, M., Lim, N. K., & Katsikas, S. L. (2005). The effects of computers on older adult users. *Computers in Human Behavior*, 21(5), 697–711. doi:10.1016/j.chb.2004.03.012
- Kilgard, M. (2000). A practical and robust bump-mapping technique for today's GPUs. *Game Developers Conference 2000*, 1–39. Retrieved from http://sylvie.alayrangues.free.fr/SiteLabo/Enseignements/DESS/Exam/bumpmap.pdf

- Krishnamurthy, V., & Levoy, M. (1996). Fitting smooth surfaces to dense polygon meshes. *Proceedings of the 23rd annual conference* .... Retrieved from http://dl.acm.org/citation.cfm?id=237270
- Mori, M. (1970). The uncanny valley. *Energy*, 7(4), 33–35. Retrieved from http://www.movingimages.info/digitalmedia/wp-content/uploads/2010/06/MorUnc.pdf
- Noma, T., & Sumi, K. (1994). Shadows on bump-mapped surfaces in ray tracing. *The Visual Computer*, (Blinn 1978), 330–336. Retrieved from http://link.springer.com/article/10.1007/BF01900827
- Peercy, M., Airey, J., & Cabral, B. (1997). Efficient bump mapping hardware. Proceedings of the 24th annual conference on Computer graphics and interactive techniques - SIGGRAPH '97, 303–306. doi:10.1145/258734.258873
- Policarpo, F., Oliveira, M., & Comba, J. (2005). Real-time relief mapping on arbitrary polygonal surfaces. *Proceedings of the 2005* ..., *I*(212), 155–163. Retrieved from http://dl.acm.org/citation.cfm?id=1053453
- Rock, I., Wheeler, D., & Tudor, L. (1989). Can we imagine how objects look from other viewpoints? *Cognitive Psychology*, *210*, 185–210. Retrieved from http://www.sciencedirect.com/science/article/pii/0010028589900078
- Schilling, A. (1997). Towards real-time photorealistic rendering: challenges and solutions. *Proceedings of the ACM SIGGRAPH/EUROGRAPHICS* .... Retrieved from http://dl.acm.org/citation.cfm?id=258701
- Sloan, P. (2006). Normal mapping for precomputed radiance transfer. *Proceedings of the 2006 symposium on Interactive 3D* ..., 23–27. Retrieved from http://dl.acm.org/citation.cfm?id=1111415
- Tao, D., Li, X., Lu, W., & Gao, X. (2009). Reduced-reference IQA in contourlet domain. *IEEE transactions on systems, man, and cybernetics. Part B, Cybernetics: a publication of the IEEE Systems, Man, and Cybernetics Society, 39*(6), 1623–7. doi:10.1109/TSMCB.2009.2021951
- Tatarchuk, N. (2006). Dynamic parallax occlusion mapping with approximate soft shadows. *Proceedings of the 2006 symposium on Interactive 3D ..., I*(March), 14–17. Retrieved from http://dl.acm.org/citation.cfm?id=1111423
- Vadhan, S. (2012). *Pseudorandomness* (Vol. xx, pp. 1–93). Retrieved from http://userweb.cs.utexas.edu/users/diz/395T/09/salil1.pdf

Wanger, L. (1992). The effect of shadow quality on the perception of spatial relationships in computer generated imagery. *Proceedings of the 1992 symposium on Interactive 3D* ..., 39–43. Retrieved from http://dl.acm.org/citation.cfm?id=147161



Appendix A

Table A-1 *JND thresholds per character* 

User ID	Group	Char 1	Char 2	Char 3	Char 4	Char 5
0	Experimental	1	1	1	6	1
71	Control	5	6	6	6	5
73	Control	5	6	6	6	5
74	Experimental		6	2	1	
75	Control	6	4	6	5	5
76	Experimental	1	1	2	2	1
77	Control	4	6	6	6	2
78	Experimental	4	2	1	1	4
79	Control	6	2	6	6	6
81	Control	1				6
82	Experimental	2	2	1	2	2
83	Control	5	4	6	6	4
84	Experimental		1			
85	Control	5	6	1		5
86	Experimental	1	1	1	1	1
87	Control	6	5	1	5	5
89	Control	6	6	6	6	4
92	Experimental	1	3	6	2	1
93	Control	6	2	6	6	5
94	Experimental	1	1	1	1	1
95	Control	6	6	5	6	5
97	Control	6	6	4	6	5
99	Control	6	6	6	6	5
101	Control	6		6	6	6
102	Experimental	6	3	2	3	3
103	Control	4	6	6	6	5
104	Experimental	1	6	1	3	2
105	Control	6	6	6	5	6
106	Experimental	1	1	1	1	
107	Control	6	6	6	6	6
108	Experimental	3	1	3	3	3
110	Experimental	1	2	2		2
111	Control	1		2	4	5
112	Experimental	3	4	6	6	6
115	Control	6			6	2
118	Experimental	1	1	1	1	1

Table A-1, continued

120	T 1			4		
120	Experimental	1		1		
121	Control	5	6	6	6	5
122	Experimental	1	1	1	1	1
123	Control	2	1	2		5
124	Experimental		2			
126	Experimental	2	2	3	2	1
128	Experimental	2	1	2	2	3
129	Control	1				6
130	Experimental	1	1	2	1	1
131	Control	6	6	5	6	6
132	Experimental	5	1	4	6	6
133	Control	6	6	6	6	6
134	Experimental	1	1	2	1	2
135	Control	5	6	1	6	4
136	Experimental		2			
137	Control				1	
138	Experimental	1	1	1	1	1
139	Control	6	5	6	5	6
140	Experimental	3				1
141	Control	5	6	1	6	1
143	Control	1	6	4	5	3
144	Experimental	1	1	1	1	1
145	Control	5	1		6	
146	Experimental		1			
147	Control	6	6	6	5	6
148	Experimental	1	2	1	5	1
149	Control	6	4	5	5	4
150	Experimental	2	2	4	2	1
151	Control		1		4	
153	Control	5	2	6	6	2
154	Experimental	1	1	1	1	1
155	Control	6	6	6	6	5
156	Experimental	2	1	6	2	4
157	Control	5	6	6	6	6
158	Experimental	5	4	1	3	6
159	Control	6	6	1	1	6
160	Experimental	1	1	1	2	1
161	Control	6	6	6	4	6
-						

Table A-2 Subject demographic data

Age	Gender	Major	Media	Graphics	Consumed	Height	Width
26-30	female	Accounting	Disagree	S. Disagree	1-5 hrs	975	1219
> 35	male	Business	Agree	Neutral	1-5 hrs	720	1280
> 35	female	Communication	S. Disagree	S. Disagree	1-5 hrs	900	1440
26-30	male	Comp & Info Tech	Neutral	Neutral	1-5 hrs	768	1366
31-35	male	Comp & Info Tech	Disagree	S. Disagree	< 1 hrs	900	1440
21-25	male	Computer Engineering	Disagree	S. Disagree	> 20 hrs	900	1440
< 20	female	Comp Graphics Tech	Neutral	Disagree	10-20 hrs	768	1366
26-30	male	Comp Graphics Tech	Agree	Agree	10-20 hrs	900	1600
21-25	male	Comp Graphics Tech	Neutral	Disagree	< 1 hrs	864	1536
21-25	female	Comp Graphics Tech	Agree	Disagree	5-10 hrs	864	1536
21-25	male	Comp Graphics Tech	Agree	Disagree	> 20 hrs	768	1366
21-25	female	Comp Graphics Tech	Agree	Neutral	> 20 hrs	1080	1920
21-25	male	Comp Graphics Tech	S. Agree	S. Agree	> 20 hrs	900	1440
21-25	female	Comp Graphics Tech	S. Agree	S. Agree	> 20 hrs	800	1280
21-25	male	Comp Graphics Tech	S. Agree	S. Agree	10-20 hrs	1200	1920
21-25	male	Comp Graphics Tech	S. Disagree	S. Disagree	> 20 hrs	800	1280
< 20	male	Comp Graphics Tech	Disagree	S. Disagree	5-10 hrs	900	1600
21-25	female	Comp Graphics Tech	Neutral	Disagree	1-5 hrs	768	1366
21-25	male	Comp Graphics Tech	S. Agree	S. Agree	> 20 hrs	768	1366
< 20	female	Comp Graphics Tech	Agree	Neutral	1-5 hrs	768	1366
31-35	male	Comp Graphics Tech	Agree	Disagree	> 20 hrs	1200	1920
< 20	male	Comp Graphics Tech	S. Disagree	S. Disagree	0 hrs	1050	1680
21-25	male	Comp Graphics Tech	Agree	Agree	> 20 hrs	1080	1920
31-35	male	Comp Graphics Tech	Agree	Disagree	1-5 hrs	1050	1680
21-25	female	Comp Graphics Tech	S. Agree	S. Agree	1-5 hrs	1024	1280
21-25	male	Comp Graphics Tech	S. Agree	S. Agree	5-10 hrs	1200	1920
21-25	male	Comp Graphics Tech	S. Agree	S. Agree	1-5 hrs	900	1600
> 35	female	Comp Graphics Tech	S. Agree	S. Agree	> 20 hrs	1050	1680
26-30	male	Comp Graphics Tech	Agree	Agree	1-5 hrs	1080	1920
26-30	male	Comp Graphics Tech	S. Agree	Agree	10-20 hrs	768	1366
> 35	male	Computer Science	Disagree	S. Disagree	10-20 hrs	1080	1920
21-25	male	Computer Science	Agree	Agree	> 20 hrs	1200	1920
> 35	male	Economics	Disagree	Disagree	1-5 hrs	568	320
< 20	male	Electrical Eng Tech	Neutral	Neutral	5-10 hrs	1080	1920
21-25	male	Electrical Eng Tech	Neutral	Disagree	5-10 hrs	864	1536
< 20	female	Electrical Eng Tech	Disagree	S. Disagree	5-10 hrs	768	1366
> 35	female	English	Neutral	Disagree	< 1 hrs	768	1366

Table A-2, continued

> 35	female	English	Disagree	Disagree	< 1 hrs	768	1366
21-25	female	Fine Arts	Neutral	Neutral	5-10 hrs	900	1440
> 35	female	Health Sciences	Neutral	Neutral	< 1 hrs	768	1366
26-30	male	History	Agree	Agree	10-20 hrs	768	1366
31-35	male	History	Disagree	S. Disagree	10-20 hrs	480	320
31-35	female	Law and Society	Neutral	Disagree	> 20 hrs	1080	1920
> 35	female	Management	Agree	Neutral	5-10 hrs	768	1366
31-35	female	Materials Engineering	Agree	Neutral	10-20 hrs	900	1600
31-35	male	Mathematics	Neutral	Neutral	> 20 hrs	568	320
< 20	female	Mech Engineering Tech	Agree	Disagree	10-20 hrs	800	1280
21-25	male	Mech Engineering Tech	Agree	S. Disagree	< 1 hrs	1200	1600
31-35	male	Meteorology	Agree	Agree	1-5 hrs	768	1366
> 35	female	Nursing	S. Disagree	S. Disagree	> 20 hrs	568	320
26-30	female	Nursing	S. Disagree	S. Disagree	5-10 hrs	568	320
21-25	female	Org Leadership & Supervis	S. Agree	S. Agree	0 hrs	1080	1920
31-35	male	Theatre	Disagree	Neutral	< 1 hrs	1024	1280
> 35	female	Visual Comm Design	S. Agree	Agree	0 hrs	1200	1920
21-25	female	None	Agree	Agree	5-10 hrs	1200	1920
21-25	male	None	S. Disagree	S. Disagree	> 20 hrs	900	1600
> 35	female	None	Disagree	Disagree	10-20 hrs	1050	1680
31-35	male	None	Agree	Agree	10-20 hrs	568	320
> 35	female	None	Disagree	S. Disagree	5-10 hrs	1080	1920
> 35	male	None	Agree	Disagree	1-5 hrs	568	320
> 35	male	None	Agree	Disagree	10-20 hrs	1080	1920
> 35	male	None	Agree	Agree	1-5 hrs	1080	1920
> 35	male	None	Agree	Agree	5-10 hrs	568	320
> 35	female	None	S. Disagree	S. Disagree	5-10 hrs	900	1600
> 35	female	None	S. Disagree	S. Disagree	10-20 hrs	1024	768
> 35	female	None	Disagree	S. Disagree	10-20 hrs	592	360
> 35	female	None	Disagree	S. Disagree	1-5 hrs	768	1024
> 35	female	None	S. Disagree	S. Disagree	10-20 hrs	768	1366
31-35	male	None	Agree	Disagree	10-20 hrs	768	1366
31-35	male	None	Agree	Disagree	10-20 hrs	768	1366
> 35	female	None	Agree	Disagree	> 20 hrs	1050	1680
> 35	male	None	Disagree	Neutral	5-10 hrs	900	1440
> 35	female	None	S. Disagree	S. Disagree	1-5 hrs	900	1600
> 35	female	None	Agree	Neutral	10-20 hrs	768	1366