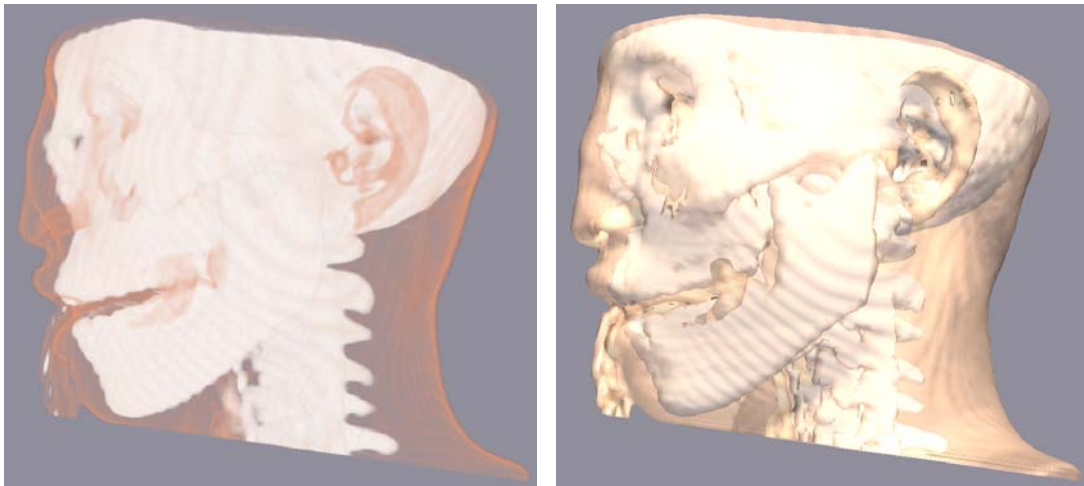


## 1. INTRODUCTION

### 1.1 Motivation

Scientific disciplines widely use visualization as a way to show data. Although data can be shown in many formats, including numbers, visualization is a good choice for data representation because the visual system is the highest bandwidth sensory input in humans. As a result, images are an excellent way to show large quantities of data, as well as a natural way to show spatially-distributed data. Spatially-distributed data means data with inherent spatial properties, such as a medical scan of a human body, as opposed to data that is not inherently spatial, like nodal relationships in a graph. Often, it is necessary or desirable to show layered data. Figure 1 shows an example of some layered, spatially-distributed data: a scan of a human head. Two common visualization methods are shown: volume and surface visualization.



*Figure 1. Volume Rendering and Surface Shading Comparison. The data shown is from the Visible Human data set of a human head, using volume and surface rendering. Layers are shown that correspond to skin and bone.*

---

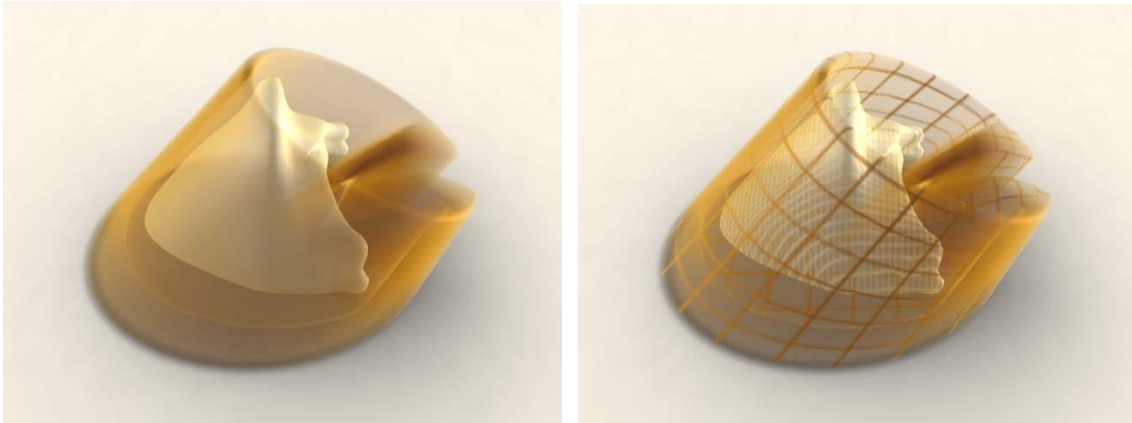
This thesis/dissertation follows the style of *ACM Transactions on Graphics*.

Reasons for visualizing layered data are varied. For example, in the medical field, doctors must understand spatial relationships between body tissue layers for surgical planning. Geologists are interested in sediment layers for understanding rock formation as well as predicting locations of natural resources such as oil and gas. Technical illustrations of machinery, anatomy, or architectural drawings often need to use layered surfaces to show relationships between parts of an object. Finally, disciplines such as meteorology and oceanography use isosurfaces of variables like pressure or temperature to analyze the dynamics of complicated flow systems.

One important topic of research is the rendering of layered surfaces. When data is layered, there is an inherent problem when data on one layer obscures and conflicts with other data. The main challenge of visualizing layered data is showing each layer of data as clearly as possible, while minimizing interference across data layers.

One way to significantly improve surface visualization is to add texture. Figure 2 shows how the addition of texture can clarify surface shape in areas where shading provides no little or no information, such as the front of the hoof. However, care must be taken in the choice of textures because there can be a strong tendency toward visual conflict between the surfaces. Since the possible texture variations are enormous, finding optimal textures is not an easy task.

The approach used here is to conduct a series of experiments designed to find guidelines for using texture. Results from each experiment are synthesized with previous work in surface visualization and texturing. A simple model is hypothesized for how to optimize texture, which will be built based on expert knowledge, the structure of the human visual system, and previous experiments in rendering and texturing of surfaces. The model consists of guidelines for how to create good textures, and theories for why the textures are good. It explores what features are most important in layered surface texturing, and ways in which the features interact both within and between surfaces.



*Figure 2. Textured and Shaded Comparison. A horse hoof is shown with an outer wall and an inner coffin bone with shaded surfaces (left) and textured and shaded surfaces (right).*

Many factors go into creating a good surface visualization. Some examples might include lighting and shading, coloring and opacity, texture, shadows, motion, or non-photo-realistic rendering techniques such as edge enhancement. Some of the other perceptual cues are discussed in more detail in the background section. Many of these cues are commonly used in scientific, and others are not for various reasons. One perceptual cue that has a lot of flexibility is texture. Textures have a broad space of possibilities, and yet little research has been done on what factors make the best textures.

## **1.2 Research Focus**

The focus of this dissertation is on texturing of surfaces. Texturing is one of the more powerful, and yet rarely used cues in surface rendering. It has been shown to be a useful perceptual cue both in single and layered surface visualization. However since it is seldom used in scientific visualization and has only occasionally been researched in perceptual studies, the huge space of texture possibilities is not well understood. One motivation for looking at texture is that it is a part of every real-world object. Even seemingly smooth objects nearly always have a very fine texture such as dust or scratches. These textures provide perceptual cues to how the surface is shaped. Figure 3 shows examples of small and large-scale textures that aid in surface shape perception.



*Figure 3. Texture Examples. A cloth's texture shows how it is folded. The texture of the rock shows how geological features are carved into the sediment layers in Big Bend National Park.*

Studies on optimization of textures have only been done for a few parameters. These generally studied the directionality of the textures. Comparisons have been made of isotropic (rotationally invariant) vs anisotropic textures [Sweet and Ware 2004 ; Interrante and Kim 2001], textures with multiple directions, and various heuristics for aligning the texture direction with surface characteristics. However, no evaluation has yet been done on stylistic aspects of texturing such as color, regularity and size. These parameters could be of critical importance for layered surface texturing, especially when interaction between the surfaces is considered.

Fully specifying the stylistic aspect of layered surface texturing requires many parameters and allows for many possible interactions among parameters. This type of problem cannot be studied with only a few controlled experiments because the number of variables is too great. Therefore, this set of studies uses two types of experiments combined with perceptual theory to triangulate results and develop theories for texturing of layered surfaces. Since little is known about the stylistic aspects of layered surface texturing, initial experiments were geared toward attaining general results about a broad spectrum of parameters. These experiments were not designed to yield statistically significant results for a large number of parameters because the amount of data required to sample a large parameter space is unfeasible. However trends were noted in order to guide the design of more specific experiments measuring the significance and optimal values for only a few parameters. These later experiments were designed to support,

disprove, and/or fine-tune theory based on the broader experiments. The result are heuristics and perceptual theories based on both broad and deep investigation into layered surface texturing. These theories will be useful to application developers that want to show layered surfaces for use in scientific analysis or explanatory visualizations.

### 1.3 Texture Parameterization

To explore the possible texture variations, it is necessary to define what a texture is, and find a set of parameters for creating textures. We consider textures to be made up of some finite set of marks. Marks have a number of features, which when varied can create any arbitrary texture. This set of features is shape, size, direction, placement, coloring and opacity, as shown in Figure 4.

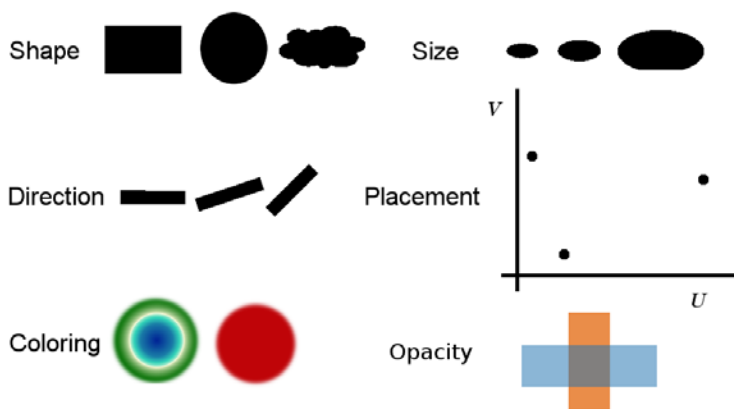


Figure 4. Texture Mark Parameterization. Examples of possible variations in shape, size, direction, placement, coloring and opacity.

Any of these features may be sub-parameterized for specific types of textures. For example, coloring might be parameterized as a hue, saturation and value. Shape might be parameterized by the major and minor axes of an ellipse, and placement might be parameterized by texture coordinates or shape parameters of the surface. Parameterization of mark features in this way sets constraints on the possible textures that can be created, as well as the distribution of textures.

In theory, each mark could vary each property independently, and the combination of all marks would create the visualization. However in practice, simplifying assumptions were made, and some attempt is made to account for the interactions between marks. In this series of studies, marks are grouped into sets with identical or similar shape, size and coloring, and the placement of each mark is not independent, but rather takes place in a general organization of marks. The background is dealt with separately as having a color and opacity. Also, the shape parameter is simplified to only a few simple cases, such as lines, curves, rectangles, ovals or dots.

Within these five broad parameters, quite a bit of interaction is possible. Following is a list of known interactions with examples. Size of marks interacts with their placing. Clearly, large marks cannot be placed very close together without overlapping; so optimal spacing will depend on the size of the mark. Mark shape interacts with mark direction because for a circular mark shape, direction does not matter, but for a line direction might matter quite a bit. Also, mark size and shape interact. Small details in a mark's shape can be lost if the mark is drawn very small. Finally, color interacts with several variables: size, shape and placement. The overall size of a mark determines how strongly its color is perceived [Stone 2003]. Similarly, thin lines may not appear to have the same color as round blobs of the same area, even if the physical color is identical. Lastly, placement of the marks affects the apparent color because of simultaneous color contrast [Albers 1975].

#### **1.4 Methodology**

The ultimate goal of this line of research is to develop theory about texturing of layered surfaces. To accomplish this goal we cycle through a three-step process repeatedly. The three steps shown in Figure 5 are design of experiments, analysis of results, and interpretation as theory. Each step must rely on the results of the previous step to proceed. The studies reported here go through this cycle a number of times in the process of gradually building up knowledge and theory behind layered surface texturing.

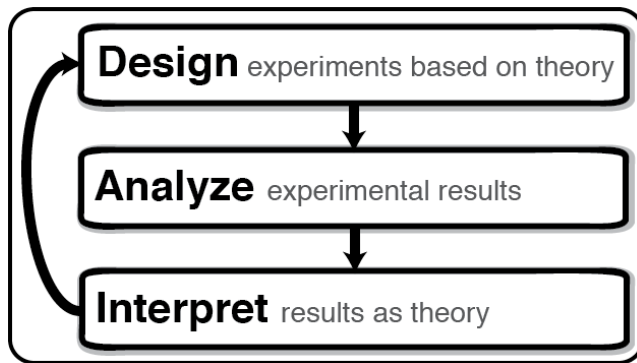


Figure 5. Methodology. Diagram of the steps used in this research of layered surface texturing.

Standard experimental design uses controlled experiments in which multiple measures are made for each possible level of one or more variable. For example, a variable might be ‘wood type’, levels might be ‘Oak, Ash, Spruce and Pine’, and the measurement might be strength. An experimenter might make strength measurements on several pieces of each type of wood, and then run statistical tests to see if the wood types had different strengths. This is easily done, but gets more difficult if more variables are included. The experimenter might also want to include information about the age of the tree, size and shape of the block of the wood, signs of rot in the wood, direction of the cut relative to the grain, and any treatments applied to the wood. The number of measurements required to test all combinations of all variables quickly becomes intractable. Running separate experiments for each variable will only work if the variables do not interact, and common sense dictates that unfortunately many variables used in layered surface texturing do interact.

Because little perceptual theory exists on the stylistic aspects of surface texturing, and a stylistic texturing parameter space is very large, initial experiments were designed with a novel methodology meant to broadly search a large parameter space. This search allows the experimenters to sparsely search the parameter space leaving the burden of finding structure in the space to the data analysis. Because the parameter space search is so sparse, these experiments would not provide reliably significant results, but

can be used to guide future controlled experiments by identifying relative importance of parameters and interactions between parameters. This is important so that time is not wasted running experiments on parameters that do not matter, or finding results that are only valid if other parameters are set to specific values. These multi-parameter experiments were designed to search an extremely large parameter space using user-guided heuristics. Although statistical significance is difficult to find with so many parameters, a variety of data mining techniques can be used to triangulate the results and gain insight into the parameter space. This multi-parameter methodology was introduced by House and Ware [2002]. Once the large parameter space has been analyzed and several hypotheses made, controlled single parameter experiments can be used to test these hypotheses. These studies varied only a few parameters, leaving others constant according to guidelines learned from theory and the previous multi-parameter experiments. Finally, results from these two-surface experiments are then applied to more than two surfaces, and analyzed to see if the two-surface methods are scalable.

The thesis is structured as follows. The background in Section 2 explores previous work in single and layered surface rendering. Work is looked at from the fields of art and perception, as well as controlled experiments related to surface rendering. Sections 3-8 describe the experiments that were run, the analysis and results. Section 3 describes a broad multi-parameter study designed to search the space of possible textures using 122 parameters to create textures. Section 4 is a similar, but slightly more focused study with only 26 parameters. Sections 5-6 document experiments varying small numbers of parameters, including size, opacity, and structure. Section 7 is an experiment designed to test the feasibility of scaling up the number of layers. Section 8 explores texturing of single surfaces to find correlations between texture, surface shape and viewing direction. Finally, the discussion and conclusions synthesize experiments and previous work into a set of guidelines with a theoretical model to motivate the guidelines.