Exploring Specular Highlight Streaks on Planar Surfaces

David Bourque

Master of Science

Computer Science

McGill University

Montreal, Quebec

2017 - 11 - 01

A thesis submitted to McGill University in partial fulfillment of the requirements of the degree of Computer Science

©David Bourque, 2017

ACKNOWLEDGMENTS

I would like to thank my supervisor, Michael Langer, for his patience, support and guidance when I was getting lost or overwhelmed. And for his suggestions, edits and help while I wrote this thesis. My Parents, and family for encouraging me to return to school to complete a Bachelors degree, which then became a Masters. And especially my wife for her unending and tireless support, and firm belief that I could accomplish this.

ABSTRACT

A highly glossy plane with small, smooth deformations viewed at an oblique angle with a light source near the horizon can produce specular reflections. The resulting specular reflections appear as long columns, oriented toward the viewer. Under the right conditions the specularities appear as illusory vertical columns below the surface, rather than as highlights on the surface. This illusion can generally be seen by observing the moon over water at night, or car headlights on a wet street. If there are several light sources the illusion of columns can be strengthened. We hypothesized that the illusion is due to the orientation of the envelope of the specularities corresponding to vertical columns, creating a vanishing point in the direction of the surface normal of the ground. This work describes the conditions under which these highlights can be seen, and details three pilot experiments performed to study their effect on visual perception of slant and material properties.

ABRÉGÉ

Un plan géométrique très brillant avec de petites déformations lisses vue à un angle oblique avec une source de lumière à proximité de l'horizon peut produire des réflexions spéculaires. Les réflexions spéculaires résultantes apparaissent sous forme de longues colonnes, orientées vers le spectateur. Dans les bonnes conditions, les réflexions apparaissent comme des colonnes verticales illusoires sous la surface, plutôt que comme des spécularités sur la surface. Cette illusion peut généralement être vue en observant la lune au-dessus de l'eau la nuit, ou les phares de voiture sur une rue mouillée. S'il y a plusieurs sources lumineuses, l'illusion des colonnes peut être renforcée. Nous avons émis l'hypothèse que l'illusion est due à l'orientation de la région occupée par les spécularités correspondant aux colonnes verticales, créant un point de fuite dans le sens de la normale à la surface du sol. Ce travail décrit les conditions dans lesquelles ces spécularités peuvent tre vues, et détaille trois expériences pilotes effectuées pour étudier leur effet sur la perception visuelle de linclinaison et des propriétés des matériaux.

TABLE OF CONTENTS

ACK	KNOW]	LEDGMENTS ii			
ABS	TRAC	Тііі			
ABRÉGÉ					
LIST OF TABLES					
LIST OF FIGURES					
1	Introd	uction			
	1.1 1.2 1.3	Introduction 1 The Illusion of Columns 3 Thesis Overview 6			
2	Litera	ture review			
	2.1 2.2	Surface Slant82.1.1Slant from Texture92.1.2Cue Combination13Specular reflections14			
3	Oculu	s Rift			
4	Specu	lar Streaks			
	$4.1 \\ 4.2$	Unique Shape26Required Surface Properties34			
5	Surfac	e Generation and Rendering			
	$5.1 \\ 5.2 \\ 5.3$	Quantitative Streak Construction39Mesh Construction41Shaders44			

6	Exper	$iments \dots \dots$
	6.1	Experiment 1
	6.2	Experiment 2
	6.3	Experiment 3 $\ldots \ldots 56$
7	Discus	sion $\ldots \ldots 57$
	7.1	Specular Streaks
	7.2	Oculus Rift
	7.3	Challenges in Defining the Task
	7.4	Future Work
	7.5	Conclusion
App	endix A	A

LIST OF TABLES

Table

4–1 Sampling the half angle vector		32
------------------------------------	--	----

page

LIST OF FIGURES

Figure		page
1–1	A sample of specular streaks	2
1-2	Specular streaks with vertical columns	4
1–3	Sidewalk art using forced perspective	5
2-1	Foreshortening example	10
2-2	Isotropy example	11
2-3	The Necker Cube	15
2-4	A sample of different reflectance types	18
4-1	Water at night cropped	27
4-2	Specularities from above	27
4-3	Single specular streak on a smooth plane	28
4-4	Specular streakcross section	30
4-5	Plot of cosine of the angle between the surface normal and the half angle vector	31
4-6	Frequency comparison	35
4–7	Lines on a plane	36
4-8	Sine wave boundary example	38
5-1	Diagram of the surface placement in Unity	40
5-2	Illumanated surface in Unity	41
5 - 3	Sample noise texture and displaced blender surface	43

5-4	Surface sample demonstrating shader differences	45
5–5	Sample surface with parallel, static, specular highlights $\ldots \ldots \ldots$	47
7–1	An example of the strength of the column illusion $\ldots \ldots \ldots \ldots$	59
7–2	Sample surface with and without visible light sources	59

CHAPTER 1 Introduction

1.1 Introduction

Humans are aware since childhood that glossy surfaces will have reflections on them. These may be mirror reflections, where elements of the world are reflected in an object, or highlights, bright patches that are direct reflections of a light source. My research for this thesis concerned the particular specular highlights that can occur on certain glossy surfaces. The surfaces are often, but not necessarily, wet ground planes. When illuminated by a light slightly above the surface at the horizon, the specularity can become a long streak, oriented towards the viewer. These specularities can be generally seen over water at night, although they are also common on wet roads at night, and on highly polished floors. See Figure 1–1.

When viewed in isolation there can be different interpretations of the scene. A streak could be interpreted as an angled spotlight, illuminating the surface, or as a spectral reflection on the surface. If the light source is not visible, or not clearly a light source, a streak could be a component of a texture on the surface. If it is unclear that it is a surface, for example a black surface with very little diffuse reflectance such as water at night, a streak could be interpreted as a vertical column, and not on the surface at all.

There are ways to disambiguate these possibilities. At close distances there are strong stereo cues, or motion parallax, that can allow us to distinguish between a



(a) Lights over water at night.



(c) Car headlights on a wet road.

(d) A sample created in Unity.

Figure 1–1: A sample of the specular streaks that I investigated. Images (a) and (b) ⓒ https://www.pexels.com, (c) ⓒ https://pxhere.com, (d)created in Unity.

horizontal or vertical surface. Furthermore specularities will behave differently than a painted streak or spotlight when the viewer moves. Specularities will ripple and move across a surface, whereas a painted streak will remain at the same position on the surface and shear as an observer moves. At larger distances stereo cues become less reliable and we must use other cues, which may not be available, to disambiguate the scene. This thesis explores this illusion of vertical columns, which I will refer to as the illusion of columns or simply the illusion, and attempts to establish how and why it occurs.

1.2 The Illusion of Columns

This illusion only appears on oblique glossy surfaces, with a small visual angle between the surface and the light source. It is generally stronger on dark surfaces, where the surface itself is difficult to see, such as water at night. We believe this is due to the long thin structure of the specularities at this angle, as well as the relative weakness of stereo cues at large distances. There are also generally a lack of cues from other sources, such as texture, as the specularities tend to occur over dark surfaces, which also creates high contrast between the specularities and the surrounding surface. This results in the strongest remaining cue stemming from the vertical structure suggested by the orientation of the specularities.

On a horizontal surface, viewed in perspective, parallel lines will converge at the horizon. On a vertical surface they will converge at a point straight down (or up if they continue upwards). If we examine the specularities we can see that, while in reality they lie on the surface oriented towards the viewer, viewed monocularly,



Figure 1–2: A surface with the specular streaks overlaid onto vertical columns. Monocularly the streaks have the same orientation as the columns.

they align with vertical columns at the same position. See Figure 1–2. We hypothesized that it is this correspondence between the specularities orientation, and that of vertical parallel lines, that cause observers to perceive the highlights as vertical.

While, to the best of my knowledge, this phenomena of orientation leading to a false perspective has not been explored in a scientific setting it is common in art. One example of this is sidewalk art creating the illusion of an opening in a ground plane, typically the street. See Figure 1–3. In Fig. 1–3a the waterfall appears vertical, with parallel lines of spray. In Fig. 1–3b we can see the the lines of spray are clearly oriented towards the camera. It is this orientation towards the camera that we think is key to creating the illusion of vertical structure. This is an example where the painted cues are favored over the physical cues when our mind interprets



(a) Viewed from the correct position.



(b) Viewed from the side.

Figure 1-3: From the correct viewpoint the waterfall looks vertical, (a). From the side, as in (b), we can see that the lines that appear vertical in (a) are all oriented towards the camera, located at the right of the image. ©Edgar Mueller http://www.metanamorph.com/index.php 5

the image. There are other perspective tricks being used in Figure 1–3, such as forced perspective. Consider the blue tanks under the raft. In Fig. 1–3b the barrels on the left of the image, farther from the camera, occupy a larger surface area compared to the left barrels. When viewed from the intended position this means the barrels all occupy approximately the same visual angle, and appear the same size, as in Fig. 1–3a. There are other techniques that are know to influence our perception in similar ways. Patrick Hughes¹ is known for his paintings that create reverse perspective. He paints on non-planar surfaces, with pyramid-like shapes protruding out towards the viewer, in such a way that what appears furthest in depth is closest physically.

This thesis explores these specularities and their effect on the perception of the surface, specifically the perception of slant and material properties. For this work I use the common definition of slant, the angular separation between the surface normal and the viewing direction.

1.3 Thesis Overview

Chapter 2 explores existing research on visual slant discrimination and shape recognition. Texture can be a rich source of visual information, and the question of how we use texture cues has been explored by many. There can be several cues present in a given scene that can influence perception, therefore I continue with a discussion on cue combination in humans. Specularities can also contain information that the visual system can use to determine shape and I discuss them at the end of the chapter.

¹ http://www.patrickhughes.co.uk/

To display the stimuli to observers I used the Oculus Rift. The Rift is a virtual reality headset with integrated motion detection that precisely tracks the users head position and gaze direction in order to present an accurate stereo representation of a scene. In Chapter 3, I detail the capabilities of the Rift. Furthermore I investigate the use of virtual reality in experimentation and the possible impacts on perception. I then discuss the potential adverse affects of using a head mounted virtual display such as the Rift.

In Chapter 4, I discuss in detail why the specularities have there long thin shape, and what lighting and surface conditions are required to form the specularities.

In Chapter 5, I detail how I constructed the surfaces, first by creating appropriate random noise, then making a mesh in Blender for export into Unity. Chapter 5 also contains a description of custom shaders I implemented for Unity.

Chapter 6 details the three experiments I created. Two as slant perception tasks, and a third as a glossiness perception experiment. To the best of my knowledge these specular streaks have never been studied, and their impact on perception was not entirely as expected. This raised some issues with the experiments, which prevented me from running them on subjects. However, they were used to gather observations by myself, my professor and other students in the lab, thus, any results are informal and should be treated as results from pilot studies, rather than psychophysics experiments. Chapter 7 presents a final discussion and conclusion.

CHAPTER 2 Literature review

2.1 Surface Slant

While there are many potential cues to surface slant I am mainly concerned with cues from texture, stereo, and the perspective cues causing the vanishing points discussed in the introduction. Knill (1998b) showed that the information content of texture is greater at high slants. When stimuli are presented at different distances they are commonly scaled so all stimuli subtend the same visual angles. Textures are often scaled as well so different stimuli always have approximately the same number of texture elements per degree of visual angle. Assuming stimuli are scaled, texture cues are unaffected by viewing distance. Stereo cues are affected by viewing distance. Even if a stimuli is scaled properly the relative stereo disparity between two points is reduced at large distances, because the distance between the eyes does not change. At a large distance motion parallax is still available but it's strength is reduced because the observer movements required to use it become large. Stimuli are not always scaled in the literature. If a stimulus is not scaled as it moves farther away, the difference in depth between points, relative to their depth in the scene, decreases. The decrease in relative disparity should reduce the reliability of stereo cues, as well as motion parallax, and experiments have shown this to be true (Howard and Rogers, 2002).

Viewed in perspective parallel lines that lie in the direction of surface slant will not appear parallel, they will converge at infinity. This perspective convergence creates vanishing points that are located where the parallel lines meet. This can provide a cue to surface slant, and is commonly used in art to create realistic scenes. Oriented structure, such as parallel lines, can be created by objects in a scene, for example railroad tracks, by the surface texture or by lighting effects, such as the specular streaks I explored. While the effect of specular highlights on shape perception has been studied, as far as I am aware no one has examined their effect on slant perception.

2.1.1 Slant from Texture

There are three main cues from texture discussed in the literature: foreshortening, density and scaling. Consider a simple polka dot texture on a flat plane. Viewed in perspective, as the slant increases away from fronto-parallel, the circles will be seen as ellipses. See Figure 2–1. This compression is referred to as foreshortening. For a surface at some slant the visual angle for circles at the bottom of the image, near an observer, is smaller than for circles at the top. The top circles are therefore more foreshortened than the bottom ones, and the visual system can use this as a cue for surface slant. The density cue stems from the fact that the dots at the top are farther away, and so there are more per horizontal degree of visual angle. A second consequence of this difference in distance gives the scaling cue. Circles at the top, farther away, will be smaller than those at the bottom.

These cues rely on the presence of texture elements, called texels. The circles in Fig. 2–1 are texels, however, not all texels are circles. For example in Fig. 2–2 the



(a) Fronto parallel polka dot texture.

(b) A polka dot texture slanted at 45° .

Figure 2–1: The texture in (a) is fronto parallel and the circles are round. In (b) the texture has been slanted 45 °. The circles have been compressed into ellipses. Those at the top of the image, farther away, are more compressed then those at the bottom.

texels are line segments. The reliability of the aforementioned cues is also dependent on the size and layout of texels being homogeneous and isotropic. Homogeneity and isotropy describe the statistical properties of a texture.

Homogeneous textures are only dependent on local position, not global position, i.e. the size, and density of texels is homogeneous throughout the texture. Figure 2–1a is an example of a homogeneous texture. If a texture is not homogeneous the aforementioned cues may be reduced, or not exist. For example if the texture were changed such that the size of the circles increased incrementally from the bottom to the top of the image in an amount corresponding to the reduction in size due to



(a) Fronto parallel isotropic texture.

(b) Isotropic texture slanted at 70° .

Figure 2–2: The texture in (a) is fronto parallel and the lines are randomly oriented. In (b) the texture has been slanted 70 °. Do to foreshortening the angle of the lines have all been brought toward horizontal, rendering the resulting image anisotropic. The perception is clearly of a slanted surface.

slant, rendering it no longer homogeneous, the scaling cue could be eliminated. For most experiments in the literature homogeneity is present in the textures.

Isotropic textures have no dominant direction. When an isotropic texture is viewed in perspective, at some slant, anisotropy is created. This can be seen in Figure 2–2. In (a) the individual texels have an orientation. However, the random placement of the texels mean the texture overall does not have an orientation. When viewed at a slant foreshortening changes the apparent orientation of the texels. The end points of the line are compressed in the same direction as the surface slant, causing the orientations to be skewed in a direction orthogonal to the slant. In Figure 2–2b this is a vertical compression, leading to a horizontal orientation of texels. Assuming the viewer has knowledge of the local texture geometry, they can then use this anisotropy at some local patch to estimate foreshortening, and from that, surface orientation. While homogeneity is important, and usually assumed, isotropy is arguably more important, as several people have shown that the foreshortening cue is the dominant cue used, followed by scaling, with almost no weight given to density (Knill, 1998c,a; Blake et al., 1993). This then raises the question of whether humans make an assumption of isotropy. Knill (1998c,a) and Knill and Saunders (2003) have shown that they generally do, although Knill and Saunders (2003) showed that for very anisotropic textures humans no longer use isotropy. Other studies however have had more ambiguous results (Rosenholtz and Malik, 1997; Todd et al., 2004).

One cue to surface slant which has been less studied is oriented structure from anisotropic textures. The specularities I am interested in, when made static, can be considered as a texture on the surface. They are anisotropic, having clearly oriented structure, and non-homogeneous. Therefore many, or all, of the cues discussed above are absent. If the texture is already anisotropic then, when viewed at a slant, the anisotropy in the image may not be orthogonal to the direction of slant, as with isotropic textures. Saunders and Backus (2006) explored oriented structure at very low slants, where there is very little anisotropy from slant, and showed they do significantly improve perception. However it is unclear what, if any, effect oriented structures have at high slants. Additionally the orientations in Saunders experiments that most improved perception were parallel and in the direction of surface slant, whereas the specularities I investigated were not parallel on the surface. Saunders textures were also highly regular whereas the specularities are not. Similarly Li and Zaidi (2000) used an ordinal depth discrimination task and showed that the presence of oriented structure in textures that did not contain texels, plaid for example, greatly improved performance. Furthermore Li and Zaidi (2000) showed we were able to use this information even when it is masked by the presence of structure at different orientations.

Field of view has also been shown to be important in slant perception (Knill, 1998a; Todd et al., 2005). Todd et al. (2005) worked with concave and convex dihedral planes. Knill (1998a) used a more conventional slant discrimination task and showed that, while changing the horizontal field of view had a small effect, changes made to the vertical field of view (the direction aligned with the slant) could make a significant difference to slant discrimination. Knill showed that reducing field of view by removing from the top caused a strong reduction in slant discrimination, whereas removing from the bottom had a much weaker effect. This due to the fact that the information content of a vertically slanted plane is greater at the top (Knill, 1998a,b).

2.1.2 Cue Combination

To effectively combine the available cues the visual system must decide how reliable the cues are, and which to use. In a linear cue combination model the cues are assigned weights and the result is the weighted sum of the available cues

$$\hat{S} = \sum_{1}^{n} \omega_i S_i \tag{2.1}$$

where S_i are the different perceptual cues e.g. slant from texture, depth from stereo etc, and ω_i is the associated weight. In the simplest models cues are assumed to be independent. The weights are proportional to the inverse of their variance, which serves as a measure of the cues reliability (Ernst and Banks, 2002; Knill and Saunders, 2003; Hillis et al., 2004). Landy et al. (1995) proposed a more complex linear model that allowed for cue interaction for what they termed *cue promotion*. They call their model *modified weak fusion*, and argue that the information provided by different cues is qualitatively different, therefore cue interactions are required to make them commensurate. Knill and Saunders (2003) suggested a weighting scheme where cue priors are mixture models and showed that their model correctly interprets human results concerning whether or not an isotropy assumption is used in a slant from texture task.

Knill and Saunders (2003) and Hillis et al. (2004) measured human performance in slant discrimination tasks against predictions from an ideal linear combination model and showed that humans combine texture and stereo cues optimally. Other research, using linear combination models, has shown human performance to be near optimal for different types of cues: vision and haptics (Ernst and Banks, 2002; Gepshtein and Banks, 2003) and audio and vision (Alais and Burr, 2004).

These models all result in non-zero weights on the cues. However there is also the possibility of winner-takes-all combination, where the most reliable cue is the only one used. Consider the Necker Cube, seen in Figure 2–3. There are two ways to perceive the cube, with the left square as the front of the cube, or with the right square as the front. Either is valid, and many people can switch between the two, however, only one percept is ever seen.

2.2 Specular reflections

Materials are commonly described as having two types of reflectance: lambertian (diffuse) and specular. A purely matte surface has only lambertian reflectance, while



Figure 2–3: The Necker cube, a wireframe of a cube, with no depth information.

a purely specular surface, a perfect mirror, has only specular reflections. Most real materials lie somewhere in between perfect lambertian and specular. See Figure 2–4.

The color for the lambertian component of a surface is a combination of the color of the surface and the color of the light source. In many cases the light is white (or near white) and the lambertian color component is simply the surface color. The brightness of the surface is dependent on the cosine of the angle between the surface normal and the light direction. Therefore it is brightest when the surface is perpendicular to the light direction. Lambertian reflectance is also independent of viewing direction, and appears the same from any direction. Consider the felt

surface of a pool table, it is not shiny at all and the color of any point on the surface appears the same as you walk around the table. See Figure 2–4a.

Specular reflectance depends on the surface normal, the viewing direction and, in the case of highlights, the lighting direction. Thus, the specular reflectance will change as the viewing direction changes. There are two types of specular reflectance, mirror reflections and highlights. Mirror reflections are reflections of elements in a scene, such as objects reflected in a mirror. Reflections therefore depend only on the viewing direction and surface normal. What is visible at a point on the surface is whatever lies in the direction of the reflection of the viewing direction about the surface normal. The color, for a perfect mirror, comes from whatever surface lies in that direction. See Figure 2–4d. The color at any point on the sphere is only the reflected color from somewhere else in the scene. Many surfaces are not perfect mirrors, and the color is then a mix of the reflected scene and the true surface color. See Figure 2–4c. The pale horizontal band at mid level is the reflection of the horizon, and the reflection of a sphere and cube can be seen in the left and center respectively.

Specular highlights are reflections of the light source, or sources. They occur on glossy surfaces when the direction to the light source is near the direction of the reflection of the viewing direction about the surface normal¹. Highlights differ from mirror reflections in another way, in that the reflected light largely overpowers the lambertian reflectance, so the highlights are the color of the illumination and are not tinted by the surface color, except on the edges. See Figures 2–4b and 2–4c.

¹ How near depends on the specific reflectance properties of the material.

The white spots in the upper right are reflections of the white light source, and are not tinted by the red surface. It is common in glossy materials to have both mirror reflections and highlights, as well as lambertian reflectance, as in Figure 2–4c.

The appearance of specular reflections, both mirror and highlights, rely on the viewing direction, and their behavior when subject to motion or stereo viewing (or both) is different than Lambertian reflectance. As the viewer moves the viewing direction to a particular point on the surface changes. Therefore the specular reflection at that point will change as well. Similarly if viewing in stereo, each eye (or camera) will have a slightly different viewing direction and so reflected objects, or highlights, will appear on different parts of the surface for each eye. How much the location of a reflection differs between eyes is called the specular disparity.

Specifically, if the specular disparity is calculated as stereo disparity, the specularities lie on a virtual surface behind a convex surface, and in front of a concave surface. How far removed from the surface they are depends on the surface curvature. By having participants adjust the level of specular disparity Blake and Bülthoff (1990) showed that, for convex surfaces, subjects correctly aligned the specular highlights so their depth lay behind the surface. As a consequence of this, in stereo vision, it is possible for the eyes to receive conflicting information. A highlight, or an object, could be visible to only one eye. Furthermore, for complex shapes, places where the curvature reverses (concave to convex or vice versa) the specularities change from in front to behind (or behind to in front of) the surface, creating a region with discontinuities in the stereo disparity (Muryy et al., 2013). Muryy et al. (2013) showed



(c) Diffuse, highlights and reflections.

(d) Perfect Mirror.

Figure 2–4: A sample of different reflectance types. (a) has only diffuse reflectance. (b) has diffuse with specular highlights (no reflections). (c) has diffuse, and both reflections and highlights. (d) is entirely specular, i.e. a perfect mirror. Rendered in Unity using the included Standard Shader. that in some regions this makes reflected images impossible to fuse. This all raises the question of how specularities affect the perception of surface properties.

To be able to use specularities effectively we would need to be able to separate them from textures, as the behavior of texture is different than that of specularities, when combining with other visual cues. Research by Blake and Bülthoff (1990) implied that we are able to do this, although they only looked at simple convex and concave shapes. Adams and Elder (2014) looked at similar shapes and showed that the presence of a highlight creates a bias towards a convex interpretation. Fleming et al. (2003) showed that humans are quite good determining the glossiness of surfaces. Muryy et al. (2013) measured observers performance in a depth estimation task for perfectly mirrored surfaces and showed that people estimated the depth of points to be at the depth of the virtual surface, rather than the real surface, although this does not necessarily mean we are able to separate the specularities from texture as there were no textures. Interestingly, in their experiments, participants were able to identify unreliable areas, where the disparity was too high, and used other means to estimate depth. The authors hypothesized participants used an interpolation strategy across unreliable regions. Similarly, Adams and Elder (2014) showed that when the specular highlight is misaligned with lambertian shading the bias toward convexity is reduced, implying we are able to disregard unreliable highlights.

Fleming et al. (2004) showed that humans are quite good at shape perception when only specular reflections are present. In their paper participants oriented gauge figures on perfect mirror surfaces, with the backgrounds removed. Similarly Norman et al. (2004) used a shape discrimination task. Participants were asked to decide if two presented shapes were the same, and showed that humans performed remarkably well when only specular highlights were present. These results seem to imply that humans can interpret specularities well. However, others have obtained conflicting results when testing whether, in the presence of additional cues, highlights improve perception of surfaces. Some studies have shown a benefit from the presence of specularities (Blake and Bülthoff, 1991; Todd et al., 1997; Norman et al., 2004). Others showed no improvement when other cues were present (Nefs et al., 2006; Muryy et al., 2013). Faisman and Langer (2013) found that the presence of specular highlights actually worsened performance in a qualitative shape judgment task.

CHAPTER 3 Oculus Rift

To present the experiment to the subjects I used the Oculus Rift Development Kit 2 (DK2), which integrates with the Unity 3D game engine using the Oculus OVR software development kit (SDK). The Rift DK2 has a 1920 x 1080, or 960 x 1080 per eye, OLED screen, with a maximum 75hz refresh rate, and is capable of displaying 3D stereoscopic images. The field of view will vary slightly depending on the distance from the eyes to the lenses, however it is approximately 90° monocularly. Due to the overlap in images to the left and right eyes the binocular field of view is approximately 100°. It uses an internal gyroscope, accelerometer and magnetometer, as well as an external near infrared CMOS sensor to perform precise head tracking (Desai et al., 2014). This allows for responsive specular highlights, calculated at run time, that change their appearance properly in relation to the position of the observer, rippling across the surface as the observers head moved. It was crucial for the surfaces to be viewed in stereo given the purpose of my research was to explore the illusory columns, and try to discover when the visual system ignores the stereo cues present. See Figure 1–1.

The interaxial distance, the distance between the center of the two lenses, is 63.5mm. The optics of the Rift are such that it is equivalent to looking at a screen

approximately 1.3 meters away. The true distance is dependent on the distance from the eyes to the lenses, which will vary slightly between users 1 .

The downside of such a large field of view is a greatly reduced resolution, per degree of visual angle compared to a standard monitor. At a distance of 1.3 meters, a 24" monitor (24" on the diagonal is 51cm width) will occupy approximately 22° of visual angle. With a resolution of 1920x1080 a monitor will have 86 pixels per degree of visual angle. The Rift has 90° field of view per eye, and a binocular field of view of 100°. Monocularly the Rift has a horizontal resolution of 960, and has 10.6 pixels per degree of visual angle. The Rift also covers the users eyes so only what is presented is visible, with nothing in the periphery.

While small light weight commercial virtual reality (VR) systems are relatively new, researchers have been using other VR systems for quite some time, and have documented some of the problems associated with them. Commonly, the physical repercussions of extended VR use can include headache, eye fatigue and nausea (Duh et al., 2004; Kooi and Toet, 2004; Shibata et al., 2011). One cause of discomfort is due to the optical distance to the screen, in relation to the virtual distance of objects in the scene the user is looking at. Often these two distances are different, causing conflicts with visual cues, particularly the vergence and accommodation cues (Hoffman et al., 2008; Kramida, 2016). Vergence is the movement of the eyes necessary to

¹ https://developer.oculus.com/design/latest/concepts/bp_app_ imaging/

fuse an object. As an object moves closer or farther the eyes must be angled inward, or outward, respectively. Accommodation is the individual eyes changing the shape of the lenses in order to change the power of the lens, thereby changing the focal distance. When viewing real scenes accommodation and vergence change together as the distance to the object changes. However, when using a VR device or monitor the screen distance does not change, regardless of the distance of the simulated objects. The accommodation cue will specify the depth of the screen (or virtual screen in a VR device, as described below), and therefore won't change, whereas vergence will change in accordance with the depth of the virtual object. This conflict of visual cues is thought to hamper fusion and increase visual fatigue. There are other visual cues in conflict, such as the lack of any blur from differences in depth, but the vergenceaccommodation conflict is thought to be primarily responsible (Shibata et al., 2011; Hoffman et al., 2008).

With existing technologies these problems cannot be eliminated, although they can be reduced in some cases. To render images with the correct focal blur requires performing eye tracking. While companies are working on including eye tracking in VR headsets, it is not currently available ². With eye tracking enabled, the software could render images with the appropriate blur. Care is needed however, as a recent study showed that adding depth of field to a gaze-contingent display may

² Tobii (https://www.tobii.com/) currently makes eye tracking hardware that can be installed in the HTC Vive. Oculus, and parent company Facebook, purchased The Eye Tribe (https://s3.eu-central-1.amazonaws.com/theeyetribe. com/theeyetribe.com/index.html) in 2016.

actually lower users comfort (Vinnikov and Allison, 2014). Vinnikov and Allison (2014) suspect that the reduced comfort stems from inaccuracies in their rendering. They note that users were aware of the blur they added to create depth of field, whereas in real scenes we are not aware of the focus blur. Further study is needed with more precise hardware/software. Conveniently, including depth of field blur could also lower the computing power needed through Foveated Rendering (Guenter et al., 2012), which involves lowering the quality of the rendered image outside the area in which the user is fixating. In the Rift the optics make the screen equivalent to 1.3 meters away. Placing virtual objects at this distance would align the accommodation and vergence cues. However, depending on what one wishes to display this can be quite restrictive. In particular our experiment required some virtual objects to be several meters farther than this. Oculus announced a new technology they call "Focal Surface Displays" to attempt to remedy both the accommodation issue, as well as focus blur (Matsuda et al., 2017).

A second issue is the possibility of nausea due to the disconnect between the visual stimuli of motion, and the lack of physical stimuli coinciding with that motion. For example people have reported nausea when playing games that involve driving, or flying. This results from the fact that the visual system is presented with scenes that clearly indicate motion, but there is no motion in the vestibular system, or pressure on the body from acceleration, or turning (Duh et al., 2004).

The second issue not a concern for my experiment, as the objects in the scene are all static, and there is no simulated motion that does not correspond to the users physical movement. The lack of depth blur may cause nausea in a small amount of participants. However, given the nature of the scenes in my experiment, it should not be a large issue. Users will mostly have their attention on the specularities, and the surrounding is black, so the lack of depth blur will not be apparent.

A third issue is the shortening of perceived distance that studies have shown to be common when using VR headsets (Creem-Regehr et al., 2015b,a; Messing and Durgin, 2005). People exploring virtual environments tend to perceive distances as shorter than they actually are. This has no effect on my experiment as all stimuli are presented in a virtual environment, and distances would be perceived as shorter for test and control surfaces. Distance is relevant to my experiment, as I will discuss in Chapter 6 the illusion is dependent on the surface being sufficiently far away. However the illusion is fairly resistant to changes in distance, and a small amount of depth compression is not an issue.

Unrelated to motion sickness or fatigue, but commonly reported by users of current head mounted VR devices are the "screen door effect" and ghosting (Desai et al., 2014). The screen door effect is the appearance of a black grid, visible in the image. This is the result of the distance between pixels which, if sufficiently large, makes the gaps between pixels visible. Ghosting stems from the pixel switching time, that is, the speed at which pixels can switch between colors, or on and off. If the pixels switching time is insufficient, compared to the users head movement it can result in a faded afterimage, or blurring. This is most noticeable when very bright area border very dark areas, since this requires the largest change in pixel intensity. My experiment does have white areas bordered on black backgrounds; however, head movements, while required, should be small and moderately slow.

CHAPTER 4 Specular Streaks

Consider an image of the specularities I wished to replicate. It has a solid, bright center, near the top of the image. The edges and the bottom portion, near the camera, are composed of smaller, separated highlights. See Figure 4–1. The specularities are thin and, although it may not appear so in an image as the specularities can normally only be seen at a large oblique angle, when viewed from the top we can see they are in fact long streaks. See Figure 4–2. Though some small changes can be made, to maintain the illusion of columns there are some surface and lighting properties that must be present to ensure the streaks resemble those that occur naturally.

4.1 Unique Shape

As part of my exploration of these particular specularities it is necessary to examine how they arise, what causes them to have their long, thin shape. The surfaces they commonly lie on have very low amplitude deformations, and they can appear on perfectly flat planes. We can use a flat plane to explain their behavior. See Figure 4–3.

A simple algorithm to render specular highlights is the Blinn-Phong model (Blinn, 1977). The model provides realistic highlights and is commonly used. At any point on a surface we can derive a vector to the light source, and a vector to the camera. The half angle vector \vec{H} , is a vector that bisects the angle between these



Figure 4–1: A single specular streak.



Figure 4–2: When viewed from above we can see that the specularities are long and thin. They are oriented toward the camera, which was aligned with the center, slightly below the edge of the image.


(a) A single streak on a smooth ground plane, as seen from the viewer in (b).



(b) A single streak on a smooth plane viewed from above. The sphere at the bottom of the image is at the location of the camera in (a), used to calculate the highlight. The streak has been texture mapped onto the surface in the same way as the static specularities. See Section 5.3.

Figure 4–3: A single specular streak on a smooth plane. It is brighter, and wider, at the top, long and thin. Rendered using my custom shader. See section 5.3 for details about the shader. In (a) the surface is a ground plane, (b) is viewed from directly above. 28

two vectors. Using two normalized vectors $\vec{v_1}$ and $\vec{v_2}$, the normalized \vec{H} is:

$$\vec{H} = \frac{\vec{v_1} + \vec{v_2}}{||\vec{v_1} + \vec{v_2}||} \tag{4.1}$$

The model depends on the angle between the surface normal and the \vec{H} . If it is 0, it means that a ray of light would be reflected directly at the camera, and so a highlight should appear. As the angle increases less light would be reflected directly at the camera. There is another parameter that influences the appearance of the highlights in the Blinn-Phong model, but it influences the size of the specularity, and not the shape, so I will not discuss it. Since we want a small angle to have a large response the cosine of the angle is used, as it is 1 when the vectors are parallel and 0 when they are perpendicular. A negative value indicates the light is on the opposite side of the surface and there is no specularity. Using normalized vectors the cosine of the angle between them is calculated using the dot product.

On a flat plane the surface normal is constant, and so changes in the highlights stem from changes in \vec{H} . Examining Figure 4–3b, it is not immediately obvious why the streaks are long and thin, i.e. why the half angle does not very much across a large vertical region, but changes rapidly as we move to the side.

Consider the scene in 4–3. The surface lies in the plane defined by the X and Z axis, with the Z-axis parallel to the streak. Let the Y-axis be perpendicular to the surface, and positive in the direction of the light source and camera. If we take a cross section in the Z-Y plane where X is equal to the position of the camera and light we get a 2D scene as in Figure 4–4. At the point centered in between the light source and the camera the normalized \vec{H} is equal to the surface normal, and



Figure 4–4: A 2D cross section of a specular streak, not to scale. Green lines are vectors from various points to the light source. Blue lines are vectors to the camers. The red arrows are the half angle vectors. The black arrows are the surface normals.

we would expect this point to be the brightest. Moving left or right alters the half angle by some amount, creating an angular difference, θ , with the surface normal. Moving equal amounts in either direction will produce the same angle difference and therefore, the same reduction in brightness of the highlights. There should be some range *d* across which the highlights appear, and beyond which θ is great enough that the highlight no longer appears.

Thus far I have used a light at a finite distance. However these specularities are also visible when the sun is near the horizon. See Figure 4–1. In the case of a light at infinity the behavior is similar, although not quite the same. Notably the direction to the light is constant, therefore the length of the specularity is determined by the direction to the camera. As a result \vec{H} will take longer to diverge from the surface normal and the specularities will be longer, particularly the end closer to the light. Consider Figure 4–4, if \vec{a} were the direction to the sun then the end of d near the



Figure 4–5: Plot of cosine of the angle between the surface normal and the half angle vector. The Y-axis is pointed out of the image. The camera is at (50, 7, 10), the light is at (50, 7, 90).

camera would be at the same position. However, \vec{c} would be closer to horizontal, parallel to \vec{a} , which would lower θ and the end of d near the light source would be much further.

Intuitively it may seem that a step of some size in the X direction should produce a change in \vec{H} equal to the same size step in the Z direction, and the highlight should be round. However by plotting $\cos(\theta)$ as a function of X and Z we can see that the angle between \vec{H} and the surface normal changes rapidly in the X direction. See Figure 4–5. By examining some sample points the reason for this becomes clear.

	Position	To Light Vector \vec{L}	To Camera Vector \vec{C}	Half Angle Vector \vec{H}
point 1	(50, 0, 50)	(0, 0.17, 0.99)	(0, 0.17, -0.99)	(0, 1, 0)
point 2	(50, 0, 40)	(0, 0.14, 0.99)	(0, 0.23, -0.97)	(0, 0.99, 0.05)
point 3	(50, 0, 25)	(0, 0.11, 0.99)	(0, 0.42, -0.91)	(0, 0.97, 0.16)
point 4	(60, 0, 50)	(-0.24, 0.17, 0.96)	(-0.24, 0.17, -0.96)	(-0.82, 0.57, 0)

Table 4–1: A small sample of half angle vectors.

Table 4–1 shows the position, the vector to the light, \vec{L} , vector to the camera, \vec{C} and half angle vector for four points. The surface normal is (0, 1, 0) across the whole surface. Point 1 is centered between the light source and camera. We can see that while the Z components of the \vec{L} and \vec{C} vectors are much larger than the Y component, they are exactly opposite. Thus, when added together to form \vec{H} they cancel out, and the result is parallel to the surface normal. Point 2 is 10 units down from point 1, towards the camera. The Z components are no longer opposite, but are still fairly close and largely cancel each other out. Going as far as 25 units towards the camera, see point 3, the Z components still largely cancel out. For the first three points the result of the Z canceling out, given the X component is always 0, is an Hthat is almost vertical, close to the surface normal. Point 4 is centered between the light and camera in the Z direction, but is 10 units away in the X direction. The change in position is small, but the change in \vec{H} is significant. As we move away from x = 50 the Z components still largely cancel out (completely in the case of point 4). However the X components have the same sign and so they amplify each other. The resulting \vec{H} is significantly farther from the surface normal.

The surfaces I rendered are not smooth planes but have very small amplitudes, and the smooth plane model largely explains the shape of the envelope of my specularities. See Figures 1–1d and 4–2. Chapter 5 provides details of the surfaces I rendered. One noticeable difference is that specularities on non-smooth surfaces are not one connected component. They usually have small isolated blobs at the outer edges, and dark patches in the center, where we may expect a bright spot. This is due to the surface normals varying slightly away from perpendicular to the plane the surface lies in. Again consider Figure 4–4. As points move close to the camera the vector \vec{H} will angle towards the light. If the surface normal is angled in the opposite direction slightly, due to a bumpy surface the highlight may not appear, even for a point in the range d. Alternatively, for point outside d, the surface normal may be angled in the same direction as \vec{H} and a highlight will appear. The same is true as we move in the X direction away from center, however \vec{H} becomes very slanted quickly, and the low amplitude of surface bumps means there is a maximum angle attainable by the surface normals. Thus there may still be unconnected blobs on the sides of the specularity, but \vec{H} will quickly become slanted enough that it is beyond the range of surface normals that would produce a highlight.

For real specularities, as in Figure 4–3 the specularity is also not symmetric. It is brighter near the light. This is simply due to attenuation. Moving away from the light source, along the surface, the amount of light hitting a point decreases, and so the highlight fades as the distance to the light increases.

4.2 Required Surface Properties

To achieve the desired properties in a highlight, a range of frequencies of surface deformations are needed. When using a uniformly bumpy surface, for example a simple sum of sine waves like an egg carton, the regularity provides additional cues and the effect of columns is weakened, or eliminated. The streaks may also no longer look like the natural specularities. See Figures 4–6 and 4–8. When shaping the surface if the frequency is too high the surface has a speckled look, and the specularities do not align in columns. See Figure 4–6a. Similarly, if the frequency is too low, the specularities become smooth, and lose the random small separate elements. See Figure 4–6b. While the low frequency surface does have oriented specularities, and the illusion of columns is still somewhat present, observers reported it is stronger when combined with some higher frequency elements. The envelope of the specularities having an orientation is key, as evidenced by the fact that some users reported seeing columns when presented only with straight lines on a surface, with the lines oriented to correspond to the specularities. See Figure 4–7.

While the surfaces I rendered were shaped using random noise, it can be useful to examine simpler surfaces to explore different frequencies. Figure 4–8a is made from a sum of sine waves, with a frequency of 12 cycles per 10° of visual angle (the image has been cropped here). We can see how the specularities are largely separate small components, but they still generally lie in columns. If the frequency were to increase by a small amount the highlight may still create the illusion of columns. However a large increase would result in something like Figure 4–6a, which has a frequency of 20 cycles per 10° of visual angle. Moving to low frequency surfaces,



(a) High frequency.



(b) Low frequency.





(a) Lines on a smooth plane.



(b) Circle indicates region of focus.

Figure 4–7: When presented with (a) observers generally reported seeing a horizontal plane. Given that edges are visible this is not surprising. However when asked to focus on the region inside the red circle in (b) (the circle was not visible, observers were simply told to attend to the center) observers reported seeing the lines as columns.

consider Figure 4–8b, which has a frequency 3 cycles per 10° of visual angle. The specularities are closer to what is desired, in that they have a solid part at the top and somewhat separate components near the bottom. They are also thinner, leading to a clear orientation. Some observers did report seeing the column illusion when viewing these surfaces but the illusion was noticeably weaker. Lower than this and we completely lose the separate components, as in Figure 4–6b, which has frequency 1.5 cycles per 10° of visual angle. At such a low frequency the specularities shorten and start to become round, making them not useful. Based on these observations we can conclude that a range of frequencies of approximately 3 to 15 per 10° of visual angle will result in good specularities, and that is what I used when generating the noise used to deform the surface. See Chapter 5 for an explanation of how I constructed the surfaces. In both previous examples the amplitude was the same, and very small. In all my experimentation very low amplitudes were required. Consider the surface of a road, or calm water at a distance.



(a) Frequency 12 cycles per $10^\circ {\rm of}$ visual angle.



(b) Frequency 3 cycles per 10° of visual angle.

Figure 4–8: The approximate upper and lower boundaries on the spectrum of frequencies that generate good specularities.

CHAPTER 5 Surface Generation and Rendering

5.1 Quantitative Streak Construction

In most cases when these specularities are seen in a natural setting it is on a horizontal ground plane, requiring a viewer to look at a slight downward angle. For my renderings the displayed surfaces were brought up from a ground plane and tilted slightly, to produce a similar viewing angle as in a real setting, while allowing participants to keep their heads upright. In Unity the X and Z axes lie in the horizontal plane, with the Y axis perpendicular and upwards. The observer was always positioned looking along the Z axis in the positive direction. To recreate the desired specularities the surfaces were positioned slightly below horizontal, and rotated about the X axis, resulting in a viewing angle of approximately 11°. A similar visual angle to a standing person looking 8 meters away at a ground plane. See Figure 5–1.

One or more point lights were placed approximately 3° above the surface, slightly farther than the center of the surface. Lights in Unity have a built in Halo option. When turned on it creates a sphere around the point light, solid in the center and hazy at the edges, similar to viewing a light through fog. When made small enough this option is a simple way to make the light sources appear as a small globe, as though the observer can see the light source shining on the surface. If the halos were visible they were 2.5° in diameter. See Figure 5–2.



Figure 5–1: The surfaces were raised from a ground plane, and angled such that the viewing angle, θ , remained the same as for a ground plane at the same depth.

The intensity of the lights are not in any real units and, in Unity, there is a range parameter for lights, which makes them somewhat difficult to describe quantitatively. Directional lights (lights at infinity) always have the same intensity at any point in the scene, assuming the light is not obstructed. Point lights (and spot lights) will attenuate, reaching 0 at a manually specified range. When used properly this will approximate real illumination, although strange things are possible, such as a very strong light that does not go far. The range parameter is used to create lights that have the desired appearance, and will save computation at runtime, as surfaces outside of the range will ignore the light.

The specularities are fairly resistant to changes in range or intensity, and those two properties share an inverse relationship. The same highlights can be achieved with a greater intensity and lower range and vice versa. The other parameters can be changed as well, to some extent. How much is subjective, and based on whether or not the specularities look acceptable. As a general guideline I found that the surface



Figure 5–2: A sample of an illuminated surface, showing the specular reflections, with visible halos. The surface is visible in this image to make it clear how the underlying surface appeared. The diffuse reflections were removed for some experiments.

angle can be varied from 90° to 70° . At shallower slants the specularities become too circular and the illusion is lost. The lights can be anywhere from 1° above the surface up to 7° (0.2 up to 1.5 meters with the values used above). Higher than that and the specularities become large oval blobs, too wide to appear as columns, and possibly overlapping.

5.2 Mesh Construction

To generate the surfaces a texture of bandpass 1/f noise was created using Matlab. The 1/f noise textures were made to be periodic using the spectral synthesis method. See Figure 5–3a. I will address the need for periodic textures later. The noise was generated using a range of frequencies from 3 to 15, as discussed in Chapter 4. The images were then loaded into Blender, and the built-in Displace modifier was used to create the bumpy surfaces. The Displace modifier uses the grayscale value of the noise images as surface displacement along a chosen axis, in this case the axis perpendicular to a flat plane, thereby creating a plane with random smooth bumps on the surface. See Figure 5–3b.

Meshes with low polygon counts were created to be exported. High polygon versions of the same meshes were used to create normal maps. Unity allows you to replace the actual surface normals with ones specified in a normal map. This allows you to simulate very detailed surfaces with out actually requiring such a precise underlying surface mesh, which lightens the computational load on the software.

The meshes and normal maps were exported to Unity, which was used to program the experiments. Because of Unity's limitations on the number of vertices allowed in a model the Blender surfaces were small and needed to be tiled to create a sufficiently large surface in Unity. Hence the need for periodic noise, which allowed for smoothly tiling surfaces. The limit on vertices per object also necessitated the use of normal maps to improve low polygon count meshes. The surfaces were presented in front of a black background, with the edges far enough away from the light source that they were outside the range of the lights, i.e. only the specularities and light sources were visible.

For the exact values used to create the surfaces see Appendix A.



(a) A sample noise texture.



(b) A sample of a plane, modified by the Displace modifier in Blender.

Figure 5–3: A sample of a noise texture, and the plane after the Displace modifier has been applied in Blender.

5.3 Shaders

Using Unity's built in shaders the surface near the specularities appeared gray, even with no diffuse component, which lent the observer undesired additional information about surface slant. To remedy this I wrote two shaders for Unity that implemented basic Blinn-Phong lighting (Blinn, 1977). By thresholding, based on the brightness, I could remove any visible surface from around the specularities. See Figure 5–4.

I was also able to test several different conditions to see if the illusion of columns still occurred. In particular, one modification, intended as a comparison surface for experiments, was to calculate the specularities based on an arbitrary viewing point in space, and not the actual position of the camera. Blinn-Phong lighting requires the position and normal of the point on the surface, as well as the position of the light source and camera. The three points are used to calculate vectors from the surface to the light source, and the surface to the camera, which are then used to calculate the amount of specular highlight. By replacing the location of the camera with an arbitrary point in space the specularities become static with respect to movement of the camera. This means that while they are real calculated specularities that would change in response to movement of the surface or lights, they do not move in response to camera movements. These were used to create what I have called *static* specularities. Any observer movement was tracked by the hardware in the Rift and used to update to position of the camera in the scene. However, the surface, light sources and the point used to replace the camera's location in lighting calculations did not move relative to one another when a surface was presented, so the specularities



(a) Surface rendered with Unity's Standard shader.



(b) Surface rendered with my custom shader.

Figure 5–4: In (a), using Unity's Standard shader, some amount of the surface is visible under the lights, even in a specular only setup. By thresholding on the grayscale value it could be removed, as in (b).

did not move. Instead they behaved as though they were a texture on the surface with diffuse lighting. The static specularities were intended as comparison surfaces for Experiment 1, and became experimental surfaces for Experiment 2. See Sections 6.1 and 6.2.

Another option for a comparison surface was to change the orientation of the specularities. We hypothesized that the illusion of vertical columns was due to the orientation of the specularities leading to a vanishing point that corresponds to vertical columns. Altering the orientation of the specularities, for example by making them parallel on the surface, removed the illusion. See Figure 5–5. To do so I moved the reference point used to replace the camera's location in lighting calculations for the static specularities back (directly behind the camera) sufficiently far that the calculated vector from any point on the surface to the reference point was approximately parallel.

Other alterations could also be made, such as reversing the colors, putting black highlights on a white surface, as well as making any highlights appear fully white, rather than shaded. Lastly, it was possible to add in varying amounts of diffuse lighting by adding a directional light at a very oblique angle to the surface. Adding a diffuse component made the surface visible, in order to see if there was a threshold at which it began to look like the correct slant.

Using a custom shader allowed for the static specularities to be calculated at runtime, rather than being pre-computed and placed on a surface as a texture, saving time while also being accurate reflections when the camera was in the same position as the reference point used to do the Blinn-Phong lighting calculations.



(a) Surface viewed from the normal observer position.



(b) Surface viewed from above.

Figure 5–5: A sample comparison surface, the specular highlights are static, and were made to be parallel on the surface. When viewed in perspective the vanishing point has moved to the horizon. 47

CHAPTER 6 Experiments

What follows is a description of three informal experiments I created. They can be considered pilot studies for future psychometric experiments. I present any data obtained as observations, not formal results.

Experiments 1 and 2 included comparison surfaces. These were surfaces that were designed to be accurately perceived in order to demonstrate that the specular highlights influenced slant perception.

With one exception, discussed at the end of section 6.1, when surfaces were being observed they were always presented in stereo, using the Rift, with the motion tracking enabled.

As discussed in section 2.1.2, past research has shown that humans tend to weigh sensory inputs based on an estimate of the reliability of that particular cue (Knill, 1998c, 2003; Landy et al., 1995; Hillis et al., 2004). The cues given by these specular highlights suggest vertical columns, while other stereo cues suggest a horizontal plane. The head tracking available with the Rift means there are also motion parallax cues available. The stereo and motion cues both suggest the true surface, and so are considered in the same group of cues, the opposing cue is the that of vertical columns provided by the specularities.

In a linear cue combination model the various interpretations of a scene, indicated by the different cues available, are assigned weights based on the reliability of their respective cues. The final interpretation is then a weighted sum of the interpretations indicated by the various cues available in a scene. If a linear scheme is used and the weights given to the stereo and motion cues are small under some circumstances then the dominant cue would be for vertical and the surfaces should be perceived more strongly as such. The strength of stereo and motion cues are weakened as distance increases. Therefore we hypothesized that when presented with surfaces with these specularities on them, viewed at a distance, the cues to vertical structure would dominate and subjects would perceive them as being closer to fronto-parallel than the true surface slant. Viewed at close distances the stereo and motion cues should be strong enough for the surfaces to be veridically perceived. It is also possible that humans will not linearly combine conflicting cues, and will instead use a winner-takes-all strategy. In this case the response would be binary, with observers either seeing columns, or correctly seeing a surface at the true slant.

Based on our own observations, and discussions with other students in the lab we roughly estimated the viewing conditions which helped or hindered the illusion. Viewing distance had a clear effect, as the stereo and motion cues are dependent on distance. To that end the scenes for all experiments were presented at multiple distances, scaled appropriately. Distance was always measured as the distance from the camera to the center of the surface along the Z-axis.

For all observations, when the surface was placed at different distances it was always scaled such that all viewing angles were preserved. The width and length of the surface, the height of the light sources above the surface and the size of the halos around the lights, were scaled such that the visual area the surface occupied and the angular separation between the surface and the lights remained constant at any distance. Thus, viewed monocularly, the surfaces looked identical at any distance. However when viewed in stereo users perception of the surfaces changed greatly.

As mentioned earlier, in Unity there is a range parameter for point lights that is used for attenuation and to define a maximum range for the light that also needed to be scaled proportionally, else the specularities would change in size at different distances.

To add a degree of randomness, for all experiments, the position of the lights was perturbed slightly every time a surface was presented. Lateral displacement was limited so that the lights never overlapped, one in front of another. The surfaces could also be viewed with visible light sources, or with the halos turned off.

In general, when a surface was placed at a far distance, 8 meters or more, surfaces with no diffuse component at all were perceived not as surfaces but as vertical columns that were located below the ground plane, i.e. the user is looking down at the columns. This was true for either glossy or static specularities. As the surfaces became more visible, by adding more diffuse reflection, people would eventually see a slanted horizontal plane. It is not surprising that the type of specularities did not matter, as when the surface is far enough away the glossy specularities do not move when the user moves, and so are identical to the static specularities. At 8 meters the glossy specularities do move on the surfaces when the observer moves their head, but by very small amounts.

For surfaces placed at a very close distance, 1 or 2 meters, all observers reported seeing a horizontal plane, even when no diffuse component was visible, although for different reasons in this case. When viewing a surface with glossy specularities the surface looked shiny. When using the static specularities the surface did not appear shiny, but was correctly perceived as a horizontal plane with streaks painted on it, or as a directed light source shining obliquely on the surface.

These observations tend to agree with our hypotheses. When the surface is far away the stereo and motion cues are less reliable, so other cues are used and the highlights are perceived as columns. When the surface is brought closer the opposite is true. The stereo and motion cues become more reliable and the surface is correctly perceived as horizontal and shiny, or painted with streaks, if viewed with glossy specularities or static.

6.1 Experiment 1

The initial experiment was a slant discrimination task for surfaces with only the glossy specularities visible, measured against performance for a comparison surface. Surfaces with static specularities were used as comparison surfaces for this experiment. Participants were presented with pairs of surfaces, one with glossy specularities and one with static specularities, and asked which was more slanted. If the hypothesis was true and the percept of the glossy surfaces was being pulled towards fronto-parallel, then beyond a certain distance when the stereo and motion cues were weaker participants should have perceived the glossy surfaces as less slanted then a comparison surface presented at the same slant.

One of the only depth cues left in the setup of our experiment was motion parallax. The surfaces were viewed at a large oblique angle, and the specularities were quite long on the surface so there normally would be a strong parallax cue as there was significant distance between the closest and farthest point on the streaks. However, when viewing correctly calculated specular highlights they are strongly dependent on viewing direction. When the surface is close, movements made by the observer will cause the specularities to ripple across the surface. The surface has many small bumps and so the specular streaks are, in reality, composed of many small non-uniform blobs. The location and size of the blobs is highly dependent on viewing direction. Therefore as the observer moves their head the blobs will change size, or disappear entirely, and new blobs will appear. Motion parallax involves comparing the relative motion of points at different depths. Nearby points will move more, relative to far away points, when the user moves. Therefore to make use of motion parallax we need to be able to track points as our visual direction changes. The blobs that make up the specularities are therefore less reliable cues for motion parallax as they are not consistent across different viewing directions.

Separate from motion parallax, the way specular highlights ripple across the surface as an observer moves can provide a cue that the surface is close. These changes, small components of the specularities appearing and disappearing, happen faster and with smaller head movements for closer points.

Alternatively, the static specularities are fixed on the surface. Their position, shape, size etc. remains constant on the surface regardless of movement by the observer. This should result in a stronger motion parallax cue for close surfaces, which, we thought, should reduce the illusion of vertical columns and improve performance for slant discrimination. On observation once these surfaces had been programmed, this did not seem true. Close surfaces with static or glossy specularities were veridically perceived. However, when placed at distances sufficiently far that the specularities were perceived as vertical columns, the static surfaces appeared more strongly vertical than the glossy ones, meaning the stereo and motion cues were weak enough to be ignored in favor of the cues to vertical columns. Thus the static specularities became another test surface, rather than a comparison.

One alternative comparison was to add some diffuse lighting component, so that the surface was partly visible, lending the subjects more cues to surface slant. The amount of diffuse reflectance could be controlled, to adjust the strength of the cue. This led to an interesting observation. When only a small amount of diffuse lighting was added some observers reported still seeing the specularities as vertical columns. However, since the surface was now visible the columns appeared to lay below a transparent surface. As more diffuse was lighting was added the illusion of columns disappeared and the stimuli were seen as shiny surfaces. The slightly diffuse surfaces could only be presented on a monitor and so were not usable as experimental surfaces. See section 7.3 for a discussion of the issues I encountered using the Rift.

Experiment 1 was intended to test our hypothesis that the cue to vertical columns created by the glossy specularities would linearly combine with the stereo and motion cues to a ground plane and draw our perception of surface slant up towards fronto-parallel. It was rejected because our intended comparison surfaces, those with static specularities, produced a stronger illusion of columns. The hypothesis was still untested and therefore remained the same for experiment 2.

6.2 Experiment 2

An alternative comparison surface could be made by changing the orientation of the specularities. Normally, the specularities would be oriented towards the viewer, which created the downward vanishing point we believe is responsible for the illusion of columns. See Figure 5–4. The static specularities could be manipulated to change the orientation of the highlights on the surface, bringing them towards parallel. Parallel lines on a plane converge at the horizon, so this modification changed the vanishing point from downwards to the horizon. Doing so removed the illusion of vertical columns, as the vanishing point cue now agreed with the stereo and motion cues. See Figure 5–5. The hypothesis was again that the specularities (correctly oriented), when sufficiently far away, would cause users to perceive the surface as more vertical than the true slant. When viewed at close distances the slant should be perceived correctly.

The second experiment used only the static specularities and was again a slant discrimination task. To test the hypothesis participants were presented with one surface with converging static specularities and one with the parallel specularities, both with the same slant, at the same distance. According to our hypothesis observers should report that, for large distances, the surface with the converging specularities was less slanted. At close distances, since the surfaces had, in reality, the same slant, the results should be random, indicating observers were guessing and that it was unclear which surface was more slanted. Observers could have learned that when there was a perceived difference the parallel specularities were more slanted, and simply always selected them. To prevent this additional pairs were added. Additional pairs consisted of both surfaces having correctly oriented specularities, both with parallel specularities, or one of each, but at different distances. For example a close surface, with the correct specularities, and a far surface with the parallel specularities, both of which should have been correctly perceived. Pairs were also presented with the halo for the lights on and off. For this experiment there was never any diffuse component present.

Alternative additional pairs, to prevent conditioning, could have been made by altering the slant between the two surfaces, for example presenting a surface with parallel specularities that is less slanted than the surface with correctly oriented specularities. If the parallel surface was made less slanted by a sufficient amount the two would be judged as having the same slant, or even more desirable, with the correct specularities judged as being more slanted, providing a clear example of when the correct specularities are the correct answer. One large problem is that, to choose the slant for the two surfaces we would need to know by how much the correct specularities affected observers perception. The experiments thus far were designed simply to show that the illusion is real, and does effect observers perception of surface slant, under certain conditions.

Adding a diffuse component illuminated the whole surface to some degree. See Figure 5–2. Illuminating the whole surface makes the edges visible, which is an undesirable additional cue to slant. Increasing the size of the surfaces so that the edges are always outside the field of view is impossible as the surfaces are near horizontal and the horizon is always visible. Furthermore, when only a very small amount of diffuse reflectance was added some people reported that the specularities remained vertical, and that they were below a transparent surface.

To summarize, our observations provide evidence that our hypothesis may be wrong. Our hypothesis that the specularities will draw perception up towards frontoparallel relies on observers using a linear cue combination scheme, combining the cue to vertical with the stereo and motion cues to horizontal. After observing these surfaces, as well as those with glossy specularities from Experiment 1, our perception seemed instead to be winner take all. We would either see a surface, at what seemed to be the correct slant, or we would see vertical columns, and no surface. This binary choice seemed strong enough that even when presented with surfaces with a small amount of diffuse reflectance observers still saw columns, under a transparent surface, rather than a shiny surface.

6.3 Experiment 3

Experiment 3 was meant to explore a different perception, that of glossy versus matte surfaces. Again a two alternative forced choice experiment was made. For this experiment the user was asked which of two surfaces, presented in random order, was glossier. When we performed the experiment ourselves the results were obvious. Close surfaces appeared glossy, while distant surfaces appeared matte, exactly as predicted.

CHAPTER 7 Discussion

7.1 Specular Streaks

While some of my research yielded interesting observations, it is clear that more work is needed to be able to perform proper experiments, primarily demonstrating in a rigorous way that the illusion of vertical columns exists. To that end it may be a good idea to more thoroughly identify the traits that cause the illusion. In Chapter 4 I described what I found produced the strongest illusion, namely long, thin, streaks that decompose into smaller disconnected components at the bottom. However we also observed that simple lines on a plane can reproduce the effect to some degree. So it is not clear how important the magnitude or frequency of the surface bumps are.

Our hypothesis is that the illusion of columns stems from the orientation of the envelope of the specularities suggesting vertical structure. This is supported by the fact that the illusion remains present when only simple lines are used. See Figure 4–7a. Saunders and Backus (2006) showed that we can make use of oriented structure in slant discrimination at low slants. Considering the absence of any other cues (at a distance when stereo and motion cues are weak) it is then logical that an observer would perceive the illusory vertical columns instead of specular highlights on a surface. Considering my observations, both that the converging specularities can create the illusion of vertical columns, and that the parallel specularities (see Section 5.3 for an explanation of how the parallel specularities were achieved) appear to be veridically perceived, it may be possible to manipulate viewers perception of slant. For example if the orientations of the specularities were altered slightly, as in the comparison surface for Experiment 2 but not to the extent that they corresponded to parallel lines on a horizontal surface, we could potentially make participants see whatever slant we wished.

The illusion of vertical columns is quite persistent when the surfaces are at a distance. Even when diffuse lighting was added and the surface became visible the illusion was still somewhat apparent. To add another cue and try to break the illusion, a horizontal cylinder was placed under the surface in such a way that it would intersect the columns if they were real. See Figure 7–1. The illusory perception of columns was largely unaffected, even when the ground was split so the cylinder was visible in the middle, which we hoped would have increased the perception of the horizontal cylinder as continuous under the surface.

The presence of a visible light source also seemed irrelevant, which is not surprising given the strength of the illusion. We made some observations with, and without visible light sources. See Figure 7–2. People were told that it was a surface, and we wanted to see if the presence of visible light sources reinforced the percept of a glossy horizontal surface with lights shining on it. We found no difference, and most people perceived columns with or without the light sources.

One condition that broke the illusion was to add large amounts of diffuse reflection. Presented with surfaces with large amounts of diffuse reflectance, observers reported seeing shiny surfaces. Although specularities in the absence of other cues



Figure 7–1: An image of several things attempted to break the illusion. The background has been made gray, so the edges of the surface are visible. A cylinder has been placed under the surface such that it would intersect, or obscure the columns, were they real. The surface has been split to try and re-enforce the cylinder as a solid object. Regardless some observers reported seeing the surface as a rectangular hole, with vertical columns in it.



(a) A sample surface with visible light (b) A sample surface with no visible light sources.

Figure 7–2: Sample surface with and without visible light sources.

have been shown to improve perception (Fleming et al., 2004; Norman et al., 2004), specularities with other cues present have, in some cases, been shown to have no effect on perception (Nefs et al., 2006; Muryy et al., 2013). This implies that, in the presence of other strong cues (e.g. a surface with large amounts of diffuse reflectance) cues to shape or slant discrimination from the specularities are ignored. In the general sense, surface versus columns, this seems to be true for my work as well, not only when the surface was visible, but also when the surface was not visible but was brought close to the observer to strengthen the stereo and motion cues. However, it is unknown if the cues are being completely ignored. If the cues from specularities are ignored, the slant perception should be as good as for other well perceived surfaces. If they are not ignored, only weakened, then they should have an effect on slant perception, drawing the percept of surface slant up towards vertical.

7.2 Oculus Rift

The resolution of the Rift is quite high, considering the size of the device. However, it is very close to the eyes, resulting in a low number of pixels per degree of visual angle and it is still possible to see individual pixels. In an immersive environment this is generally not a problem, as people will not notice the pixels unless they divert their attention to them. This may be an issue as the subject of attention in my experiments is the almost entirely white streaks. In a fully white area the RGB colors that make each pixel are displaying at full luminance and can be visible, which some observers reported. Given the experiments were not successful for other reasons it is unclear whether this would pose a problem or not. I used the second edition development kit, with a resolution of 960 x 1080 per eye, whereas the release version, as well as the HTC Vive, have a resolution of 1200 x 1080 per eye. The increase in resolution of current state-of-the-art head mounted displays is likely not large enough to resolve the issue. The Rift was desirable for the large field of view and ease of use, but is not essential to the experiments. They could also be performed on a standard 3D monitor, with head tracking hardware. Because it covers the users eyes, the Rift allows for complete control over what is presented. A monitor may have visible edges, as well as visible objects behind the monitor. This should not be an issue as the illusion is quite persistent, including to other objects being visible, like the light sources or the horizontal column in Figure 7–1.

An unexpected consequence of the Rift was the brightness of the display in dark regions. Surfaces that appeared very dark on a monitor appeared brighter in the Rift, making it very difficult to display a surface that was very dimly illuminated.

7.3 Challenges in Defining the Task

One of the main challenges in defining the experiments was the ambiguity of what was being displayed. Asking participants which ground plane is more slanted, when they see only vertical columns, is unclear. One attempted remedy of this was to add a small amount of diffuse reflectance to the surface. However, when using the Rift, even a small amount of diffuse lighting made the surface clearly visible, breaking the illusion for most people. See Figure 5–2. The surface has been made quite bright to provide an example of how the surfaces appeared in Unity. The diffuse reflectance can be darkened to the point that it is barely visible in a monitor. However, when viewed in the Rift, it always appeared much brighter. I was therefore unable to display a slightly illuminated surface, one that appeared transparent, using the Rift. A solution to this may be to edit the shader such that only a portion of the surface, in the center, is visible. This may clarify that it is a surface, but still allow for ambiguity as to what the specularities are, streaks or columns.

It is also possible that a slant discrimination task, displaying pairs of surfaces and asking which is more slanted, is unsuited to these specularities. When a small amount of diffuse reflectance was added to surfaces presented on a monitor, some observers reported seeing the specularities as columns beneath a transparent surface. As more diffuse reflectance was added observers saw a surface that was slanted near a ground plane. We were generally unable to display a surface that was seen as a surface, but at a significantly different slant. This may be an indication that we adapt a winner-takes-all cue combination strategy, as opposed to linear combination. See Section 2.1.2 for a discussion of cue combination. If that is true than our perception will always be binary, we will see either columns, or the true surface, similar to our binary perception of the Necker cube. See Figure 2–3.

It was somewhat surprising that the static specularities were perceived more strongly as columns. It has been shown that highlight disparity aids in the perception of the glossiness of a surface (Blake and Bülthoff, 1990; Wendt et al., 2008, 2010). Recall that highlight disparity refers to the fact that a highlight will appear at different points on the surface for each eye. See section 2.2. We therefore hypothesized that removing the highlight disparity would improve the perception of the static specularities as texture on the surface, which would then improve slant perception. Furthermore, when viewing a texture on a surface there will be a shearing effect when the observer makes lateral movements. An oriented texture, like the static specularities, will point in a noticeably different direction in the scene as the observer moves. The size of this shearing, however, is dependent on viewing distance, and is largely not noticeable for distance surfaces.

It is unknown if the static specularities effected slant perception at close distances as surfaces with either specularities seemed to be veridically perceived. Slant perception still may differ at close distances between the two types of specularities. Further study is required to resolve this point, and past research has had conflicting results on the effect of gloss on shape perception.

For distant surfaces we found that neither specularity type was perceived as highlights on a surface, and that the static specularities created a stronger effect of columns. I suspect this is due to the reliability of stereo and motion cues reducing as distance increases. Furthermore it is possible that our perception of the glossy specularities as columns is weaker than for the static specularities because of the highlight disparity, as well as the way the smaller components of the specularities appear/disappear. Normally the highlight disparity and inconsistent appearance of the specularities will allow us to recognize the highlight as such, and not a texture, and will strengthen our perception of surface gloss. In the case of the column illusion the behavior of the specularities is contradictory to our perception of the scene as columns, which could then reduce the strength of the illusion.

7.4 Future Work

The obvious direction is to refine the experiments so that they are clear, and to test participants to rigorously demonstrate the illusion. At this point it is unknown whether observers will resolve a binary choice, either to see vertical columns or a shiny
surface (with the correct slant), or if there is a point at which the specularities will influence perception of surface slant towards vertical. Alternatively, will observers separate the surface and specularities and see a transparent surface, above columns?

An experiment to determine if the specularities affect slant perception can still be performed. However the surfaces must only be presented at distances close enough that participants clearly perceive them as surfaces.

7.5 Conclusion

It can be frustrating at times to have failed experiments. However, to my knowledge, no one has studied these specularities and it was satisfying to broach a new subject, and my work did yield some interesting observations, notably that our perception of these specularities may be binary. I hope that this work will inspire further studies of these specularities, and that those studies will benefit from the observations I have made.

Appendix A

This appendix contains detailed instructions to create the specular streaks as I did, using Blender and Unity.

Create an image with a range of frequencies from 3 to 15. Using 1/f noise is not necessary, however the sample must be periodic. I used a 2048x2048 image to be able to create a highly detailed, smooth surface.

In Blender, create 2 planes with size 3. The size must be 3 or the frequencies will change once the final surfaces are made in Unity. Create one surface with a high polygon count, 263169 faces, to create a normal map, and one with only 16641 faces to be exported to unity. Use the Displace modifier on both planes, with the noise as a texture, and the strength set to 0.03. Bake the normal map, and export only the low polygon count surface and the normal map to your unity assets folder. Instructions on how to bake a normal map can be found here: https://www.katsbits.com/tutorials/blender/bake-normal-maps.php.

In Unity place the camera at (0, 1, 0), looking directly along the Z axis. Scale the imported surfaces to 25 in the X,Y and Z dimensions, and tile several surfaces in a square 5 or 6 tiles wide, with the center tile positioned at (0, 0, 8) to create a single large surface. For ease of use it is recommended to create a new game object to be the combined surface, with each tile as a child object. Set the X rotation of the complete parent surface to -7° . Place the number of point lights desired 0.5 units above the surface and 9.5 meters in depth. Again, it is recommended to make the lights a child of the combined surface so they remain at a constant distance to the surface when it is rotated. Set the Range parameter of the lights to 5.25, and the Intensity to 3. If using Unity's Standard shader set the Metallic parameter to 0.35, and the Smoothness to 0.75. Set the normal map for the material to the one created in blender.

References

- Wendy J Adams and James H Elder. Effects of Specular Highlights on Perceived Surface Convexity. *PLoS Computational Biology*, 10(5): e1003576, may 2014. ISSN 15537358. doi: 10.1371/journal.pcbi. 1003576. URL http://www.ncbi.nlm.nih.gov/pubmed/24811069http://www. pubmedcentral.nih.gov/articlerender.fcgi?artid=PMC4014396.
- David Alais and David Burr. The ventriloquist effect results from near-optimal bimodal integration. Current Biology, 14(3):257 - 262, 2004. ISSN 0960-9822. doi: https://doi.org/10.1016/j.cub.2004.01.029. URL http://www.sciencedirect. com/science/article/pii/S0960982204000430.
- Andrew Blake and H Bülthoff. Shape from specularities: computation and psychophysics. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, 331(1260):237-252, 1991. ISSN 0962-8436. doi: 10.1098/rstb. 1991.0012. URL http://rstb.royalsocietypublishing.org/content/331/ 1260/237.
- Andrew Blake and Heinrich Bülthoff. Does the brain know the physics of specular reflection? *Nature*, 343(6254):165–168, jan 1990. ISSN 0028-0836. doi: 10.1038/ 343165a0. URL http://www.nature.com/doifinder/10.1038/343165a0.
- Andrew Blake, Heinrich H. Blthoff, and David Sheinberg. Shape from texture: Ideal observers and human psychophysics. *Vision Research*, 33(12):1723 – 1737,

1993. ISSN 0042-6989. doi: https://doi.org/10.1016/0042-6989(93)90037-W. URL http://www.sciencedirect.com/science/article/pii/004269899390037W.

- James F. Blinn. Models of light reflection for computer synthesized pictures. SIG-GRAPH Comput. Graph., 11(2):192–198, jul 1977. ISSN 0097-8930.
- Sarah H. Creem-Regehr, Jeanine K. Stefanucci, and William B. Thompson. Perceiving absolute scale in virtual environments: How theory and application have mutually informed the role of body-based perception. *Psychology of Learning and Motivation - Advances in Research and Theory*, 62:195–224, 2015a. ISSN 0079-7421. doi: 10.1016/bs.plm.2014.09.006.
- Sarah H. Creem-Regehr, Jeanine K. Stefanucci, William B. Thompson, Nathan Nash, and Michael McCardell. Egocentric distance perception in the oculus rift (dk2). In *Proceedings of the ACM SIGGRAPH Symposium on Applied Perception*, SAP '15, pages 47–50. ACM, 2015b.
- Parth Rajesh Desai, Pooja Nikhil Desai, Komal Deepak Ajmera, and Khushbu Mehta. A review paper on oculus rift-a virtual reality headset. International Journal of Engineering Trends and Technology, 13(3), 2014. URL http://arxiv. org/abs/1408.1173.
- Henry Been-Lirn Duh, Donald E. Parker, James O. Philips, and Thomas A. Furness. Conflicting motion cues to the visual and vestibular self- motion systems around 0.06 hz evoke simulator sickness. *Human Factors*, 46(1):142–153, 2004.
- Marc O Ernst and Martin S Banks. Humans integrate visual and haptic information in a statistically optimal fashion. *Nature*, 415(6870):429–433, 2002.

- Arthur Faisman and Michael S. Langer. Qualitative shape from shading, highlights, and mirror reflections. *Journal of Vision*, 13(5):10, 2013. doi: 10.1167/13.5.10. URL +http://dx.doi.org/10.1167/13.5.10.
- Roland W. Fleming, Ron O. Dror, and Edward H. Adelson. Real-world illumination and the perception of surface reflectance properties. *Journal of Vision*, 3(5):3, 2003. doi: 10.1167/3.5.3. URL +http://dx.doi.org/10.1167/3.5.3.
- Roland W. Fleming, Antonio Torralba, and Edward H. Adelson. Specular reflections and the perception of shape. *Journal of Vision*, 4(9):10, 2004. ISSN 1534-7362. doi: 10.1167/4.9.10. URL http://journalofvision.org/4/9/10/http://jov. arvojournals.org/article.aspx?doi=10.1167/4.9.10.
- Sergei Gepshtein and Martin S. Banks. Viewing geometry determines how vision and haptics combine in size perception. *Current Biology*, 13(6):483 – 488, 2003. ISSN 0960-9822. doi: https://doi.org/10.1016/S0960-9822(03)00133-7. URL http:// www.sciencedirect.com/science/article/pii/S0960982203001337.
- Brian Guenter, Mark Finch, Steven Drucker, Desney Tan, and John Snyder. Foveated 3d graphics. ACM Trans. Graph., 31(6):164:1–164:10, 2012.
- James M. Hillis, Simon J. Watt, Michael S. Landy, and Martin S. Banks. Slant from texture and disparity cues: Optimal cue combination. *Journal of Vision*, 4(12):1, 2004.
- David M. Hoffman, Ahna R. Girshick, Kurt Akeley, and Martin S. Banks. Vergenceaccommodation conflicts hinder visual performance and cause visual fatigue. *Journal of Vision*, 8(3):33, 2008.

- Ian P Howard and Brian J Rogers. Seeing in depth, volume 2: Depth perception. Ontario, Canada: I. Porteous, 2002.
- David C. Knill. Discrimination of planar surface slant from texture: Human and ideal observers compared. Vision Research, 38(11):1683–1711, jun 1998a. ISSN 00426989. doi: 10.1016/S0042-6989(97)00325-8.
- David C. Knill. Surface orientation from texture: ideal observers, generic observers and the information content of texture cues. Vision Research, 38(11):1655 – 1682, 1998b. ISSN 0042-6989. doi: https://doi.org/10.1016/S0042-6989(97)00324-6.
- David C. Knill. Ideal observer perturbation analysis reveals human strategies for inferring surface orientation from texture. Vision Research, 38(17):2635–2656, 1998c.
- David C Knill. Mixture models and the probabilistic structure of depth cues. Vision Research, 43(7):831 – 854, 2003.
- David C. Knill and Jeffrey A. Saunders. Do humans optimally integrate stereo and texture information for judgments of surface slant? Vision Research, 43(24):2539– 2558, 2003. ISSN 00426989. doi: 10.1016/S0042-6989(03)00458-9.
- Frank L Kooi and Alexander Toet. Visual comfort of binocular and 3D displays. Displays, 25(2-3):99–108, 2004. ISSN 01419382. doi: 10.1016/j.displa.2004.07.004.
- Gregory Kramida. Resolving the vergence-accommodation conflict in head-mounted displays. *IEEE Transactions on Visualization and Computer Graphics*, 22(7): 1912–1931, jul 2016. ISSN 10772626. doi: 10.1109/TVCG.2015.2473855.
- Michael S. Landy, Laurence T. Maloney, Elizabeth B. Johnston, and Mark Young. Measurement and modeling of depth cue combination: in defense of weak fusion.

Vision Research, 35(3):389 - 412, 1995.

- Andrea Li and Qasim Zaidi. Perception of three-dimensional shape from texture is based on patterns of oriented energy. *Vision Research*, 40(2):217 – 242, 2000. ISSN 0042-6989. doi: https://doi.org/10.1016/S0042-6989(99)00169-8. URL http:// www.sciencedirect.com/science/article/pii/S0042698999001698.
- Nathan Matsuda, Alexander Fix, and Douglas Lanman. Focal surface displays. ACM Trans. Graph., 36(4), 2017.
- Ross Messing and Frank H. Durgin. Distance perception and the visual horizon in head-mounted displays. ACM Trans. Appl. Percept., 2(3):234–250, 2005.
- Alexander A Muryy, Andrew E Welchman, Andrew Blake, and Roland W Fleming. Specular reflections and the estimation of shape from binocular disparity. Proceedings of the National Academy of Sciences, 110(6): 2413-2418, feb 2013. ISSN 0027-8424. doi: 10.1073/pnas.1212417110. URL http://www.ncbi.nlm.nih.gov/pubmed/23341602http://www. pubmedcentral.nih.gov/articlerender.fcgi?artid=PMC3568321http: //www.pnas.org/cgi/doi/10.1073/pnas.1212417110.
- Harold T. Nefs, Jan J. Koenderink, and Astrid M.L. Kappers. Shape-from-shading for matte and glossy objects. Acta Psychologica, 121(3):297 – 316, 2006. ISSN 0001-6918. doi: https://doi.org/10.1016/j.actpsy.2005.08.001. URL http://www. sciencedirect.com/science/article/pii/S0001691805000909.
- J. Farley Norman, James T. Todd, and Guy A. Orban. Perception of threedimensional shape from specular highlights, deformations of shading, and other types of visual information. *Psychological Science*, 15(8):565–570, 2004. doi: 10.

1111/j.0956-7976.2004.00720.x. URL https://doi.org/10.1111/j.0956-7976. 2004.00720.x. PMID: 15271003.

- Ruth Rosenholtz and Jitendra Malik. Surface orientation from texture: Isotropy or homogeneity (or both)? Vision Research, 37(16):2283 - 2293, 1997. ISSN 0042-6989. doi: https://doi.org/10.1016/S0042-6989(96)00121-6. URL http://www. sciencedirect.com/science/article/pii/S0042698996001216.
- Jeffrey A. Saunders and Benjamin T. Backus. Perception of surface slant from oriented textures. *Journal of vision*, 6(9):882–897, aug 2006. ISSN 1534-7362. doi: 10.1167/6.9.3.
- Takashi Shibata, Joohwan Kim, David M. Hoffman, and Martin S. Banks. The zone of comfort: Predicting visual discomfort with stereo displays. *Journal of Vision*, 11(8):11, 2011.
- James T Todd, J Farley Norman, Jan J Koenderink, and Astrid M L Kappers. Effects of texture, illumination, and surface reflectance on stereoscopic shape perception. *Perception*, 26(7):807–822, 1997. doi: 10.1068/p260807. URL https://doi.org/ 10.1068/p260807. PMID: 9509135.
- James T. Todd, Augustinus H.J. Oomes, Jan J. Koenderink, and Astrid M.L. Kappers. The perception of doubly curved surfaces from anisotropic textures. *Psychological Science*, 15(1):40–46, 2004.
- James T. Todd, Lore Thaler, and Tjeerd M.H. Dijkstra. The effects of field of view on the perception of 3d slant from texture. Vision Research, 45(12):1501 – 1517, 2005. ISSN 0042-6989. doi: https://doi.org/10.1016/j.visres.2005.01.003.

- Margarita Vinnikov and Robert S. Allison. Gaze-contingent depth of field in realistic scenes: The user experience. In *Proceedings of the Symposium on Eye Tracking Research and Applications*, ETRA '14, pages 119–126, 2014. ISBN 978-1-4503-2751-0. doi: 10.1145/2578153.2578170. URL http://doi.acm.org/10. 1145/2578153.2578170.
- Gunnar Wendt, Franz Faul, and Rainer Mausfeld. Highlight disparity contributes to the authenticity and strength of perceived glossiness. *Journal of vision*, 8(1): 14.1–10, jan 2008. ISSN 1534-7362. doi: 10.1167/8.1.14. URL http://jov. arvojournals.org/article.aspx?doi=10.1167/8.1.14.
- Gunnar Wendt, Franz Faul, Vebjørn Ekroll, and Rainer Mausfeld. Disparity, motion, and color information improve gloss constancy performance. *Journal of vision*, 10(9):7, sep 2010. ISSN 1534-7362. doi: 10.1167/10.9.7. URL http://jov. arvojournals.org/Article.aspx?doi=10.1167/10.9.7.