UTILIZING VISUAL ILLUSIONS TO IDENTIFY AND UNDERSTAND PERCEPTUAL DISCREPANCIES IN PRODUCT DESIGN

by

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ABSTRACT

There are often discrepancies in how a product is perceived in different representation media employed in typical product development processes. The first goal of this research project was to determine how visual illusions influence a designer’s perception of a product across three representations: industrial design sketches, computer aided design (CAD) models, and physical prototypes (FDM rapid prototyping). A visualization experiment was conducted in which participants were asked to report how they perceived the shape and size of certain features, representing two types of illusions across the three model representations. Their statements were analyzed to identify the trends of how these two illusions affect overall appearance, categorized by representation type and the users’ backgrounds (i.e., specialization and years of experience). The participants included students and professionals with various levels of engineering and industrial design experience. The analysis shows that there are differences in how designers see models depending on the representation media, and to some degree depending on the participants’ professional background. The second goal was to explore the process of identifying such illusions automatically during the design process. In this regard, a discussion on how to implement the results from the visualization experiment is presented. Emphasis is on the potential development of a tool in CAD systems that would identify illusory effects and subsequently suggest potential design solutions. The possibility of using spectral analysis (fast Fourier transform) for an automated shape recognition capability in CAD systems is discussed.
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CHAPTER 1

INTRODUCTION

In a typical product development process, a product is displayed in different representation media ranging from industrial design concept sketches, via computer aided design (CAD) models, to virtual reality (VR) and physical prototypes. However, the appearance of a product is often not consistent across the media. These inconsistencies occur both because products evolve throughout the development process, but also because of the different characteristics of each representation medium. The research presented in this thesis investigated differences in three of the common representation media: industrial design sketches, CAD models, and physical prototypes made using the fused deposition modeling (FDM) rapid prototyping system.

The differences seen in a product as it progresses through the development process are two-fold. There are differences related to actual geometrical changes in the product that are necessary to implement due to constraints. There are also discrepancies related to differences where the product looks different depending on the representation medium and on the person evaluating it.

Issues related to actual geometrical differences are most obvious when conceptual industrial design sketches are compared with the finished product, for example the BMW depicted in Figure 1.1.

![Figure 1.1](image.png)

Figure 1.1. An example of how much an exaggerated concept sketch (a) can differ from the final product (b). This is also an excellent example of aesthetic expression being lost during the development process. These illustrations are of the BMW 1-series [CarDes06].
Concept sketch features are often exaggerated to emphasize important features and make the product aesthetically pleasing to engage managers and other stakeholders. Because features are out of scale, it becomes difficult to extract the correct shape for further product development while maintaining the aesthetic expression.

In many development processes, a hand-made physical model is made for better understanding of the concept, and for development and verification of the shape. The geometry of a hand-made prototype is not necessarily mathematically defined. In addition, the prototype can rarely be built using the same materials as intended for the finished product. This forced material selection might affect the ability to model the desired shape as well as obtaining a surface finish equal to that of the real product. Secondary surface treatments like sanding and polishing alter the surface.

Reproducing the desired shape when developing a CAD model is sometimes challenging because CAD systems require the shapes to be mathematically defined. In addition, the designer’s skills using the CAD system is critical. Meeting prescribed constraints, such as manufacturability and material selection, often calls for compromises with aesthetics, again putting the desired shape at stake.

Issues related to the display of virtual models are summarized in Figure 1.2. A virtual model is a common descriptor for CAD models displayed in media ranging from computer monitors to immersive virtual environments (VEs). Despite extensive research on virtual reality, and impressive technological advancement, there are still discrepancies in how a model is displayed and perceived [Ferwerda04] [Rolland95] [Söderman05].
Perceptual differences between CAD models and their exact physical replica are common, and particularly evident in design for ergonomics [PerCom06]. Exact prototypes (within specific tolerances) can be made using various numerically controlled systems such as CNC machines and rapid prototyping (RP) systems. The surface finish of such prototypes is sometimes an issue because of the limited material selection and the characteristics of the various systems in terms of tolerances and accuracy. Most RP models require surface treatment because they are built in layers and have stepped curvatures. Sanding and polishing alter the surface and the mathematically defined shape. Using different materials than for the real product results in different surface finishes as well. These factors, and more, may cause the exact physical prototypes to look different.

Since we currently are not able to explain all differences between media, we have decided to investigate if there are certain geometries that are likely to be perceived erroneously. Two-dimensional geometries that are consistently misperceived are visual illusions, many of which are well known in experimental psychology and visual sciences [Coren78a] [Gregory97] [Oppel54]. Real products occasionally have geometry very similar to known two-dimensional illusions. In this research, an attempt is made to explain some of the perceptual differences by investigating how visual illusions in real products are perceived depending on media and evaluators’ experience.
Illusory effects have been widely researched by psychologists since the 1850s [Oppel54], though no examples have been found where real three-dimensional products were used as stimuli. Culture and background have been reported to have impact on the susceptibility to such effects [Stewart73], [Jahoda70]. However, group differences between engineers and industrial designers have not been considered, mainly because most research on illusions has been performed within the fields of psychology [Coren78a] [Gregory97] and vision science [Vos60], and not in product development.

Two illusions, architrave and irradiation, were selected for this study (Figure 1.3). The selection was based on the different nature of the illusions and the fact that identical and similar geometry can be found in several everyday products, such as automobiles, consumer products and not the least buildings. That these shapes are representative for several everyday products is considered very important for the future application of the results from this study.

![Variations of the architrave illusion](image1)

![Variations of the irradiation illusion](image2)

**Figure 1.3.** Two visual illusions common in many everyday products. In this experiment, the curved variation of the architrave illusion represents the window of a car. By coloring the window and the car body in contrasting colors, the irradiation illusion is represented.

It is difficult to predict what kind of geometry will be perceived differently in the different representation media. Currently, the designers’ experience is fundamental to avoid surprises due to perceptual differences. To make the design process more robust, so that it does not depend solely on professional experience, an automated shape recognition capability should be available in CAD systems. Such a capability would assist the designer in identifying shapes that are likely to be perceived different than was intended. In this thesis, the possibility of using spectral analysis to detect illusory shapes and contours is discussed. In this proposed tool, the actual 2D illusions will be compared with projections of the CAD model using frequency characteristics instead of the actual
The implementation of a repair capability that would suggest what changes should be made to avoid unintended illusory effects is also discussed.

1.1 PROBLEM STATEMENT

The main objective of this thesis is to quantify the effect certain visual illusions have on a designer’s impression of a model depending on the representation media and the designer’s professional background. A derived objective is to discuss to what degree spectral analysis can be employed to develop an automated shape detection tool in CAD systems. The findings presented in this thesis can be applied in any product development process using multiple representation media.

1.2 SOLUTION OUTLINE

Understanding how geometries are perceived differently during development processes is important. Development time and cost can be saved if designers can predict how certain geometries are likely to be perceived differently depending on the representation media. A first step towards identifying such high-risk geometries could be to compare known visual or optical two-dimensional illusions to geometry in real products. A next step would be to investigate effects of these illusory shapes at different stages in a development process. The representation media affects the way models look, but perceptual differences may also depend on the person viewing the model.

Perceptual differences that are likely to occur in a product development process can be quantified by having designers with various backgrounds in product design and development view models presented in different display media. The results from such a visualization study would reveal differences depending on both display media and professional experience.

Automobiles contain geometry similar to some known visual illusions. The outline of the side window represents a common geometrical illusion called the architrave illusion (Figure 1.3 a). By coloring the car body and the window in contrasting colors, the car can represent another visual illusion called the irradiation illusion (Figure 1.3 b). The geometry of the window can be varied in small steps to gradually account and
overcompensate for the illusory effects. These two illusions can be found in other everyday products as well.

The findings from the visualization study could be implemented in the development process by developing a shape recognition capability for CAD systems. Spectral analysis using Fourier transforms is one of most the established methods for shape recognition [Loncaric98]. The suitability of this technique for a recognition tool in CAD software should be determined.

With an automated shape detection tool in place, designers can choose whether they want to utilize the illusory effects, or suppress them if they cause the product to be perceived in an unfavorable way.

1.3 THESIS ORGANIZATION

Chapter 2 of this thesis focuses on building a good foundation to ease the understanding and the necessity of the product visualization study. The chapter presents a review of literature treating model visualization in different representation media as well as visual illusions. Methods for shape recognition and Fourier transform are also reviewed to give background for the discussion on an automated shape recognition capability in CAD systems.

Chapter 3 presents the method employed to develop and conduct the visualization study. It also details the results and discusses the perceptual differences between the representation media and the participants for the two selected illusions. Lastly, Chapter 3 presents a discussion on the use of spectral analysis for automatic shape detection in CAD systems.

Chapter 4 contains conclusions and recommendations for future work.

Several appendices are included to capture necessary documentation for a more comprehensive understanding of the research performed and to form the basis for future work.
CHAPTER 2
LITERATURE REVIEW

The need to understand how a VE can represent the real world truthfully is growing. The most significant driving force behind the development of virtual technology in product development is the need to cut down on costly and time-consuming manufacturing of physical prototypes. This need is most prominent in industries developing complex and large products with high focus on aesthetics, such as the automobile industry.

This chapter will first give the reader a general understanding of some of the efforts that have been made to make shape discrimination in virtual models easier and more robust. Next, the chapter presents background on visual illusion research, from the fields of psychology and vision research. Lastly, the background necessary to understand the discussion on the implementation of an automated shape recognition tool is presented.

2.1 VISUALIZATION OF MODELS

Research on differences between virtual reality and real environments often focus solely on how the technology can be improved to make a model look more real in terms of included detail. This approach usually works well, but the increased level of detail requires a large increase in computational power when rendering complex models and environments. Understanding the human perceptual system, visual and cognitive, is important in the attempt to decrease the level of detail without affecting the amount of information provided by the model. Studies of the human visual system show that a very high level of detail in a rendered image does not necessarily make the model look more real to observers [McNamara05]. The details the brain does not need to generate a realistic impression of the image are now oftentimes excluded so that less computing power is needed for rendering.

One example is Level of Detail (LOD) rendering [Parkhurst04]. The main approach within this technique is to adjust the rendering detail to where the person viewing the model is looking. Since our ability to perceive details is most accurate in the center of view, objects in the periphery can be rendered with less detail without loss of
information. Localizing where the viewer looks can be done using eye tracking devices. Eye trackers must not be confused with head tracking devices, which are already well integrated in Virtual Environments (VEs). Head trackers only track the position of the head, not where the person is looking. The issue with both eye- and head tracking is that the model can only be adapted to one person at a time. For other people viewing the model at the same time, the model will be distorted and blurry.

While LOD rendering focuses on displaying highly realistic environments, other methods are more efficient when the primary goal is to detect surface shapes. Applying surface textures and shading patterns to models allows for more consistent and easier shape discrimination [Weiskopf06] [Sweet04]. In some cases, when the finished product is intended to have texture, it is applied directly to the surface. Surface texture in this context, however, is a method used in rendering and involves simulating the surface texture using luminance [Kim04]. One basic texture is shown in Figure 2.1c). Illumination patterns for shape discrimination are applied in the same manner as surface texture, but are usually displayed as stripes. The pattern follows the surface such that curvatures are easy to detect (Figure 2.1d) and e)).

![Figure 2.1](image)

**Figure 2.1.** A sample model rendered using different parameters to show how surface illumination and texture can be used to communicate shapes. This test model was modeled with $C^1$ continuity, meaning that adjacent faces are tangent, but do not have the same curvature. The models are rendered with a) no ambient lighting (only directional), b) default lighting settings, c) basic surface texture, d) zebra stripes, and e) colored stripes. The two latter rendering methods are most frequently used to check for continuity between surfaces.
Most CAD systems have basic versions of both texture and shading pattern methods integrated and easily accessible. The most commonly used shape discrimination method is the “zebra stripes”. Figure 2.1 shows how the “zebra stripes” and other basic surface shadings and textures reveal shape variations differently. Patterns like the “zebra stripes” are common to use to test for tangency and continuity between surfaces (the model in Figure 2.1 has $C^1$ continuity). Some more sophisticated patterns (for example cycle shading and hatched cycle shading [Weiskopf06]) can reveal $C^2$ surface discontinuities. In addition to surface textures and shading patterns, the point of view is also of great importance for shape detection [Ferwerda04] [Sweet04].

However, the shape discrimination methods employed for shape discrimination do not make models look more real. Consequently, it does not make sense to compare these virtual representations to their real counterparts. On the other hand, when the goal is split, into render both unambiguous shapes and realistic models, Ferwerda et al. investigated the effect global and local illumination rendering methods have on shape discrimination [Ferwerda04]. Global illumination is a rendering algorithm that takes into account light that bounces off neighboring surfaces in addition to direct (local) light. The surface curvature of a feature on the test object was varied in small steps (Figure 2.2). Subjects compared virtual models of varying geometry with a real reference model, and assessed how different each virtual shape looked from the real shape. Their results show that advanced rendering methods such as global illumination have a large impact on the ability to discriminate shape differences. They also found that the viewpoint is of great importance for shape discrimination.
Figure 2.2. The test object used in the study by Ferwerda et al. This image shows how the surface shape was varied from the base model (high curvature) to almost straight line (Reproduced from [Ferwerda04]).

Not many studies in the engineering field have been performed where more than two representation media are included in the evaluation. Söderman makes an exception in [Söderman05] when comparing concept sketches, VR models, and real models. The motivation behind this study was to determine if sketches and VR models provide sufficient information for effective product evaluations with customers. The test object was a Volvo S80 1999 model represented by hand drawn concept sketches, VR models in an immersive VE, and real cars. Both exterior and interior of the car were included in the study. The representations were evaluated and compared to assess how they influence a customers’ understanding of a product concept. Focus group interviews were employed to analyze the responses. Thus, the results are conceptual and not in terms of how certain geometries are perceived inconsistently in the different representations by designers and engineers.

Common theories about perceptual differences between CAD or VR models and real models involve distortion in the display media. Common types of image distortions are shown in Figure 2.3 and include barrel, pincushion, trapezoid, and perspective distortion. With the introduction of flat screens, barrel and pincushion distortions are less problematic for computer monitors. In addition to these four types of distortion, the aspect ratio (the ratio of the width to the height of an image) also influences the display. The dimensions of computer monitors are standardized, but that is necessarily not the case for the image shown within the frame. The user is for example free to adjust these
display properties, adding more uncertainty to the correctness of the display. If these properties are different between display screens, the model will look different on each screen. These issues are also present for projectors and VEs. A rather obvious problem with projectors is perspective distortion occurring because the image is not projected exactly perpendicularly onto the viewing screen.

Rolland et al. show that pincushion distortion for the individual monocular images has the effect of bringing objects closer to the eyes in VEs [Rolland95], and hence also make them appear larger. Monocular images are images produced with slightly different viewpoint to simulate the position of each eye. These images are displayed on two screens in a head mounted display (HMD) or VE screens resulting in a stereographic image. Because the distance between people’s eyes is not constant for all people, an average interpupillary distance must be used when calibrating the HMDs and VEs. This interpupillary distance on HMDs can be difficult to adjust accurately. Therefore, people

![Common image distortions](image)

**Figure 2.3.** Common image distortions often seen on computer monitors and projected images; a) pincushion distortion, b) barrel distortion, c) trapezoid distortion, and d) perspective distortion.
with different interpupillary distance will not see the display the same way [Willemsen02]. Usually an average value is used (between 58 and 72mm).

The most common approach when looking at differences between representation media is to look at the characteristics of the media and try to make the models similar. The approach in this thesis is to accept that there are differences and instead investigate if there are certain geometries that are more likely to be different across representation media. As a first cut, geometries resembling known visual illusions are investigated. The next section gives some general background on the research field of visual illusions.

2.2 VISUAL ILLUSIONS

Illusions can be defined as “systematic visual and other sensed discrepancies from simple measurements with rulers, photometers, clocks and so on” [Gregory97]. This means that illusions are predictable differences between what we logically would believe is correct and what we actually see as correct. The literature generally classifies visual illusions into optical and geometrical illusions. Some illusions occur due to various physical causes while others are due to cognitive misinterpretations. These very different causes of illusory effects may cause very similar phenomena, such as distortions of length and curvature. Because of the similar results, classification of illusions is not straightforward and requires experimental evidence.

Pure two-dimensional illusory effects have been widely researched by psychologists and vision researchers since the mid 1850s, starting with a controversial paper by Oppel in 1854 [Oppel54]. Over the years, numerous illusory geometries and images have been discovered and developed. Figure 2.4 presents a selection of the most common geometrical illusions.
We expect converging lines to be simulating perspective and our brain tells us that there are several examples of these illusions in the real world. The Ponzo illusion is utilized is in the fashion industry. When designers want to make clothes with a “slimming” effect, they utilize this illusion by using vertical striped patterns. The most common physical example of the horizontal-vertical illusion is a picture of a top hat where the hat looks taller than it is wide even though the dimensions are equal. A common physical example of the Poggendorff illusion is a window in a church with a column in front that breaks the arc on the window. This arc then looks discontinuous.

There are several examples of these illusions in the real world. The Ponzo illusion, for example, is perceived oddly because of our knowledge about perspective. We expect converging lines to be simulating perspective and our brain tells us that objects should become smaller closer to the converging point. One example where the Oppel illusion is utilized is in the fashion industry. When designers want to make clothes with a “slimming” effect, they utilize this illusion by using vertical striped patterns. The most common physical example of the horizontal-vertical illusion is a picture of a top hat where the hat looks taller than it is wide even though the dimensions are equal. A common physical example of the Poggendorff illusion is a window in a church with a column in front that breaks the arc on the window. This arc then looks discontinuous.

One of the first proofs that people were aware of geometrical illusions in general is the Parthenon temple in Athens, built between 448 and 432 BC [Coren78a]. The Greeks built the architrave on the temple curved slightly upwards to compensate for the illusion of it bulging downwards (Figure 2.5). This illusory effect has given name to the architrave illusion, which is the first illusion studied in this thesis. Other examples of this illusion are shown in Figure 2.6.
Figure 2.5. The Parthenon temple is supposed to look like a). Due to perspective distortions and the architrave illusion, the temple would, if it were built like a), look like b). Therefore, the Greeks built it like c) (Images reproduced from [Coren78a]).

The Greeks were also aware of the irradiation illusion, which is the other illusion studied in this thesis. The irradiation illusion is a misinterpretation of size due to color contrasts. Dark features on bright background appear smaller than their inverse. The Greeks accounted for this effect when they dimensioned the columns in their temples in relation to the space between the columns. Other real examples of the irradiation illusion can be seen in Figure 2.6 below.

The irradiation illusion also occurs for other color combinations. Vos is one of the researchers who investigate color stereoscopy [Vos60]. Color stereoscopy means that the color of an object has influence on its apparent distance in binocular perception.
Usually, objects in red illumination look closer to the observer than identical objects in blue illumination, though some people may see the opposite. This specific phenomenon is known to vision researchers as chromostereopsis. Furthermore, the chromostereopsis theory implies that red objects look larger than blue objects with identical dimensions. The irradiation illusion is also evident in products with grid or grating (similar to the example of columns in the Greek temples) where the space between ribs might be perceived as larger even when it is the same width as the ribs themselves (Figure 2.6).

Several factors may influence people’s susceptibility to illusions. Contributing factors include age, gender, culture, environment, and professional training. The participants in the study described in the next two chapters will be from similar culture and environment, but their age, gender, and professional training will vary.

The susceptibility to illusions generally decreases with age [Coren78b], but naturally, there are variations. One physiological explanation to why people get less susceptible is a result of an age-related increase in the macular pigmentation of the eye [Stewart73]. The macula is an area on the light-sensitive retina that has impact on color vision but also the ability to discriminate contours. The retinal pigmentation is also directly related to skin color, and hence explains some of the differences seen between subjects from different races.

Jahoda and Stacey investigated group differences concerning culture and educational training with participants from Ghana and Scotland [Jahoda70]. The participants were either novices or they had at least two years of experience in art and architecture. The cultural differences were significant between the Ghanaians and Scots. The authors explain part of the cultural differences with the effect of living in a “carpentered” environment or not. A “carpentered” environment refers to the common environment in Western communities where rectangular shapes, straight lines, and square corners dominate. While there are many different illusions with very different characteristics, the Ghanaians were more susceptible than the Scots to only two out of seven illusions that were tested. This cultural effect is also a topic in [Stewart73] where an increase in illusion-susceptibility was found with an increase in the degree of environmental “carpenteredness”. The differences due to art and architecture training
indicate that training decreases the susceptibility for all illusions but one (13 illusions were tested). However, this effect was only found to be moderate within each culture.

Gender differences are usually found in studies of illusion-susceptibility. In most cases, females are found to be more susceptible than males (e.g. [Miller01]), but again there are variations. Mary Stewart, who was one of the researchers investigating the cultural effect of “carpenteredness” discussed above, found in that same study that males were more susceptible [Stewart73].

As has been discussed, culture, gender, and professional training have impact on a person’s susceptibility to illusory effects. However, no examples have been localized where group differences as specific as those between industrial designers and engineers have been investigated. Psychology studies measure the susceptibility to illusions, an ability that is purely perceptual. The constraints are not as firm in engineering evaluation studies where analytical skills play a larger role. Since the results are intended for application in the engineering field, most weight should be put on evaluation techniques.

2.3 AUTOMATED SHAPE RECOGNITION TOOL

The knowledge gained about visual illusions and visualization should be integrated in the product development process. One solution is an automated shape recognition tool in CAD systems. Product designers currently rely on experience when evaluating the possibilities for perceptual differences between representation media [PerCom06]. Still, multiple iterations with physical prototypes are common in development processes.

The two-dimensional projection of the CAD model can be compared to images of known illusions stored in a library. One could use the actual spatial images, but correlation algorithms are particularly expensive when carried out on such images. A better way would be to correlate the frequency information of the images. The next paragraphs give background necessary to understand this statement.

Images only differ from “traditional” signals by the way they store information over space instead of over time. The frequency of an image is a measure of how quickly brightness or color variations occur across an image. Low frequencies represent coarse spatial structure of the image, while high frequencies describe details and sharp edges. The frequency response of an image contains the exact same information as the input
image, and if inversed, the original image can be restored. The transform of a boundary generates a set of complex numbers, descriptors, which represent the shape in the frequency domain. A subset of these descriptors is often enough to discriminate different shapes [Loncaric98].

Signals are transformed into the frequency domain using the Fourier transform [Horn86]:

\[ F_{m,n} = \sum_{k=0}^{M-1} \sum_{l=0}^{N-1} f_{k,l} e^{-\frac{2\pi i (km ln)}{MN}} \]  

(2.1)

where \( M \) and \( N \) are the dimensions of the image in pixels, \( k = 0, 1, \ldots, M-1 \) and \( l = 0, 1, \ldots, N-1 \). The traditional method to transform the image to the frequency domain requires \( M^2N^2 \) computations because each term is computed separately. The fast Fourier transform (FFT) algorithm, however, only requires \( 4MN \log_2 MN \) computations.

The process of correlation is practically identical to that of convolution [Lewis90] [Horn86]. The only difference in the spatial domain is that if the image is to be convoluted it must be rotated 180 degrees relative to an image to be correlated. The computational load for the two operations is identical, if not considering the rotation. Convolution uses a matrix (mask) with values that is convolved with the reference image. When this matrix is large (typically larger than 9 x 9 pixels), these calculations become heavy if computed in the spatial domain. Because convolution in the spatial domain translates to multiplication in the frequency domain, it is often beneficial to transform the image to the frequency domain, perform the convolution, and then inverse transform it back to the spatial domain. The same principle is valid for correlation.

Correlation is performed using an image with the geometry to be localized (window) instead of a filter mask for convolution. The window is also a matrix with numbers, with the values being the brightness of each pixel in the image. In some cases, the window can be as large as the reference image itself. Therefore, it is rather obvious that this task should be performed in the frequency domain. The correlation expression is

\[ f(x,y) \odot g(x,y) \Leftrightarrow F(u,v)G(u,v) \]  

(2.2)

where \( f \) is the reference image and \( g \) is the window in the spatial domain. \( F(u,v) \) and \( G(u,v) \) are the Fourier transforms of the reference image and the window respectively.
The correlation in the spatial domain is equivalent to the multiplication of $F(u,v)$ and the complex conjugate (denoted by the bar over $G(u,v)$ in Equation (2.2)) of $G(u,v)$ in the frequency domain. The complex conjugate of a number $z \equiv a + bi$ is simply $z \equiv a - bi$. The complex conjugate of a matrix is obtained by replacing each element by its complex conjugate. The required steps to perform a correlation include transforming both the reference image and the window using FFT and form the complex conjugate of the window frequency matrix. Lastly, the reference image transform is multiplied by the complex conjugate of the window transform to correlate the two images.

One disadvantage with the Fourier transform is that local shape information is distributed to all coefficients after the transform is applied [Loncaric98]. This is explained by the following: low frequencies represent coarse features and high frequencies represent sharp edges in images. In the frequency transformed image, the frequency increases towards the edge of the image. The correlation is performed by aligning the centers of the window transform and the reference image transform. By doing this, high frequency components are excluded because the window is (usually) smaller than the reference image. Other feature recognition methods such as the wavelet transform might therefore result in a more robust detection tool.

Different methods for shape and feature recognition are being heavily researched in the computer vision and engineering fields. Many of the results applied to product development revolve around constructing databases of models with indexing and query possibilities [Bespakov03].

Implementation of aesthetic features in CAD was researched in the international FIORES II project [Cappadona03]. Their objective was to develop a method of editing shapes in CAD while maintaining the aesthetic expression. More specifically, they developed free-form modeling tools for curve modification driven by perception and aesthetic properties. They developed a software prototype where users can modify the shape by adjusting parameters numerically. The aesthetic properties are maintained for example by having the user specify the level of continuity between surfaces and curves. A tool that identifies and suggests fixes for illusory geometries should be implemented in a similar way.
2.4 OBSERVATIONS

The literature suggests the following about the three main topics investigated in this thesis:

2.4.1 Visualization of models

- Differences seen between models represented in different media may be due to actual geometrical changes occurring as the product is developed, such as mathematically defining the CAD model, or adjusting the model to meet manufacturing requirements. In addition, the designer’s skills using the modeling software is crucial [PerCom06].
- Differences seen between models represented in different media may also be due to the characteristics of each representation media, including distortions, illumination techniques, color scheme and level of detail [Rolland95] [Willemsen02].
- The rendering methods employed affect how shapes are perceived [Ferwerda04] and how realistic a virtual environment appears [McNamara05] [Parkhurst04].
- Several algorithms have been developed purely to aid in discriminating shape and surface variations [Weiskopf06] [Sweet04] [Kim04].

2.4.2 Visual illusion research

- Illusory effects have been known for many years [Oppel54] [Coren78a].
- A person’s susceptibility to illusions may be affected by factors such as age, cultural background, environment, professional training, and gender [Coren78b] [Jahoda70] [Miller01] [Stewart73].

2.4.3 Using spectral analysis for shape recognition in proposed CAD tool

- Images can be represented by their frequency information using Fourier descriptors [Loncaric98]. Images can be transformed into the frequency domain efficiently using the fast Fourier transform (FFT) [Horn86].
- Images can be correlated (compared) using their frequency information instead of the real spatial information to save computational power and time [Lewis90].
CHAPTER 3

UTILIZING VISUAL ILLUSIONS TO IDENTIFY AND UNDERSTAND PERCEPTUAL DISCREPANCIES IN PRODUCT DESIGN

The trend in past and current research is to improve rendering methods to display a virtual model more realistically and thus making the transition between virtual and physical prototypes more predictable. The approach in this thesis is to accept that there are differences between the representation media and instead focus on what shapes are likely to be problematic in this transition. The geometries of interest here are those known to produce illusory effects. The remainder of this chapter details the experiment carried out to investigate how two different visual illusions affect how engineers and industrial designers with various experience evaluate models presented as sketches, CAD models and RP models. A suggested implementation into the product development process, in form of an automated shape recognition tool in CAD systems, is also discussed.

The format of the remainder of this chapter is that of a manuscript for a scientific paper to be submitted for review in an archival journal. Preliminary results were compiled, submitted to, and presented at the International PACE Forum on Collaborative Visualization in Darmstadt, Germany on November 15-17, 2006. The paper has three authors: this thesis author, Prof. Jan Helge Bøhn (committee chair), and Prof. Dr.-Ing. Reiner Anderl (committee co-chair). The research was conducted entirely by this thesis author, including the literature review, experimental design, conduction of experiment, analysis, and write-up. The two professors served as supervisors and reviewers.
UTILIZING VISUAL ILLUSIONS TO IDENTIFY AND UNDERSTAND PERCEPTUAL DIFFERENCES IN PRODUCT DESIGN

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ABSTRACT

There are often discrepancies in how a product is perceived in the different display media employed in typical product development processes. Product developers in many cases rely on different display media for design realizations. However, since design iterations are costly and time-consuming, it is desirable that the perceptual discrepancies between the media at different development stages are consistent. This study investigated if visual illusions can be used to understand these discrepancies. The perceptual differences of a simplified model of a car were compared for three representation media: industrial design sketches, computer aided design (CAD) models, and physical prototypes (FDM rapid prototypes). The geometry of the car window was varied to simulate the two visual illusions called architrave and irradiation illusions. The test subjects were industrial designers and engineers with varying levels of experience (students and professionals). Significant differences were encountered between the three representation media for both illusions. The engineering professionals were also found to be significantly different from both industrial design students and professionals for the irradiation illusion. It is suggested that the results are implemented into the product development process in the form of an automated shape recognition tool for CAD systems, possibly based on spectral analysis for image correlation and recognition.
3.1 INTRODUCTION

In a typical product development process, a product is displayed in different representation media ranging from industrial design concept sketches, via computer aided design (CAD) and virtual reality (VR) models to physical prototypes. The appearance of a product is often not consistent across these media. Inconsistencies occur both because products evolve throughout the development process, but also because of the different characteristics of each representation medium. In this paper, we look at differences in three of the common representation media: industrial design sketches, CAD models, and physical prototypes made using the fused deposition modeling (FDM) rapid prototyping (RP) system.

In industrial design concept sketches, features are often exaggerated to emphasize important features and make the product aesthetically pleasing to engage managers and other stakeholders. The problem is that it becomes difficult to extract the correct shape because features are out of scale. Producing the desired shape for a computer model may be challenging because CAD systems require the shapes to be mathematically defined. In addition, the designer’s skills using the CAD system is critical. Meeting prescribed constraints, such as preparing the product for manufacturing, calls for compromises with aesthetics putting the desired shape at stake. Perceptual differences between CAD models and their exact physical replica, made using a rapid prototyping system, are also common, as will be shown in this paper.

Real products occasionally have geometries very similar to known two-dimensional visual illusions. Illusory effects may play a role in the differences we perceive across different representation media. The two illusions in this study were selected because of their different characteristics, but foremost because identical and similar geometry can be found in many everyday products. Selecting different types of illusions allowed us to investigate whether one type of illusions is perceived differently than the other type of illusion.

As mentioned, the focus in this research project is on determining if certain geometries are more likely than others to be perceived differently depending on the representation media. Any findings with regard to this first objective would be desirable
to integrate in the product development process. One solution might be an automated shape recognition capability in CAD systems that can detect potentially problematic geometries. One possibility is to use spectral analysis and fast Fourier transform (FFT) for shape recognition. The frequency information of two-dimensional projections of the CAD models would be compared with two-dimensional images that clearly depict various illusions. We suggest implementing this method in CAD as an automatic identifier, and possibly also a repair-tool. Such a tool would make the designer aware of any high-risk geometries at an early stage, and hence make the transition from CAD model to physical prototype more predictable.

3.2 BACKGROUND

The major part of this paper is concerned with the visualization study conducted to investigate perceptual differences across the different display media as well as differences between persons with various backgrounds. The following section provides the necessary background, describes the experiment and results, and discusses the results.

3.2.1 Visualization of models

The need to understand how a virtual environment (VE) can represent the real world truthfully is growing. The most significant driving force behind the development of virtual technology in product development is the need to cut down on costly and time-consuming manufacturing of physical prototypes.

Research on differences between virtual reality and real environments often focus solely on the technology and how it can be improved to make a model look more real in terms of included detail. Studies of the human visual system show that a very high level of detail in a rendered image does not necessarily make the model look more real to observers [McNamara05]. The details that the brain does not need to generate a realistic impression of the image are therefore oftentimes excluded so that less computing power is needed for rendering [Hubbold95].

Improving rendering techniques for more consistent and easier shape discrimination is a heavily researched topic. In [Kim04], shading is complemented with surface textures that are simulated using luminance to represent surfaces less ambiguously. Other examples include [Weiskopf06] and [Sweet04]. These examples all
show that surface texture and patterns aid in correctly displaying shape variations, but the rendering techniques deployed are solely for shape discrimination. Because these methods do not make models look more real, it does not make sense to compare these virtual models to their real counterparts. When the goal is split, however, into making both unambiguous shapes and realistic models, it was shown by Ferwerda et al. that global illumination better discriminates shape than local illumination [Ferwerda04].

Not many studies in the engineering field have been performed where sketches are included in the evaluation. Söderman makes an exception in [Söderman05]. The motivation behind his study was to determine if sketches or virtual reality (VR) models provide sufficient information for effective product evaluations with customers. Product representations in form of sketches, VR models, and real models, were evaluated and compared to determine how they influence customers’ understanding of a product concept. However, these results are conceptual and not in terms of how geometry is perceived inconsistently in the different representations by designers and engineers.

Common theories about perceptual differences between CAD or VR models and real models are for example distortion in the display media such as aspect ratio inconsistencies, and barrel, pincushion, and trapezoid distortion. One example is [Rolland95], in which the authors look at how to accurately represent depth and size in virtual reality. In addition, for head mounted displays, the field of vision and interpupil distance are critical parameters, especially when distance perception is evaluated [Willemsen02]. No examples have been found in which visual illusions are utilized to explain differences between representation media.

### 3.2.2 Visual illusions
Illusions can be defined as “systematic visual and other sensed discrepancies from simple measurements with rulers, photometers, clocks and so on” [Gregory97]. This means that illusions are predictable differences between what we logically would believe is correct, and can measure, and what we actually see as correct. The literature generally divides visual illusions into optical and geometrical illusions [Gregory97]. Some illusions occur due to various physical causes while others are due to cognitive misinterpretations. These very different causes of illusory effects may cause very similar phenomena, such as distortions of length, area and curvature. Pure two-dimensional illusory effects have
been widely researched by psychologists and vision researchers since the mid 1850s, starting with a controversial paper by Oppel in 1854 [Oppel54]. However, since this research is tailored towards understanding the human perception and vision, clear 2D illusory stimuli are used instead of real 3D products. The illusions chosen for such studies are those with strong and easily measurable effects. The most common illusion is the Müller-Lyer illusion, which is used for screening and training purposes to check for susceptibility to illusions in this study. This illusion is strong and the effect is easy to measure. Several of the well-known illusions can be identified as shapes and contours in actual everyday products.

Probably the first evidence that people were aware of geometrical illusions is the Parthenon temple in Athens, built between 448 and 432 BC [Coren78a]. The Greeks built the architrave on the temple curved slightly upwards to compensate for the illusion of it bulging downwards. The architrave illusion is one of the two illusions investigated in this study. The Greeks were also aware of the irradiation illusion, which is the other illusion studied in this paper. The irradiation illusion is a misinterpretation of size due to color contrasts. Dark features on bright background appear smaller than their inverse even when they are equal in size. The irradiation illusion also occurs for warm/cold color combinations as is shown in [Rolland95], where an object in red illumination was reported to seem closer to the viewer than an identical object in blue illumination. This finding implies that a red object looks larger than a blue object. This knowledge may be applied in any product development process, including products with grid or grating and features with different colors.

It has been reported that culture, gender, and professional training have an impact on a person’s susceptibility to illusory effects [Stewart73] [Jahoda70], but no examples have been found where group differences for engineers and industrial designers have been investigated. Jahoda also investigated group differences with regards to educational training in art and architecture [Jahoda70]. The subjects were either novices or they had at least two years of experience. The effect such training had on the susceptibility to geometrical illusions was only found to be moderate. Furthermore, most studies investigating gender differences in perception find that females are more susceptible to illusions than males (e.g. [Miller01]); however, in [Stewart73] the opposite was found.
3.3 METHOD

This section describes the experiment conducted to investigate perceptual differences between the three different representation media: industrial design sketches, CAD models, and physical prototypes (FDM rapid prototyping). The two geometrical illusions chosen for the first experiment (architrave and irradiation) are shown in the Figure 3.1 together with the illusion used in the introductory screening test (Müller-Lyer).

The two horizontal lines in Figure 3.1a) have equal length, but the top line appears shorter than the bottom line due to the orientation of the arrowheads. The illusory effect for the architrave illusion is that the horizontal line appears to be curved slightly downwards. Curving this line upwards will compensate for this effect. For the irradiation illusion, the dark area on bright background appears smaller than the bright area on dark background. Making the small white area smaller than the small black square will compensate for this illusory effect.

3.3.1 Participants

96 people (27 females and 69 males) with various backgrounds from product design and development participated in the experiment, including a control test and a main experiment. The group characteristics are presented in Table 3.1. The industrial design students received course credit for participation. All participants had normal or corrected-to-normal vision. The eligibility criterion for the student participants was that they had some experience in product design and development from schoolwork or internships. The professionals were required to have at least 2 years of experience in their respective field. A within-subject experimental design was used in which all
participants were tested for both illusions. The sequence in which the display media (sketch, CAD model, and RP model) were presented was randomized using complete counterbalancing. This technique accounts for symmetric carry-over effects, including learning effects.

Table 3.1. The characteristics of each of the four groups, as well as the total characteristics. The number of participants in each group are multiples of 6 because of the properties of complete counterbalancing.

<table>
<thead>
<tr>
<th></th>
<th>Average age</th>
<th>Average years of experience</th>
<th>Males</th>
<th>Females</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Industrial design students</strong></td>
<td>21.23</td>
<td>2.95</td>
<td>17</td>
<td>13</td>
<td>30</td>
</tr>
<tr>
<td><strong>Engineering students</strong></td>
<td>24.03</td>
<td>1.38</td>
<td>25</td>
<td>5</td>
<td>30</td>
</tr>
<tr>
<td><strong>Industrial design professionals</strong></td>
<td>37.28</td>
<td>12.17</td>
<td>13</td>
<td>5</td>
<td>18</td>
</tr>
<tr>
<td><strong>Engineering professionals</strong></td>
<td>36.44</td>
<td>11.50</td>
<td>14</td>
<td>4</td>
<td>18</td>
</tr>
<tr>
<td><strong>Average/Total</strong></td>
<td>29.75</td>
<td>7.00</td>
<td>69</td>
<td>27</td>
<td>96</td>
</tr>
</tbody>
</table>

3.3.2 **Control test**

The screening test was performed for two reasons. Firstly, it was used to make the subjects comfortable with the procedures through the completion of a short training session. Secondly, it was used to assess each participant’s susceptibility to illusions. The Müller-Lyer illusion is appropriate for this purpose because it is the most widely used geometrical illusion in perception and vision research. The stimuli consisted of a set of 10 screens, identical to the image in Figure 1a). The length of the upper horizontal line was increased in steps of 5% from -15% to +30% of its initial length for each screen. The figures were displayed sequentially on a HP LP2065 20” LCD monitor. The participants were asked to go back and forth and then decide on which screen they perceived the two horizontal lines to be equal in length. Their responses were recorded.
3.3.3 Main experiment
The object used in the experiment was a simplified model of a car, shown in Table 3.2. The overall dimensions of the car were 150mm by 50mm. The bottom edge of the window was 65mm by 15mm. The height of the window was 15mm. These dimensions were the same for all three representations.

<table>
<thead>
<tr>
<th>Industrial design sketches</th>
<th>CAD models</th>
<th>RP models</th>
</tr>
</thead>
<tbody>
<tr>
<td>Architrave illusion</td>
<td><img src="image1.png" alt="Architrave illusion" /></td>
<td><img src="image2.png" alt="Architrave illusion" /></td>
</tr>
<tr>
<td>Irradiation illusion</td>
<td><img src="image4.png" alt="Irradiation illusion" /></td>
<td><img src="image5.png" alt="Irradiation illusion" /></td>
</tr>
</tbody>
</table>

For the architrave illusion, the participants were presented with 7 models in each of the three media: industrial design sketches, CAD models, and RP models. The curvature of the bottom line on the window was varied for each model by displacing the midpoint of the line in 0.5mm steps from -1.5mm to +1.5mm. Each participant evaluated the models and selected the instance where the bottom line of the window seemed straight. If the participants were affected by the illusory effect, they would pick a model where the bottom line had upwards curvature, i.e. a positive displacement.

For the irradiation test, the subjects compared one white car model with black window to 7 black car models with white windows. The size of the white windows was varied by changing the length of the bottom line and the height of the window in steps of 5% from -15% to +15%. The participants selected the instance where the white window looked the same size as the black reference window. If the participants were affected by the illusory effect, they would pick a model where the white window was smaller than the black window, i.e. a negative percentage.
The sketches and RP models were randomly distributed on a table in front of the participants. The CAD models were presented sequentially on the same monitor as in the screening test. Only one CAD model was displayed at a time, because the size had to be consistent across media to avoid possible scaling effects. Randomizing the sequence was not desirable because the participants would then have trouble navigating through the models while trying to compare the different geometric variations.

Many researchers control the environment carefully, for example by having the subjects look through a small aperture when viewing both virtual and physical scenes [McNamara05] [Ferwerda04]. However, when designers evaluate models in real life, they will most likely look at the models from different angles and from different viewing distances. In this study, we chose not to control these parameters because we want to make the results general and applicable to other environments than the experimental setup. The participants were allowed to pick up the sketches and RP models to evaluate them in the way they preferred. Any special techniques the participants employed were recorded together with the standard results.

3.4 RESULTS

This section presents the results of the visualization study based on the data collected from the 96 participants. The data was first analyzed using descriptive statistics, and then checked for statistical significance using Analysis of Variance (ANOVA) with unequal samples and 95% confidence. SAS statistical software was employed for this work.

Table 3.3 shows the results from the introductory screening test. The participants generally underestimated the length of the top line in the Müller-Lyer illusion (Figure 3.1a)). Industrial design professionals are the most susceptible to this illusion, closely followed by engineering students. The industrial design professionals are at the same time the group with the highest internal variability. The industrial design students are the least susceptible to the Müller-Lyer illusion, while the engineering professionals are the most consistent group with low internal variability. The significance of the difference between the groups was analyzed using one-way ANOVA. This difference can only be said to be significant with 84% confidence (p=0.16).
Table 3.3. Means with corresponding standard deviations from control test using the Müller-Lyer illusion. Generally, the participants picked an instance where the illusory effect was accounted for.

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>St.dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industrial design students</td>
<td>3.67%</td>
<td>5.24%</td>
</tr>
<tr>
<td>Engineering students</td>
<td>6.83%</td>
<td>6.50%</td>
</tr>
<tr>
<td>Industrial design professionals</td>
<td>6.94%</td>
<td>8.25%</td>
</tr>
<tr>
<td>Engineering professionals</td>
<td>4.72%</td>
<td>4.69%</td>
</tr>
<tr>
<td>Overall</td>
<td>5.47%</td>
<td>6.29%</td>
</tr>
</tbody>
</table>

Table 3.4 and Table 3.5 present the means and standard deviations for all groups and media tested. For the architrave illusion, the positive numbers show that the subjects on average picked a model where the bottom line was curved upwards to compensate for the illusory effect. Negative percentages for the irradiation illusion indicate that the subjects picked a model with a smaller window than the reference, which also compensates for the illusory effect.

Table 3.4. Means and corresponding standard deviations for the architrave illusion test.

<table>
<thead>
<tr>
<th></th>
<th>Sketch</th>
<th>CAD</th>
<th>RP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>St.dev.</td>
<td>Mean</td>
</tr>
<tr>
<td>Industrial design students</td>
<td>0.200</td>
<td>0.249</td>
<td>0.017</td>
</tr>
<tr>
<td>Engineering students</td>
<td>0.200</td>
<td>0.249</td>
<td>0</td>
</tr>
<tr>
<td>Industrial design professionals</td>
<td>0.278</td>
<td>0.256</td>
<td>0</td>
</tr>
<tr>
<td>Engineering professionals</td>
<td>0.194</td>
<td>0.251</td>
<td>0</td>
</tr>
<tr>
<td>Overall</td>
<td>0.214</td>
<td>0.249</td>
<td>0.005</td>
</tr>
</tbody>
</table>

Table 3.5. Means and corresponding standard deviations for the irradiation illusion test.

<table>
<thead>
<tr>
<th></th>
<th>Sketch</th>
<th>CAD</th>
<th>RP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>St.dev.</td>
<td>Mean</td>
</tr>
<tr>
<td>Industrial design students</td>
<td>-0.83%</td>
<td>4.75%</td>
<td>-1.83%</td>
</tr>
<tr>
<td>Engineering students</td>
<td>0%</td>
<td>4.35%</td>
<td>-1.17%</td>
</tr>
<tr>
<td>Industrial design professionals</td>
<td>0%</td>
<td>4.20%</td>
<td>-2.78%</td>
</tr>
<tr>
<td>Engineering professionals</td>
<td>1.94%</td>
<td>4.58%</td>
<td>-0.83%</td>
</tr>
<tr>
<td>Overall</td>
<td>0.10%</td>
<td>4.53%</td>
<td>-1.61%</td>
</tr>
</tbody>
</table>
The overall results show that the participants had problems evaluating curvature and size correctly in all cases except for the architrave CAD model. The reason why almost all participants picked the straight line for the CAD model is that the pixelation clearly revealed curvature. It can be argued that the line should have been smoothed or forcefully angled by rotating the image. This was not done because it would imply not using the real images a designer actually will have to evaluate in real life.

Figure 3.2 and Figure 3.3 summarize the results, and clearly depict the differences between the display media and between the groups. The error bars of each average point were calculated by dividing the standard deviation (as listed in Table 3.4 and Table 3.5) by the square root of the sample size of each group. The sample size for the two student groups were 30, while the sample size for each of the two professional groups were 18.

![Figure 3.2](image)

**Figure 3.2.** Results from the architrave illusion test for all conditions and groups. The midpoint of the bottom line of the window was displaced in 0.5mm steps from -1.5mm to 1.5mm.
Figure 3.3. Results from the irradiation illusion test for all conditions and groups. The bottom line and the height of the window were varied in 5% steps from -15% to 15% of the reference size.

All data follow normal distribution, exhibit independence, and for the irradiation illusion, have homogeneous variance within groups. Since the latter is not true for the architrave illusion, because almost all participants selected the nominal CAD model, an ANOVA approach called the Satterthwaite Approximation was employed to determine the significance for media and group differences for the architrave illusion experiment.

The results for the architrave illusion are as expected with the sketch being harder to estimate than CAD models and physical prototypes. The opposite is the case for the irradiation illusion. From Figure 3.3 it can be concluded that a bright feature on dark background looks larger as a physical model than as CAD model or sketch. This trend is actually linear for industrial design professionals ($R^2=1.00$) and almost linear for engineering students ($R^2=0.97$).

The engineering professionals seem to be the least susceptible to illusions in both cases. However, the engineering professionals have problems evaluating the irradiation illusion when it is presented as a sketch. In fact, they overcompensate for the illusory effect by picking a model with a larger window than the reference. The industrial design professionals seem to be the group that is the most susceptible to illusions. This group
also exhibits the largest internal variance for the architrave illusion (see Table 3.4 and Table 3.5).

The difference between the media is highly significant for both illusions (p<0.0001). The difference between groups for the architrave illusion is only significant with 73% confidence (p=0.36). Because almost all participants selected the CAD model with a straight line, this instance may be the reason why no groups are significantly different. Therefore, an ANOVA was performed including results from only sketch and RP representations. In this case, the overall assumptions (including homogeneous variance within groups) were met and standard ANOVA was employed. The media differences are still highly significant. The group differences are more significant, but still not with 95% confidence (p=0.29).

For the irradiation illusion, the overall group differences are highly significant with a p-value of 0.0005. An analysis of the difference between means shows that the engineering professionals are significantly different from both industrial design students and industrial design professionals. Other groups are not significantly different.

A last ANOVA was performed where all data for both illusions were included. In addition, the participants’ gender was specified. This analysis confirmed the significant difference between media and revealed that the opposite trends seen between the architrave and irradiation illusions are highly significant. This test also reveals a barely significant difference between groups (p=0.047). The gender differences are in fact significant (p=0.0059). Lastly, significant interactions include interaction between media and illusion type, and between gender and media. Other interactions are not significant. An analysis of the difference between means again shows that engineering professionals and industrial design professionals evaluate models differently (p=0.019).

3.5 DISCUSSION

3.5.1 Evaluation techniques
When evaluating sketches and RP models, most participants first eliminated obvious “wrong” geometries ending up with two or three instances. For the architrave, the straight line and the model with a 0.5mm upwards curvature were always two of these, indicating that the illusory effect is indeed present. None of the participants selected a
model with downward curvature. The participants were less consistent when evaluating the irradiation illusion models, showing that areas are more difficult to evaluate than curvatures. To support this finding, it can be noted that pie charts are known in statistics to not communicate information clearly because people have trouble comparing the areas.

Even though several industrial design students employed certain techniques in evaluating the curvature of the window edge, their average was the same as for the engineers. One of the techniques they used was to look at the architrave sketches and RP models from different angles, either by holding the sketch or RP model up to their eyes or putting their head down on the table to see if the line was straight. Out of the 48 engineers, only one professional used this technique. This shows that industrial designers have more experience in evaluating models; still, their experience did not result in more accurate estimates.

Since the surface of the car model is not flat and the RP models are built in layers, contours are clearly visible on the surface. Two participants reported that they tried to use these lines to assess the curvature for the architrave illusion, but it did not help them much since these contour lines are not parallel with the bottom line of the window.

Several participants from all four groups reported that they used reference points when evaluating the irradiation illusion. The most common technique they used was to draw imaginary lines from the two corners of the window down to the wheels. Some also reported that they tried to use the distance between the window arc and the roof. However, since the roof follows the size of the window, this technique did not give consistent results. This use of reference points cause some of the instances where participants chose a window larger than the reference.

### 3.5.2 Knowledge of illusions

Some participants were aware of the illusory effects of the Müller-Lyer and irradiation illusions, but none reported that they were familiar with the effect of the architrave illusion. A few participants admitted that they adjusted their response to what they believed was right for Müller-Lyer and irradiation illusions. This effect is part of the reason some participants selected a model with a larger window than the reference. The responses collected from these participants were not eliminated because this is probably how they would evaluate a product in a real development process as well. Additionally,
it would be impossible to extract the participants who selected a larger window due to this reason from the participants who selected it for other reasons.

3.5.3 Differences between media
We expected physical prototypes to be easier to evaluate than sketches and CAD models for both illusion types. We anticipated differences between both media and groups when selecting the two very different types of illusions, but the opposite trends for the two illusions were unforeseen. The differences between media are statistically significant with 95% confidence for both illusions.

Industrial design sketches are rarely geometrically identical to CAD and RP models. For the models in this study, the size of the wheels is exaggerated in the hand sketches relative to the CAD and RP models. The geometry of the window was identical across the three representation media.

All but one participant selected the architrave CAD model with the straight line. The reason is the line aliasing. As mentioned earlier, the pixels on the line were not smoothed because that would imply altering the display the designers actually see. The differences between the sketch and the RP model were also significant when the results for the CAD model were excluded in the analysis. The sketches and the RP models could be evaluated using the same techniques, for example viewing the model from different angles. The exaggerated wheels on the sketch can be assumed not to affect the assessment of the curved line because none of the participants reported using the wheels as reference for this evaluation. It can then be concluded that the differences between these two media are mainly due to perceptual differences.

The results show that the sketch was easier to evaluate for the irradiation illusion than both the CAD and the RP model. In addition to perceptual differences, it is probably easier to draw accurate reference lines for the sketch to assess the size of the window because the wheels are larger. The CAD and RP models were identical, and the differences seen between these media are mainly due to characteristics of the media. However, a second factor is the techniques possible to employ when evaluating these models. The CAD models could only be viewed from one angle, while the participants were free to move the RP models around at their convenience. While viewing the architrave illusion from different angles help in assessing the straightness of the line, the
size of the window is evaluated best when looking straight at the model. The viewpoint constraint for the CAD model versus the RP model can be assumed to be negligible.

### 3.5.4 Differences between groups

Industrial design students have more design experience than engineering students at the same academic level (junior, senior, or graduate). The industrial design student group had 1.57 years more experience than the engineering group. It was noted that industrial design students employed certain techniques when evaluating the architrave illusion that were used by only one engineer. Nevertheless, since the engineering education and profession is more analytical than industrial design it was expected that industrial designers would be more susceptible to the illusory shapes than engineers.

The four group averages for the introductory task (Müller-Lyer) were not significantly different. Based on this non-significance, it is tempting to conclude that the participants’ susceptibility to illusions does not depend on professional background. Even though it does give an indication, drawing such a conclusion would be premature because the Müller-Lyer illusion is only one out of many different illusions. The group differences seen for the main experiments are due to both susceptibility to the two illusions, and other factors such as evaluation techniques and experience.

The differences between groups for the architrave illusion were not significant. This finding indicates that the additional training the industrial design students have in evaluating models does not give them any advantage over engineering students for this particular task. It might be that the industrial design students need this extra evaluation training to “account for” the engineers being more analytical. These insignificant group differences also indicate that professional experience does not improve a designer’s evaluation skills when evaluating this kind of geometry.

For the irradiation illusion, on the other hand, the group differences were found significant. Analysis of the differences between the means revealed that the engineering professionals were significantly different from both the industrial design students and industrial design professionals. These results indicate that the experience gained as professional engineers or industrial designers, and not from educational training, is what makes these groups different. The results found by Jahoda and Stacey in [Jahoda70] indicate that the susceptibility to illusions decreases when people are trained in art and
architecture, though this effect was only found to be moderate for people with similar cultural background, as is the case for the present study. In addition, their comparison was between people with no experience and people with two years of training. The experience of the latter group roughly corresponds to the experience of the student participants in the study presented here. However, similar trends to those found by Jahoda and Stacey are present for the engineering groups in the present study. The trend for the industrial design groups is opposite. Since the industrial design and architecture educational curriculums are similar, the trends found by Jahoda and Stacey should have been more comparable to the two industrial design groups studied in this project than to the engineering groups.

The type of experience is the only difference between the engineering professionals and the industrial design professionals. The average age and average number of years of experience for the two groups differ by less than one year (Table 3.1), so these parameters can be assumed not to affect the differences between the professional groups. Since the industrial design professionals seem to be the most susceptible to illusions and is the group with the highest internal variance, the assertion that engineers are more analytical still seems to hold. Research in psychology has shown that susceptibility to illusions generally decrease with age [Stewart73] [Coren78b]. This can explain part of why engineering professionals are different from industrial design students (the age difference between these two groups is 15 years). However, the effect of age is believed not to be the main contributor to the difference seen between the professionals and the students. For the irradiation illusion, the industrial design professionals are the most susceptible and the engineering professionals are the least susceptible. The two student groups fall between the two professional groups. Therefore, there seems to be other factors that affect the susceptibility to the irradiation illusion more than the age factor.

The gender differences that emerged, when all the collected data was analyzed, might have affected the results between the groups. When looking at the overall averages for each illusion and media, the females are more susceptible than the males. This confirms the general trend in psychology research, including [Miller01]. Even though females are more susceptible overall, the female industrial design students are actually
more correct than their male colleagues when evaluating the architrave sketch (-0.38% and -1.18% respectively). The industrial design student group is fairly well balanced (17 males vs. 13 females, Table 3.1), but since this trend is only seen for one media for one illusion, it may be a coincidence. Similar trends are seen for engineering students evaluating the RP model for both illusions, and for the engineering professionals evaluating irradiation illusion sketches and CAD models. However, since these groups are not well balanced, these results cannot be considered general. Since the groups of engineering professionals and industrial design professionals are almost identical, the significant difference found between them has not been affected by gender differences. However, it is possible that the group differences are affected if these groups were more heterogeneous.

3.6 AUTOMATED SHAPE RECOGNITION TOOL

As was shown in the previous section, the participants evaluated shapes differently both depending on the display media and on the illusion type (architrave or irradiation). Differences were also found between groups with different background. These results support the need for an automated tool in CAD software that can alert the designer of potential illusory effects. Product designers currently rely on experience when evaluating the possibilities for perceptual differences between representation media [PerCom06]. Still, multiple iterations with physical prototypes are common in product development processes.

The attention in this section will be directed towards the architrave illusion. Schematics of geometrical illusion are compared to 2D projections of the CAD models to detect illusory effects. Using frequency response instead of spatial information reduces the computational load. Using spectral analysis on illusions appearing from edge contours is more feasible than applying it to area comparisons. Other methods are more realistic for use with the irradiation illusion, for example algorithms linking color contrasts and area ratios. Such algorithms will not be discussed here.

3.6.1 General background

Images only differ from “traditional” signals by the way they store information over space instead of over time. Hence, the phase and a power (amplitude) spectrum of a 2D
luminance image can be analyzed in the same manner as “traditional” signals using FFT. Low frequencies represent coarse spatial structure of the image, while high frequencies describe details and sharp edges. The FFT of a boundary generates a set of complex numbers, called Fourier descriptors. These descriptors represent the shape in the frequency domain. A subset of these descriptors is often enough to discriminate different shapes, thus comparing frequency information requires less computational power than comparing spatial information [Loncaric98].

Different methods for shape and feature recognition are being heavily researched in the computer vision and engineering fields. Most of the results applied to product development revolve around constructing databases of models with indexing and query possibilities [Bespakov03].

One disadvantage with the FFT is that local shape information is distributed to all coefficients after the transform is applied, making it more difficult to extract the shape of interest [Loncaric98]. Other feature recognition methods such as the wavelet transform might result in a more robust detection tool. The wavelet transform is localized in space in addition to frequency, whereas Fourier transform is only localized in frequency.

Implementation of aesthetic features in CAD was researched in the international FIORES II project [Cappadona03]. The objective of this project was to develop a method of editing shapes in CAD while maintaining the aesthetic expression. When a user wants to modify a shape, parameters can be adjusted numerically, and the feature updates. A similar technique should be employed when adjusting features prone to illusory effects.

### 3.6.2 Suggested process

The overall process from initiating the check for illusory shapes to a possible update of the CAD model is outlined in the flow diagram in Figure 3.4. The dialog boxes referred to in the flow diagram are shown in Figure 3.5. In this section, the use of such a tool for CAD systems is emphasized. However, the recognition process can also be performed for 2D sketches. The process would then be to scan the sketches, if they are not already in digital format, and then run the shape recognition check in the same manner as for the CAD model. The only difference between using a sketch and a CAD model in this process is that it will not be possible to update the geometry of a scanned sketch.
automatically. Because people see geometry differently, such a tool would need to be calibrated with the end user in mind.

Figure 3.4. Suggested procedures for an automated shape recognition and fixing tool in CAD systems. This process detects illusory geometries and alerts the user, then subsequently giving the user choices as to how to override or take the advantage of the illusory effects.
Figure 3.5. Dialog boxes illustrating the process of identifying and fixing illusory effects.

- a) Dialog box 1: User initiated illusion check

- b) Dialog box 2: Modify shape?

- c) Dialog box 3: Automatic or manual modification
The process outlined in the flow diagram is performed on a solid model. In this case, it is suggested that the user initiates the process. A process could run in the background continuously checking if illusory geometries are being designed. However, this would require that the tool checks geometry in three dimensions and would involve using more computational power. Another possibility is to run the check only when sketches are developed. In this case, the process could extract the curves being modeled on the sketch plane and process these. The advantage would be that it is not necessary to perform the edge detection because the sketch curves could be used as direct input to the FFT. However, there are other methods than sketching that form features and contours in CAD models. Limiting a check to sketches only would exclude potential illusory shapes. Therefore, it should be an option to have the shape recognition tool process the geometry of the model visible to the user, be it the designer or the customer. The designer should initiate the check because it would require too much computational power to let the check run in the background while building a complex CAD model, in particular in assemblies of individual parts. It may very well be that the interaction between multiple parts can create an illusory effect.

MatLab 7.0 was used to run some simple experiments to test the basic principles outlined in the flow chart shown in Figure 3.4. The top two images in Figure 3.6 are the input images for the correlation process. The next to images are the edge images of the 2D architrave illusion and the 2D projection of the architrave CAD model used in this study. Adobe Photoshop 7.0 was used to extract the edges of the CAD model. Using Photoshop was preferred because the edge detection functions in MatLab typically produce a lot of noise. The threshold function in Photoshop was set to a pixel value of 200 on the grayscale images (0 is black and 255 is white). When implementing the shape detection tool in a CAD system, the threshold specification and the method used to do the edge extraction must be carefully selected.

The two bottom images in Figure 3.6 show the frequency spectra when the edge images are transformed using the FFT. The magnitudes of the complex numbers output from the FFT were computed to be able to display the frequency spectra. In many cases, this magnitude contains sufficient information to compare images.
a) 2D architrave illusion

b) 2D projection of architrave CAD model

Figure 3.6. The edges of the 2D architrave illusion and the CAD model were first extracted using the threshold feature in Photoshop. These edge images were then transformed into the frequency domain using MatLab’s two-dimensional FFT function.

Two of the most important properties of a shape recognition tool are that it must be able to recognize shapes independent of scale and rotation; that is, it must be scale and rotation invariant. The most intuitive way to achieve this is to store the frequency spectrum for images with different rotations and scaling. Thresholds must then be defined for both rotation (angle) and size (percent), which would make the tool less accurate. The correlation algorithm would also be more computationally expensive due to the large number of images to correlate. Figure 3.7 below shows that rotating the input image results in a rotation of the frequency spectrum that is angularly equal, but opposite in direction. This figure illustrates the importance of making the frequency spectrum invariant of rotation.
Figure 3.7. The 2D projection of the CAD model with 0 and 45 degrees rotation. This rotation results in an equal angular rotation of the frequency spectrum, though in the opposite direction.

The solution to the rotation issue lies in modifying the Fourier descriptors to be invariant of scale and rotation. Arbter et al. developed an algorithm that makes the descriptors invariant of translation, rotation, scale, and shear [Arbter90]. The process is called normalization and can be performed completely in the frequency domain, making it more efficient than when performed in the spatial domain.

3.7 CONCLUSIONS

The results from the visualization experiment have suggested that there are highly significant differences between the representation media employed in a typical product development process. The results may be applied in both engineering and industrial
design fields to expedite the design and development processes where aesthetics are important. For the architrave illusion, where the curvature was examined, it was shown that industrial design sketches are more often misperceived than physical prototypes. The average curvature selected was 0.21mm upwards for sketches and 0.09mm for RP models. The CAD models were very easy to evaluate because of line aliasing (all participants except one selected the straight line). Since the illusory effect is that the line seems to bulge down, the positive averages indicate that the participants were affected by this illusion.

The results from the size estimation (irradiation illusion) were more surprising, showing opposite trends with the physical models being more difficult to estimate correctly than both sketches and CAD models. The overall averages were 0.1% misestimation for the sketches, -1.61% for the CAD models and -3.54% for the physical prototypes. The negative numbers mean that the bright window that the participants chose was on average smaller than the dark window they were it comparing to. The trend is fairly similar for all four groups. Since the illusory effect is that the white window seems larger than the black window, the negative averages indicate that the participants were affected by this illusion for the CAD and the RP model.

Differences between the groups of participants with different backgrounds are significant for the irradiation illusion. Analysis of the differences between the means revealed that the engineering professionals and industrial design professionals were the most different. Generally, a sample size of at least 30 subjects is preferred. However, the sample sizes of the two groups with professionals were only 18. Hence, it is possible that the significance will change if the sample size is increased.

The process of the proposed shape recognition tool, from the designer’s point of view, has been outlined. In addition, this paper has provided a general discussion of using spectral analysis to implement this capability. The main conclusion in this regard is that it is feasible to use the FFT with translation, rotation, scale, and shear invariant Fourier descriptors. However, other methods such as the wavelet transform should be considered as well.
In order for the proposed feature recognition tool to become reality, more known illusions must be tested in the same manner to build a library of illusions used for the automated shape recognition capability.

The visualization study conducted in this project measures a combination of the participants’ perception and evaluation skills. A study that tests only the perceptual differences between people might be desirable. In such a study, pure geometrical shapes and not real products should be used to eliminate effects introduced by distracting surrounding geometry. In particular, this would result in the participants not using reference points, which may have affected the results presented in this paper especially for the irradiation illusion.
CHAPTER 4

CONCLUSIONS AND CONTRIBUTIONS

This thesis has presented results that clearly show that model geometry looks different depending on the representation method used. The differences in how designers visually evaluate concept sketches, CAD models, and FDM rapid prototypes were significant for both illusions tested. The results also show that designers with various backgrounds in engineering and industrial design evaluate models differently. The most significant differences were found between engineers and industrial designers with more than 2 years of industry experience. Novice engineering designers were not significantly different from novice industrial designers. In addition, this thesis has presented a discussion on the possibilities and constraints in using spectral analysis for shape recognition.

4.1 CONCLUDING REMARKS

The scope of the visualization study was narrowed down to two visual illusions and three representation media due to resource and time constraints. However, since responses were collected from a large pool of participants, the results are assumed to be typical for the designer groups tested. The number of participants was large enough to reliably measure significant differences between designers with different levels of experience for one of the two illusions investigated.

A model of a real product was used as a test object instead of a generic shape because it was desirable to make the evaluation process realistic. At the same time, it was considered important that the model did not have too much detail that would distract the subjects evaluating it. Using a generic geometrical shape would assess differences in media, but would not necessarily produce results that could be applied directly to a product development process.

As was discussed in Section 3.4.1, the participants employed various evaluation techniques. They would likely employ the same techniques in a real development
process, so limiting them to use solely perceptual skills when viewing the models would be too artificial.

The findings in this thesis may be applied to product development processes where aesthetics and visual expression are important. Even if this research is not continued, the results presented here could be used to highlight that certain shapes and features do in fact appear different in different representation media and to different people. The discussion of the suggested shape recognition tool in CAD systems is conceptual, and may be applied in product development processes independent of the 3D CAD system used.

4.2 CONTRIBUTIONS

This thesis addresses the differences many designers experience as a product progresses through the product development process. Specifically, the implementation of the results found in the visualization experiment described in this thesis may help reduce the overall product development time and cost by making the transition between two representation media more predictable. This is especially important for developers of large and complex products where there is little room for multiple design iterations.

First, the results presented in this thesis strongly suggest that there are differences in how models containing geometry similar to two visual illusions are perceived depending on the representation media. The representation media included in this study were industrial design sketches, CAD models and RP models. Second, this thesis reveals statistically significant differences for one of the two illusions between how engineers with professional experience evaluate models differently than industrial designers with and without professional experience.

Quantifying the differences due to both media and professional background is beneficial for a smooth and predictable transition between representation media. Specifically, to standardize the transition between CAD models and physical prototypes, this thesis suggests how an automated shape recognition tool in CAD systems could be implemented. Because people see geometry differently, such a tool would need to be calibrated with the end user in mind.
4.3 RECOMMENDATIONS FOR FUTURE WORK

The natural continuation of work relating visual illusions and product development would be to investigate the effect of additional illusions. Based on these investigations, a library of illusory shapes should be built to serve as a reference for designers and help them predict the transition between CAD models and physical prototypes. The automated recognition tool needs to be further explored, and a prototype should be developed.

One interesting possibility is to integrate this work with the FIORES II project [Cappadona03]. Here a working prototype with a graphical user interface was developed for shape modifications that preserve aesthetic expressions. In addition to modifying CAD models with respect to illusory effects, it is also crucial to maintain the aesthetics of the product. Of course, to make such a tool work, a comprehensive library of illusory shapes must be built. It is probably not necessary to perform experiments as extensive as the one presented in this thesis. However, the results presented here can be used as guidance to decide on what is necessary to include when building the library.
REFERENCES


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APPENDIX A: EXPERIMENTAL DESIGN

This appendix outlines how the experiment was designed and provides sufficient detail to replicate the experiment. The goal of the project is to determine how visual illusions influence a designer’s perception of a product across three representations: industrial design concept sketches, computer aided design (CAD) models, and physical prototypes (FDM rapid prototyping).

**Equipment**

- Sketch rendering software: Adobe Photoshop 7.0
- 3D CAD modeling software: UGS NX 3.0
- Rapid prototyping software: Stratasys Catalyst 4.3
- CAD modeling and RP processing were performed on a Dell Precision 360 workstation with the following specifications:
  - CPU: 3.0 GHz Pentium IV
  - Hard disk: 80 GBytes ATA-100 IDE (7,200 RPM)
- Rapid prototyping hardware: Stratasys Dimension SST 768 (http://www.dimensionprinting.com)

**The illusions**

The two illusions in the experiment are the architrave and the irradiation illusion shown in Figure A.1.

![Figure A.1](http://www.dimensionprinting.com)

*Figure A.1.* The two illusions tested in this experiment, (a) the architrave illusion where the horizontal line seems to dip down slightly, and (b) the irradiation illusion where the small black square seems smaller than the small white square due to the color contrast.
**Independent variables**

The independent variables were a) the curvature of the horizontal line for the architrave illusion and b) the size of the side window for the irradiation illusion.

**Test object design**

The models were made starting with the sketch shown in Figure A.2. The geometry of the window was exactly the same for all three representation media for each illusion.

![Figure A.2](image)

*Figure A.2.* The base design for the test objects.

Since scaling effects were to be eliminated, all models needed to be the same size. Since the physical prototypes were manufactured and their size was constrained by the build volume of the RP machine, this was also the limiting size for all models. The dimensions of the car and the side window are given in Figure A.3.

![Figure A.3](image)

*Figure A.3.* The dimensions of the car were determined based on the build volume of the FDM RP machine.
For the architrave illusion, the curvature of the bottom line on the side window was varied as shown in Figure A.4.

![Figure A.4.](image)

**Figure A.4.** The displacement of the midpoint of the horizontal line (d) was varied from -1.5mm to +1.5mm in 0.5mm steps. Subject was presented with 6 different models. The subject then picked the model where the horizontal line was perceived to be straight.

For the irradiation illusion, the size of the side window was varied as shown in Figure A.5.

![Figure A.5.](image)

**Figure A.5.** The size of the side window was changed by varying L and H in 5% steps from -15% to +15% of the reference geometry. Subject is presented with one model with dark internal area and 6 models with bright internal area. Subject picked the one model with bright area that was perceived the same size as the dark area.

**Dependent variable**

The dependent variable was the illusory effect and was measured by recording \( d \) in millimeters for the architrave illusion, and \( L \) and \( H \) in percent for the irradiation illusion.
**Controlled variables**

The following variables were controlled throughout the experiment:

- Subject characteristics were carefully recorded including:
  - Exact experience (coursework and industry / teaching experience)
  - Age
  - Gender
  - Any particular techniques employed during the experiments or comments made

- All models were viewed in a naturally well lit room
- The models were colored using shades of grey corresponding to RGB 51 51 51 (dark grey) and RGB 209 209 209 (light grey)
- All models were viewed against a white background
- All models had the exact same size to avoid any effects scaling might have
- Viewing angle
  - Sketches and RP models could be viewed from any angle or distance
  - CAD models could be viewed from any distance, but could not be rotated

**Test subjects (participants)**

The subjects were engineers and industrial designers with various experience, and were selected based on the following criteria:

- Student participants:
  - Senior or junior undergraduate and/or graduate
  - Some experience with product design and development

- Professional participants:
  - Professional experience working in the industry and/or as university professors
  - Hands on experience with product design and development
  - Confident in using CAD
  - Experience with evaluating physical prototypes

A within-subject experimental design was used where complete counterbalancing was used to randomize the sequence in which the models in the three representation media were presented.
**Experiment setup**

The test objects were presented to the subjects as shown in Figure A.6.

![Architrave sketches](image1)
![Irradiation sketches](image2)
![CAD model setup, architrave and irradiation](image3)
![Architrave RP models](image4)
![Irradiation RP models](image5)

**Figure A.6.** The sketches and the RP models were distributed randomly on a table in front of the subject. The CAD models were shown sequentially on a computer screen where the subject navigated through the different geometrical variations.
APPENDIX B: EDGE PROCESSING AND SPECTRAL ANALYSIS FOR SHAPE RECOGNITION TOOL, CODE AND COMPARISONS

This appendix contains the exact code used to perform the fast Fourier transform (FFT) for the automated shape recognition tool proposed implemented in CAD software. The code was run using MathWorks’ MatLab version 7.0.

The edge detection in MatLab produces significant noise. To illustrate the process in the best way, it was therefore decided to use Photoshop instead. The edges of the CAD models were extracted using the threshold function in Adobe Photoshop 7.0. The threshold was set to a pixel value of 200 on a 0 (black) – 255 (white) grayscale. Figure B.1 shows a comparison of the edge maps and the resulting frequency information using MatLab Sobel edge detection and Photoshop thresholding.

a) Using MatLab Sobel edge detection with a threshold of 0.08.  
b) Using Photoshop threshold function at a pixel value of 200.

Figure B.1. Illustration of how the noise from the edge map affects the frequency spectrums.
clear all;

% LOAD IMAGES

Ia = imread('Architrave.png');% Load edge image of 2D illusion
E1 = rgb2gray(Ia);            % convert to greyscale

Ib = imread('CAD.png');  % Load edge image of the 2D projection
E2 = rgb2gray(Ib);            % convert to greyscale

Ic = imread('Edge0deg.png'); % Load edge image of large zero-rotation
E3 = rgb2gray(Ic);      % convert to greyscale

Id = imread('Edge45deg.png'); % Load edge image of large 45deg-rotation
E4 = rgb2gray(Id);            % convert to greyscale

% 2D FFT

fftImage1 = fftshift(fft2(E1));   % 2d fft
ampImage1 = abs(fftImage1);
figure(1); imshow(ampImage1, [0 1e5]);
saveas(figure(1),'Arch.png');

fftImage2 = fftshift(fft2(E2));   % 2d fft
ampImage2 = abs(fftImage2);
figure(2); imshow(ampImage2, [0 1e5]);
saveas(figure(2),'180.png');

fftImage3 = fftshift(fft2(E3));   % 2d fft
ampImage3 = abs(fftImage3);
figure(3); imshow(ampImage3, [0 1e5]);
saveas(figure(3),'0deg.png');
fftImage4 = fftshift(fft2(E4));  % 2d fft
ampImage4 = abs(fftImage4);
figure(4); imshow(ampImage4, [0 1e5]);
saveas(figure(4), '45deg.png');

INPUT IMAGES:

**Figure B.2.** The input images treated in the MatLab code provided.
APPENDIX C: A POSSIBLE SCENARIO: ILLUSORY SHAPE DETECTION AND MODIFICATION

This appendix outlines how the CAD designer could experience and use the proposed automated shape recognition tool. Each step is illustrated by showing a possible screenshot and an explanatory text.

Figure C.1. Step 1: User initiates check for illusory shapes by first selecting the view the model is to be evaluated from (Dialog box 1).

Figure C.2. Step 2: Clicking “Next...” initiates the edge detection, the FFT algorithm and the correlation check with the library of illusory shapes (Dialog box 1).
Figure C.3. Step 3: If illusory shapes are found, the dialog box identifies the illusion, explains the effect, and explains how this illusion is likely to be perceived as a physical model. The user is given the choice of modifying the shape to override the illusory effect, or ignore it (Dialog box 2).

Figure C.4. Step 4: Next the user is given the choice of an automatic modification of the shape according to the library, or manually adjust the shape. A preview option should be available (Dialog box 3).
Figure C.5. Step 5: By clicking "Preview", the modified geometry is displayed on the model together with the original. Clicking "OK" on this dialog box will replace the illusory shape with the new modified geometry (Dialog box 3).