On the Evaluation of Print Mottle

CARL-MAGNUS FAHLCRANTZ

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Abstract

Print Mottle is perhaps one of the most disturbing factors influencing overall Print Quality. Mottle has traditionally been evaluated by estimating the reflectance variation in the print. Although the amplitude of the reflectance variation is probably the most important aspect of print mottle, other aspects may also influence the perceptibility of mottle. Since the human visual system is optimised to fit the conditions prevailing in its surroundings, it is also important to consider aspects such as mean reflectance factor level, spatial frequency content, structure of the mottle, and colour variations.

In this thesis, a new evaluation model for the estimation of print mottle is proposed. The model is best explained as a six-step chain. First, a digital RGB image of the print is acquired with a scanner. The digital RGB image is then calibrated and transformed into the $L^*a^*b^*$ colour space. Next, the three colour components are transformed into the frequency domain by a Fourier transform and the power spectra are calculated. The power spectra are thereafter filtered with respect to the contrast sensitivity functions representing the human eye's sensitivity to spatial variations in the three colour channels. To account for systematic variations in the sample, the spectra are filtered a second time with texture enhancement filters, which are based on local calculations of chi-square measures in the power spectra. The energy within the visually detectable area of the filtered power spectra is then integrated to obtain a single measure of the variation for each colour component. A single mottle estimate is obtained as the square root of the sum of the squared variation measures for the three components. To acknowledge the influence of mean lightness level on perceived print mottle in a way that agrees with the results presented in Paper I, the mottle estimate obtained is finally multiplied by the sixth root of the mean reflectance factor level.

The theoretical foundations of the model are consecutively developed through the first five papers of the thesis. The first paper considers the influence of the mean reflectance level on perceived print mottle. The second and third papers describe the contrast sensitivity filter and the texture enhancement filter applied. The fourth paper compares the new model with other models for print mottle evaluation. The fifth paper extends the grey-scale version of the model into colour. The sixth paper presents the unified model that takes all the mentioned factors into account.

To test the model, samples from both simulated sets of prints with various degrees of colour and/or systematic mottle and sets of real prints from various conventional presses were analysed a) visually, b) with traditional print mottle evaluation models, and c) with the new model. Results obtained using the different evaluation models were compared with visual assessments of the sets of prints. In each one of the evaluations the new model was found to be as good as or superior to the traditional print mottle evaluation models in its agreement with visual assessment. The new model is particularly promising in cases where the evaluated prints show colour and/or systematic disturbances.

Keywords: Mottle, Print quality, Texture, Image analysis, and Perception.

Sammanfattning

Tryckflammighet är en av de faktorer som sannolikt har störst inverkan på den övergripande kvaliteten hos ett tryck. Flammighet har traditionellt sett utvärderats genom att skatta reflektansvariationen i trycket. Trots att amplituden av denna variation antagligen är den viktigaste aspekten av tryckflammighet så kan även andra faktorer påverka det visuella intrycket av flammighet. Eftersom det mänskliga synsystemet är optimerat för att fungera i den miljö som det opererar i så är faktorer som medelreflektansnivå, spatial frekvensfördelning, struktur i flammigheten, och färgvariationer också viktiga att beakta i sammanhanget.

I denna avhandling presenteras en ny modell för att skatta tryckflammighet. Modellen förklaras enklast som en kedja i sex steg. Först läses en färgbild av trycket in med en skanner. Sedan kalibreras den digitala RGB-bilden och bilden överförs till $L^*a^*b^*$ färgrymden. De tre färgkomponenterna överförs därnäst till frekvensdomänen med Fourier transformen och effektspektra beräknas. Effektspektrumen filtreras sedan en första gång med det mänskliga ögats kontrastkänslighetsfunktioner för spatiala variationer i de tre färgkanalerna. För att ta hänsyn till systematiska störningar i provet filtreras spektrumen en andra gång med texturförstärkningsfilter baserade på lokala beräkningar av X^2-mått i effektspektrumen. Därefter summeras energin inom det visuellt detekterbara området i de filtrerade effektspektrumen så att ett variationsmått för varje färgkanal erhålls. En skattning av flammigheten tas därpå fram genom att dra kvadratroten av summan av de tre kanalernas kvadrerade variationsmått. För att ta hänsyn till medelreflektansens inflytande, på ett sätt som överrensstämmer med resultaten i avhandlingens första artikel, så multipliceras slutligen skattningen med sjätteroten av medelreflektansen.

Modellens teoretiska fundament utvecklas successivt genom de fem första artiklarna i avhandlingen. Den första artikeln behandlar medelreflektansens inverkan på visuell bedömning av flammighet. Den andra och den tredje artikeln berör kontrastkänslighets- och texturförstärkningsfiltren. Den fjärde artikeln jämför den nya modellen med andra utvärderingsmodeller för tryckflammighet. Den femte artikeln utökar modellen från gråskaleutvärdering till färg. Den sjätte artikeln presenterar den sammanslagna modellen som beaktar samtliga av de faktorer som behandlats i de fem första artiklarna.

För att pröva modellen empiriskt undersöktes både simulerade provset med olika grader av färg och systematisk flammighet och provset med riktiga tryck från olika konventionella tryckpressar a) visuellt, b) med traditionella flammighetsutvärderingsmodeller, och c) med den nya modellen. Resultatet från modellernas utvärderingar jämfördes med visuella bedömningar av trycken. Den nya modellen visade sig i samtliga fall överstämma lika bra eller bättre med visuell bedömning än vad de traditionella modellerna gjorde. Den nya modellen visade sig synnerligen lovande i fall då de utvärderade trycken uppvisade färg- och/eller systematiska störningar.

Sökord: Flammighet, Tryckkvalitet, Textur, Bildanalys, och Perception.

“The voyage of discovery is not in seeking new landscapes but in having new eyes.”

Marcel Proust, 1871-1922.

Acknowledgements

“I always do the first line well, but have trouble doing the others.”

Moliére, 1622-1673.

Why was the problem of print mottle evaluation treated this way, you may ask? I think that most of the time influence from the social milieu decides the cause of action – not the problem as such. Like it or not – an idea always belongs to a setting.

For their participation in this particular setting I would first and foremost like to thank my supervisors **Jan-Olof Eklundh** and **Per-Åke Johansson** for their invaluable contributions to the work. As the work has progressed, I have realized that the combination of personalities and expertise that they represent together with my own style has indeed been a fortunate one.

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Finally, I would like to thank **Anthony Bristow** not only for his supreme language examination but also for his valuable comments on my work.

I thank you all,
Carl-Magnus Fahlcrantz, 2005-11-04.

This thesis consists of an overview and seven papers:

1. **The Influence of Mean Reflectance on Perceived Print Mottle.**
   Carl-Magnus Fahlcrantz, Per-Åke Johansson & Peter Åslund.
   The Journal of Imaging Science and Technology, Volume 47, Issue 1, Pages 54-59, 2003.

2. **Evaluating Systematic Print Mottle.**
   Carl-Magnus Fahlcrantz.
   Presented at the IPGAC 2002, Bordeaux. Journal of Graphic Technology, Volume 1, Issue 2, 2003, Pages 19-28.

3. **Perceptual Assessment of Simulated Print Noise with Random and Periodic Structure.**
   Siv Lindberg & Carl-Magnus Fahlcrantz.
   Journal of Visual Communication and Image Representation, Volume 16, Issue 3, June 2005, Pages 271-287.

4. **A Comparison of Different Print Mottle Evaluation Models.**
   Carl-Magnus Fahlcrantz & Per-Åke Johansson.
   Presented at TAGA 2004, San Antonio. Accepted for publication in the TAGA Journal, 2005.

5. **Evaluating Colour Print Mottle.**
   Carl-Magnus Fahlcrantz & Kristoffer Sokolowski.
   Submitted to the 33rd iarigai Research Conference, Leipzig, Germany, 2006.

6. **Print Mottle Evaluation - An Integrated Approach.**
   Carl-Magnus Fahlcrantz & Jessica Christoffersson.
   Submitted to the international conference, Printing Technology SPb'06, St. Petersburg, Russia.

7. **Print Mottle Evaluation of Flexographic Prints – Using a Scanner-based Measurement System.**
   Carl-Magnus Fahlcrantz & Per-Åke Johansson.
   Presented at the FFTA Conference 2004, Dallas. A condensed version of the paper was published in the Flexo Magazine, October Issue 2004, Pages 14-16.

Other Related Paper by the Author:

Topographic Distribution of UnCovered Areas (UCA) in Full Tone Flexographic Prints.
Gustavo, Gil Barros, Carl-Magnus Fahlcrantz & Per-Åke Johansson.
Presented at TAGA 2004 San Antonio. TAGA Journal, Volume 2, No. 2, 2005, Pages 43-57, Edition 1.

Contents:

1. Introduction & Background

"Learn from me . . . how dangerous is the acquirement of knowledge, and how much happier that man is who believes his native town to be the world, than he who aspires to become greater than his nature will allow."

Frankenstein to Walton in Mary Shelley's, 1797-1851, Frankenstein, 1818.

Among the many issues that can be addressed in life, there is one that seems to stand out as being more important than all the others; an issue on which most other concerns seem to be more or less founded, namely the duality between how we experience ourselves as one person from the inside but how we are viewed by others as a completely different person from the outside; the absurdity of being what we really are, or to be provocative, the problem of Frankenstein's monster.

This interface problem, i.e. the interaction between the inner self and the external reality, seems to be a considerable part of the ultimate cause of many of the controversies that hamper not only science, but also disagreements ranging from tiny personal, private, ones to grand scale differences on the political and social agenda in our world. In science, the big question is how to interpret the empirical results given by a particular study. What do they really mean to the individual? Is it possible for us to interpret them in similar ways, or do we necessarily have to disagree because of who we are – on the inside, and on the outside.

Although most problems somehow seem to relate to this controversy, they do so to different degrees. Some problems are only vaguely related to the interface problem, whereas other problems are intimately connected to the dilemma. In this thesis, we shall consider the notion of how reflectance disturbances in a printed surface are experienced by a common observer, and this is in fact a problem that is very closely related to the dilemma because it immediately addresses the problem of the inner-outer world interface. How can we use the measurement of the physical reflectance variations in the surface on the outside to predict the inner experience of the magnitude of the lightness variations in a printed surface that otherwise is intended to be experienced as homogeneous?

This may sound trivial compared to the question of how we can predict the inner experience of the pleasure (or pain) when a person is listening to, for example, the tones of Gershwin's "It ain't necessarily so", played by Oscar Peterson, and recorded at Universal Recording Studios, Chicago, Illinois, 1959. The advantage of addressing a somewhat less complex question is, however, that it may actually be possible to present a reasonable answer which in turn has a practical use.

Practical usefulness is, of course, the foundation of this kind of applied scientific work. Reflectance variations in prints are considered to be among the most detrimental artefacts to print quality, and it is the product quality, together with price, that in the end generally determines whether or not a certain product is going to be purchased. Thus, if we can develop a measurement model with reasonable prediction capabilities, it may have an immediate use if we desire to be able to predict experienced quality, and if it can help us to determine the willingness to pay for a particular printed product.

This is not however the only reason for developing a lightness variation evaluation model. The way in which this development was carried out, the arguments for choosing a certain approach, and the accumulated understanding of the interface – in this case, the human visual system - are in turn yielding knowledge that may be valuable in attempts to obtain an understanding of far more complex problems regarding the experience of products and its features. Product experience starts as a typical interface problem: if you want to understand how people experience a product, you must try to determine their perception of the product and the variability of this perception between different individuals and from occasion to occasion due to variations in contextual attributes. Only then can you start to fully understand how later, cognitive processes, emotional processes and personality factors result in a purchase or not. By considering the basic problem of the perceptual interface, we can thus learn much more about the human experience of products, and hopefully also about how to interpret the world we live in and understand why it simultaneously emerges as both simple and obscure.

The layout of the thesis is as follows; in Chapter 2 we attempt to circumscribe the problem by defining a few key concepts and formulating the mission. In Chapter 3, some the central theoretical foundations behind the approach are presented. Chapter 4 goes through the seven papers, one by one, and tries to show how the results from each of the papers contribute to the general model. Chapter 5 is a discussion of the separate papers and the model, its advantages and limitations, indicating which parts that were examined thoroughly and which parts that may require more attention. In Chapter 6, we attempt to draw the most important conclusions from the work as such. The thesis ends with the full versions of the seven papers included.

2. Definitions, Objective & Content

"This deals with epiphenomenalism, which has to do with consciousness as a mere accessory of physiological processes whose presence or absence makes no difference. ... Whatever are you doing?"

Audrey Hepburn, as Jo Stockton, in Funny Face, 1957.

2.1 Definitions

This thesis is concerned with many subjective concepts; subjective experiences and interpretations that in the end are always unique and exclusively personal matters. It is not possible for anyone else to understand and experience the world exactly as you do, because whenever an eyewitness is about to account for something, he must always use an extensive knowledge of persons, places, things, the use of language, and social conventions none of which are immediately observable (Popper, 1963). This fundamental philosophical statement suggests that we should treat entirely subjective concepts with more than a little caution. It is thus appropriate to attempt to explicitly define the main concepts that fall into this category in the best possible way. By doing so we can better agree on the meaning of the results at the end. Nevertheless, it is still important to point out that such definitions certainly do not remove the core of the problem concerning subjectivity. The concepts underlying such definitions still conceal the same big questions - how do we interpret the underlying concepts of the concepts we try to define and so on (ad infinitum)?

2.1.1 Print Quality

It is first important to emphasis that the definitions that follow are not necessary applicable outside this thesis. They are not put here to be normative, but rather to help the reader to understand the perspective from which things are dealt with here.

We start with the easy definition:

> *To print:* Transfer to a surface; to make a mark on a surface by pressing something on to it. Originally from Latin premere – to press. (Pearsall, 2001).

The above definition concerns the verb – to print, or to press. What we are reaching for is more exactly printing quality, because in the end we are aiming for the general quality of the output of a *printing device*.

Here we are, of course, interested only in a very small subset of all possible printing devices – those machines which are usually referred to as a printing presses and those devices, usually connected to a computer, which are referred to as printers. Today, most of these devices do not apply a mechanical force to create the mark on the surface. Instead they use, for example, chemical or electrostatic methods for the purpose. The word "transfer" is therefore much more appropriate to use than the word "press". The word "mark" on the other hand is perhaps too general in this case, and we probably clarify matters by referring instead to an "image", meaning information either as a pictorial image or as an image of plain text. Since printing devices usually operate by applying ink to the surface, it is fairly reasonable to change the word "something" in the definition, to the word ink, which leads to the definition:

To Print: To create an image on a surface by transferring ink to it.

What we are ultimately seeking is the quality of a device that operates by printing (perhaps with the limitation that the device has a certain configuration, i.e. uses a specific type of substrate, ink etc.). Words belonging to the group of abstract nouns such as quality are more difficult to define, but we start with a dictionary definition, which give us something to refer to:

Quality: Degree of excellence of something (Pearsall, 2001).

If this definition were satisfactory, Print Quality would simply be the Degree of Excellence of the output of a printing device. The problem is of course that this does not get us any closer to our goal, finding a definition of Print Quality that can be quantified. “Excellence” is just as vague as “quality” in this sense. This all rests on the abstraction and subjectivity of the concept of quality. As long as we agree that quality is a private experience, we must also accept that it cannot be directly measured because the only way to communicate with the private is by using some kind of language, and the interpretation of a language is always a personal affair. So even if we move forwards by using the word “excellence”, we shall never be able by the use of words to give a definition of quality that can be related to some measurement scale.

What we can do is to ask a lot of people for their assessment and then try to make a population estimate from their replies. By doing so we attempt to incorporate the general opinion of what quality means for the population in general into our estimate, and by doing so we can make some sort of quantification of the print quality that we ask people to assess; which will be more or less rough depending of how careful we are. However, we will still not have defined the concept of print quality, only the relationship in terms of some general agreement of Print Quality between the particular samples that were assessed.

Human interpretation is always relative to something (even in the sense of a population expectancy value) - an assessment is always made in some context – and this means that, no matter how much control we try to exert over our evaluation, there will always be external factors (e.g. expectations) that make the evaluation valid only within a certain domain and over a certain time. This is not however something unique. The same is also to some extent true of physical measurements if, for example, they are treated from the perspective of relativity theory and quantum physics. It is always necessary to identify the perspective from which we are considering the issue.

The question is therefore: how do we obtain an absolute measurement of print quality? It has already been suggested that we cannot, but what we can do, in addition to making subjective evaluations, is to measure certain parameters of the print itself. Such parameters will never tell us how good or bad the print quality is but, if they are cautiously defined and based on things that we do know (or at least suspect is true) about the human sensory systems, we may in the end be able to say that they correlate fairly well with rigorous subjective print quality evaluation, and this is the topic to which the rest of this thesis is dedicated.

To summarize:

1. It may be possible to give a fairly decent definition of Print Quality for communicative purposes,

- The degree of excellence of the output of a printing device,

but it is not possible to give a definition that can be explicitly related to measurements.

2. By agreeing on such a communicative definition, it may also be possible to make fairly accurate quantitative estimations of print quality by allowing a group of subjects to assess the quality of prints. Such an evaluation will however always be relative to something and will be valid only within a certain domain.

3. If we aim for an absolute quantification we need a physical measurement device that can estimate print quality. Due to the subjective nature of print quality, such estimations can however never be made. It is however possible to make accurate physical measurements of the print that are found to correlate well with rigorous subjective evaluations of print quality.

2.1.2 Print Mottle

Print mottle can be thought of as reflectance disturbances in the print that leads to a deterioration in the perceived quality of the print. The lack of such inhomogeneities can thus be assumed to correspond to a high print quality. Definition as follows:

> *Print Mottle:* perceived inhomogeneities in the print due to unintentional variations in the lightness of the printed surface when it is viewed under homogeneous illumination.

The use of the word "perceived" deserves a comment here. Since print mottle is considered as an aspect of perceptual print quality throughout this thesis, it is the subjective perception that is in focus. Physically, things may be very different, but this is less important from a print quality point of view.

2.1.3 Systematic Print Mottle

In our context systematic print mottle can be defined as follows:

> *Systematic Print Mottle:* print mottle that is perceived as ordered or structured by the Human Visual System.

Again the word "perceived" is used to underline that systematic print mottle is something that is interpreted by the Human Visual System. Here, the use of the word "perceived" certainly is important, because the difference between physical structure and perceived structure can be considerable in the case of systematic print mottle.

2.1.4 Colour Print Mottle

Here we define Colour Print Mottle as:

> *Colour Print Mottle:* print mottle that is perceived by the Human Visual System as a variation not only in lightness level but also in colour.

Colour mottle thus incorporates lightness, colour nuance and saturation variations.

2.2 Objective & Content

The main goal throughout the work has been to present a general model that can measure print mottle in a way that corresponds well with the way in which it is perceived by human observers. To do so, several key issues concerning the way in which humans interpret lightness and colour variations have been treated in the first six papers of the thesis.

In Paper I, the very important topic of how the perception of the lightness variation in the print is affected by the mean reflectance factor level of the print is addressed. In this case, the objective was to find the best way to acknowledge this by an instrumental mottle evaluation.

Paper II considers systematic print mottle and proposes a new model to evaluate systematic print mottle in a way that correlates well with the visual evaluation of systematic mottle and is fairly easy to apply. It then examines how well the proposed model can solve the task.

Paper III deals with several issues. It first addresses the question of how human beings assess and perceive systematic print mottle. Secondly it attempts to demonstrate how simulation can be a valuable tool to isolate the impact of a single print quality factor from the uncontrolled influence of other factors in the printing chain. Thirdly, it deals with whether other methods such as a two-dimensional magnitude scaling can be used instead of time-consuming pairwise comparison to investigate the relationship between different aspects of a print quality parameter (such as print mottle).

In Paper IV, different models to evaluate stochastic print mottle are compared, including a stripped version of the new model presented in this thesis. The paper examines how the three factors a) amplitude, b) coarseness and c) mean reflectance factor level are treated in the various models.

Paper V regards the complicated issue of colour variations. The model presented in Paper II is extended from lightness to colour, and four empirical evaluations to demonstrate when and how such an extension may be useful are presented.

Paper VI compiles the findings from Papers I to V and presents a complete model for the evaluation of print mottle in the general case. The model uses the findings concerning mean reflectance factor level compensation in Paper I, the attempt to consider systematic print mottle in Papers II and III, the general conclusions about amplitude, coarseness and mean reflectance level in Paper IV, and the generalisation of the model in Paper V to incorporate colour variations.

Paper VII deals with the traditional print mottle evaluation model that has been developed at STFI-Packforsk, and can be regarded as a background to the new model presented in this thesis. It may also act as a first reading on the instrumental evaluation of print mottle.

3. Theoretical Foundation

"You have to ask children and birds how cherries and strawberries taste."

Johann Wolfgang von Goethe, 1749-1832.

3.1 The Human Visual System – An Overview from the perspective of Print Mottle Evaluation

The Human Visual System (HVS) is in many ways one of the most magnificent achievements of evolution. It is indeed so remarkable that some people still use it as an example for raising doubts about the theory of evolution (Behe, 1996; Orr, 1997; Dembski, 2001; Dembski & Orr, 2002). Doubts or not, it is hardly surprising that an evolutionary game would attempt to develop some kind of system that can detect locations and movements of objects in the surrounding environment. However, it is important to remember that a system based on the capability of detecting electromagnetic radiation of wavelengths between about 420 and 720nm, is far from being the only feasible and applicable solution to the problem. We have only to take a look around in nature to discover other remedies for the task, such as, for example, the sonar systems used by bats and dolphins. The HVS is simply one of many possible solutions to the problem, which is sensitive to what we call "visual light" merely because the electromagnetic radiation from the sun is most intense in this interval of the spectrum, i.e. there is a good chance that radiation in this interval is available in many of the different situations that a ground-living mammal can face in this world.

Since the HVS is so optimised, one useful way to better understand how it operates is to start at the basics and to try to identify the parts that are required to comprehend the locations of objects and movements in the surrounding environment.

First, to map the surroundings one needs some kind of detector; in this case a detector that can register radiation reflected from objects in the environment. Then, if we want it to be able to discriminate between light arriving from different directions, we need a multitude of detectors, placed in some kind of matrix.

Next, if we want each detector to register only light from a specific direction, we need to deflect all light from all other directions. To get maximum detection performance we also want all the light entering our system from this specific direction to arrive at this particular detector. To achieve this we may use a very small entrance into the eye through which only a tiny amount of light can enter. If we want more light to enter we have to use a larger apparatus, but then we also need to use some type of lens system, otherwise light from several directions will hit the same detectors.

Having detected the arriving light we would then like to convey the information collected in our detectors to some type of processing unit, in our case the cortex of the brain. For this purpose we need some kind of link between the detectors and the cortex.

This down-to-earth outline of a visual system actually describes the overall function of the HVS quite well. The main corner stones of the HVS are indeed, detection, transmission, and processing. All these cornerstones will be addressed briefly and in a simplified manner in the sections that follow, and we shall consider mainly those topics that are important for the understanding of the work presented in this thesis. Other, perhaps even more remarkable functions such as 3D vision, and the perception of object category and functionality will not be dealt with here. Since colour vision necessarily complicates matters considerably, we will first regard the overall functioning by ignoring colour as such. Colour vision is treated separately in 3.1.5.

3.1.1 Preparing for detection - The Eye

In addition to the outline stated above, it is important to keep a few more constraints in mind when one considers the architecture of the eye. Light, or in broader sense electromagnetic radiation, can (if we believe what the physicists say) be described as a stream of photons emitted from a radiation source. Due to the fundamental aspects of quantum physics, however, the number of photons emitted from such a light source has a statistical character, i.e. it fluctuates. To stabilize the signal, the HVS must therefore perform a smoothing operation, either by spatial or by temporal integration, i.e. integrating over a certain detection area, over a certain time, or over both. Otherwise the world will not be perceived in a stable way.

A second very important fact to consider is that most objects are merely reflecting objects and are not self-luminous. This means that the amount of light reflected by those objects is totally dependent on the illumination conditions in which they are observed. For example, the amount of light reflected from a ball on a sunny beach is much larger than the amount reflected from the same ball in a dark room lit by a few candles. Critical for perception constancy, i.e. that we are able to see the ball as the same in both situations, is therefore not the absolute amount of light in the different locations, but rather the amount of light approaching from that specific ball *relative* to the amount of light arriving from surrounding locations. The implication of this is that it is more important for the HVS to be sensitive to differences in relative luminance levels than to absolute differences.

Figure 3.1.1 shows a schematic cross-section of a human eye. When a photon enters the eye it first passes the cornea, a transparent bulge on the front of the eye. It then continues through the aqueous humor, a cavity behind the cornea filled with a clear liquid. Behind the aqueous liquid it passes through the pupil, which is a variable sized opening surrounded by the opaque iris (giving rise to the external colour of the eye). After passing through the lens, the photon has attained its final bearing, and is heading for the appropriate detector. Deflected it travels through the vitreous humor that fills the central chamber of the eye, before it finally strikes the retina and its destined photoreceptor.

All these components fulfil an important part of the visual chain (which is one of those evolutionary issues that was heavily debated half a decade ago – irreducible complexity - remove one link from the chain and it will work no more). The cornea, and not the lens, is chiefly responsible for the bending of the incoming light. The lens however performs the important task of being able to change shape (accommodation) so that it is made thinner when focusing on distant objects, and thicker when focusing on closer objects. The dilation of the pupil surrounded by the iris is responsible for the amount of light that finally hits the retina. Under darker, scotopic, conditions the pupil dilates so that more light can pass through.

So far everything looks great, and it appears that it should be possible to project a perfect 2D representation of the visual field onto the retina. Unfortunately the imperfections of the eye, such as Spherical Aberrations, Chromatic Aberrations, Light Scattering, Diffraction of Light, Imperfect Focus, Slow Focus, Multiple Depths, Instability of the Eye, Vibration of the Eye and Head movements, etc., impoverish this.

When you first see the length of the list of deficiencies, it is hard to understand how it is possible to detect anything at all. Fortunately, evolution also equipped the eye with some countermeasures to tackle such problems. A decrease in pupil diameter in bright light reduces the impact of the aberrations; directionality of the receptors reduces the effect of aberrations and effects of light scattering, maximum cone sensitivity in the middle of the visible spectrum reduces the impact of chromatic aberrations etc. Nevertheless, it is important to keep in mind when examining the architecture of the retina that all light from a certain direction in space does not hit a single spot on the retina, but that there is a distribution with a spatial extension, a so-called point spread function.

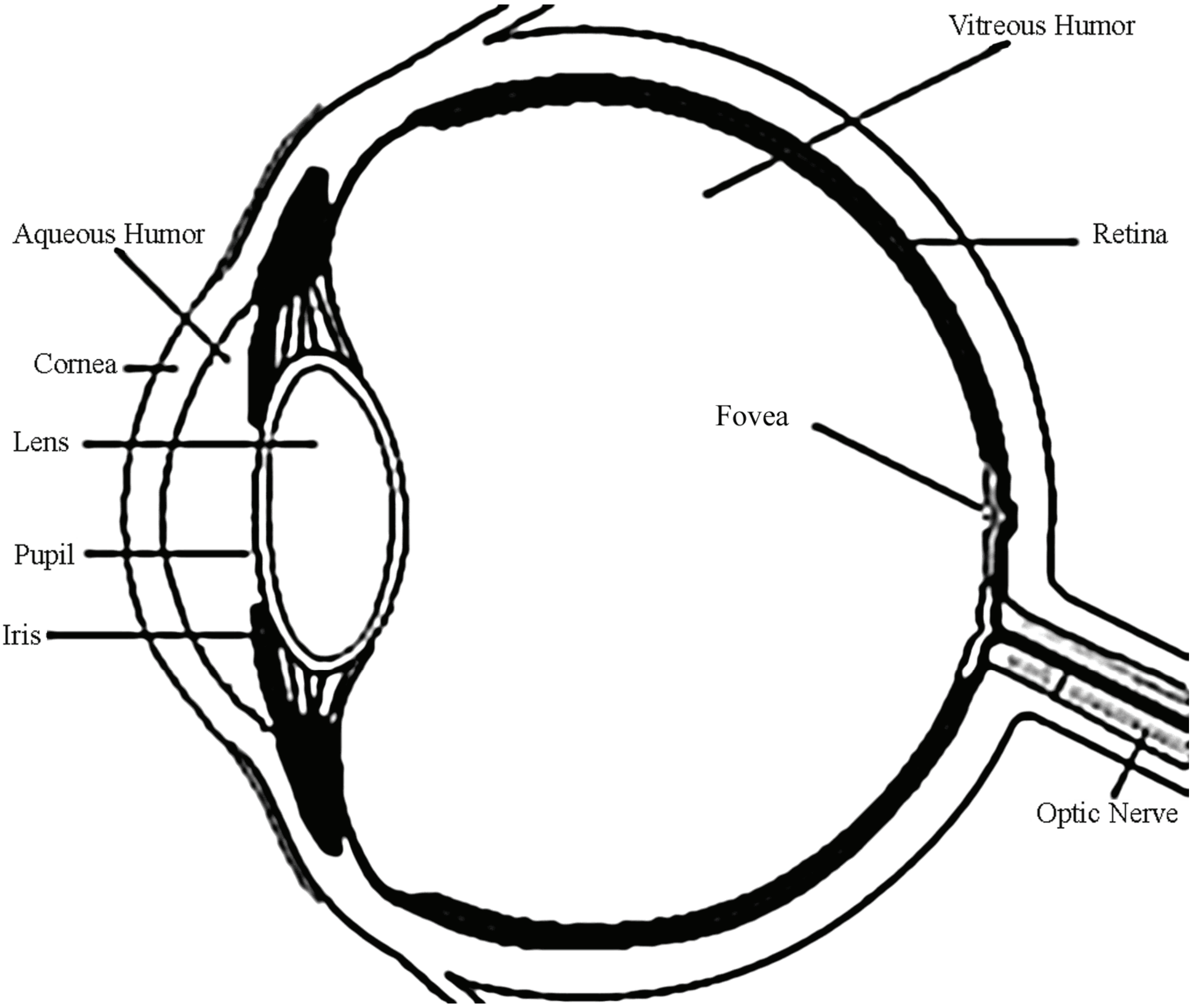

Figure 3.1.1. *Schematic view of the Human Eye.*

3.1.2 Detection - The Retina

The retina has two major functions, it is responsible for a) the detection of the incoming radiation stimulus, and b) the optical information and the way in which this information is to be transmitted to the brain.

The detection function is handled by the photoreceptors. There are two distinct classes of receptor cells in the retina, rods and cones. The names indicate the shapes of the receptors; rods are typically longer and have rod-like ends, whereas cones are shorter and thicker and have narrowed ends. There are about 15 times as many rods as cones on the retina. The 120 million rods are located virtually everywhere on the retina, except at the centre, the fovea. The fovea is the area of the retina responsible for our focally highly resolved vision. The rods are very sensitive to light and are used at very low, scotopic, light levels. The about 8 million cones are much less sensitive to light and are concentrated mainly in the foveal region of the retina. The cones are responsible for our perception of colour and are used under normal, mesopic, to bright, photopic, conditions.

An interesting question is how these receptors manage to convert the electromagnetic energy of the photons into neural activity. The fairly complex and smart solution is that this, for a long time not very well known but today reasonably well understood, process is based on biochemical processes. A pigment in the receptors, a photosensitive molecule, converts the photon energy into electrochemical energy and by changing its shape it alters the flow of electric current in and around itself. As a result, electrical charges are produced in the outer membrane of the receptor, which then propagate to the synaptic region of the receptors, where the neurons take over.

The ratio of rods to cones might give the impression that the number of neurons connected to rods by far surpasses the number of neurons responsive to cones, but this is not however the case. While each rod typically has contact only with only one or two bipolar cells (Figure 3.1.2), which typically are connected to several rods, the cones on the other hand often have contacts with several bipolar cells which often only have contact with one or a few cones.

There are basically four categories of neurons, all with different functions, in the retina - Bipolar cells, Horizontal cells, Amacrine cells, and Ganglion cells. The bipolar cells are directly connected to the photoreceptors and usually also with the ganglion cells, whose axons together constitute the optical nerve that transfers the information from the retina to the cortex. The horizontal cells, as indicated by their name, are responsible for horizontally transferred spatial excitations between neighbouring receptors and bipolars. By analogy, the amacrine cells are responsible for horizontal excitations between neighbouring ganglion and bipolar cells. Many bipolars, or perhaps all, that are connected to rods are not directly connected to ganglion cells, but are connected only to amacrine cells, which in turn are connected to the ganglion cells.

This cell architecture implies several things. Since the peripheral parts of the retina are mainly inhabited by rods, which have contacts with only a few bipolar cells, which in turn are in contact with several rods, the information that is conveyed from the bipolar cells that integrate information over a large spatial area cannot contain information as spatially high-frequent as information from cells that are located in the foveal region where the bipolar cells are connected to only one or a few cones. In other words, already here at the retinal level it appears that the HVS is less sensitive to high frequency information the further away from the foveal region the stimulus is located. In addition, since the rods and cones operate differently under different conditions, the sensitivity to high frequency stimuli must depend on the conditions. It can therefore be said that spatial frequency processing of the visual input takes place already at the retinal level of the HVS using local low pass filtering (Chapter 3.4) of the input information.

3.1.3 Transmission - Lateral Geniculate Nucleus

The axons of the ganglion cells leave the eye in what is referred to as the Optic Nerve, which is destined for two main areas, the Lateral Geniculate Nucleus (LGN) and the Superior

Colliculus (Figure 3.1.3). Compared to the about 130 million receptors available on the retina, only about 1 million axons pass through the optic nerve, which is one very compelling explanation of why the peripheral input is so heavily spatially low pass filtered and compressed by the retinal cell structure. There is simply not sufficient bandwidth available to convey any more information along the visual highway (De Valois & De Valois, 1988, p.334).

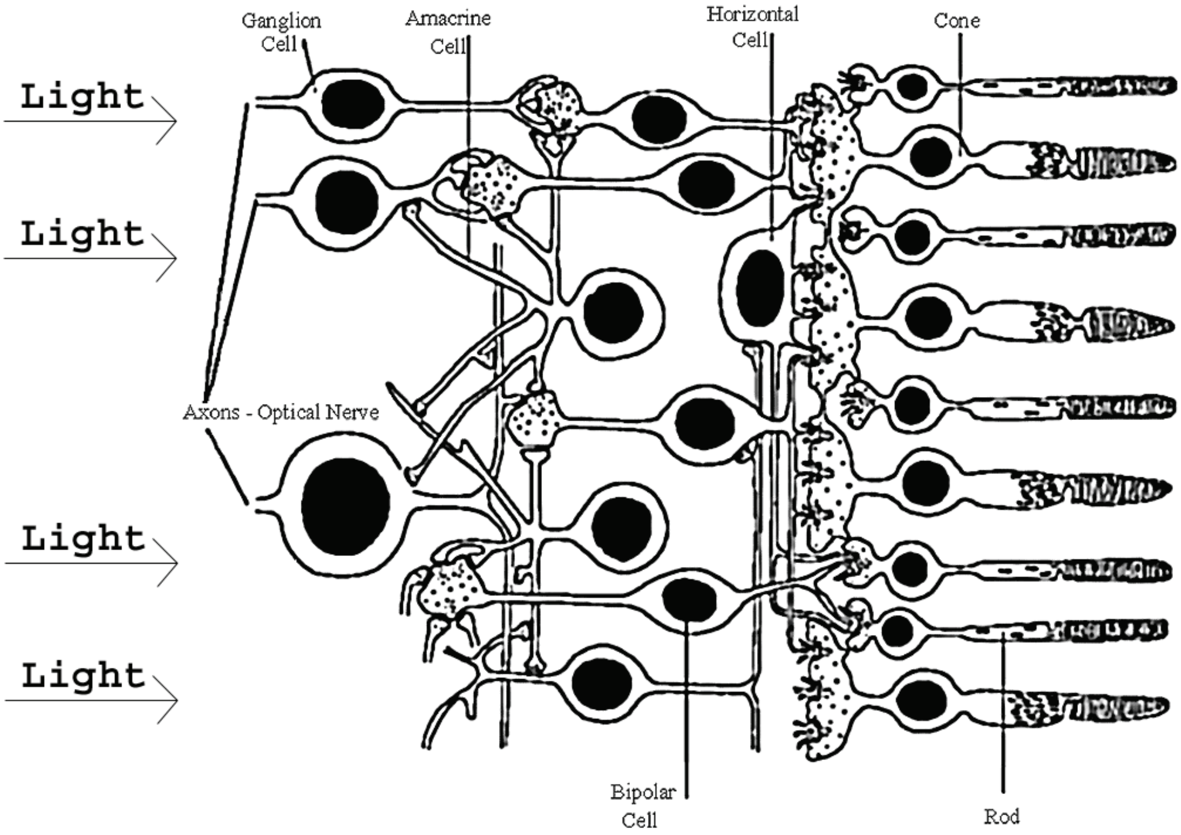

Figure 3.1.2 *Schematic view of the cellular structure in the Retina. The retinal structure is for some reason inverted – the light, arriving on the left-hand side, must pass through layers of nerves in the retina before they can be detected by the photoreceptors.*

With the evolution of the LGN and the Cortex in primates, the Superior Colliculus no longer plays a governing role for the processing of visual information, but it is still very important for the control of eye movement, and this, more primitive, visual pathway probably also plays other roles for the final experience. This is however still not a very well understood topic.

The LGN can be seen as a relay station where the fibres from each half of the retina break up into three layers, and get interwoven with those from the other eye to form a six-layered arrangement. The separation into layers is not based on any spatial region, and it must therefore reflect some functional division. The axons from the Ganglion cells here connect to the dendrites of the LGN, whose axons in turn connect directly to the striate cortex. Interneurons in the LGN perform similar functions as the horizontal and amacrine cells in the retina, i.e. spatial filtering of the visual information.

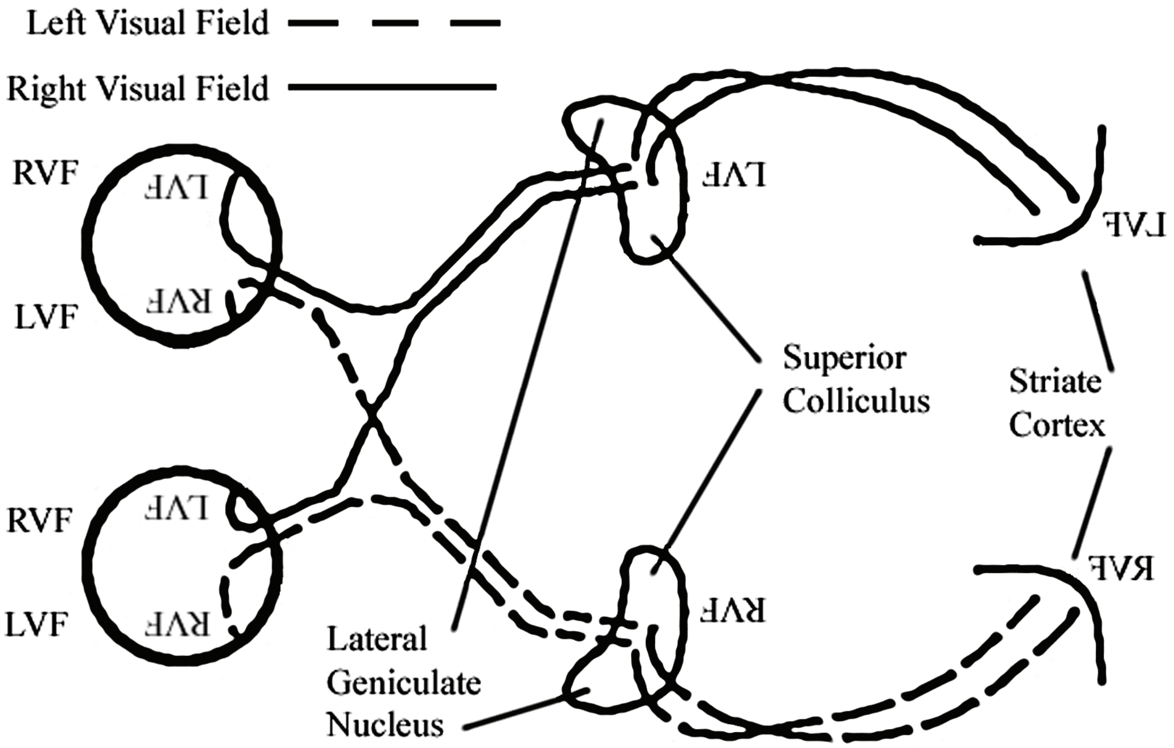

Figure 3.1.3. *The Visual Pathways. The sketch shows how the visual information, inverted by the lens, pass from the left and right visual fields of both eyes through the optical nerve. The optical nerve diverges so that the information from the right visual field passes through the Lateral Geniculate Nucleus in the left part of the brain. The information is then once again inverted so that the right part of the right visual field is projected to the right side of the left part of the striate cortex (still upside down, however).*

3.1.4 Final Processing – Visual Cortex

The visual stimuli eventually arrive at the visual cortex, or to be more precise at the part of the occipital lobes of the brain called the Striate Cortex. The left visual field is projected onto the right side, and the right visual field onto the left side of the striate cortex. The mapping from the retina to the striate cortex is topographical, that is, nearby regions on the retina are projected to nearby regions in the striate cortex, but the proportions are distorted heavily so that the foveal regions are projected on a proportionately larger area in the striate cortex than the more peripheral regions. This does not, of course, imply that we see things in a distorted way, simply that the brain, just as in the case of the retina, has more processing capability allocated to the central regions of the visual field.

At this level, the rather compressed information that passed from the retina is thoroughly analysed by a myriad of cell clusters (a total of more than 500 million cells). There are several theories as to how this processing is achieved, but the main controversy concerns the degree of frequency analysis involved and the amount of structural identification at this level. One theory, based on empirical physiological data, suggests that the cell clusters act as a number of line and edge detectors at different spatial scales from which the final visual experience is later integrated. If this is the case, it is certainly no wonder that, as the results of Papers II and III of this thesis suggest, systematic disturbances in prints are easier to detect than random noise.

The main alternative to this model is the idea that the cell clusters instead act as local spatial frequency and orientation channels that are sensitive to stimuli within certain frequency and orientation ranges. Because this type of filtering has proven to be more efficient to describe so-called natural images with structured contents than unnatural images (Field, 1994), such as random noise images, this model also suggests that we are more sensitive to systematic than to random mottle. It is also not very far fetched to suggest that such analysers may act in a similar way as compressing wavelets, focusing on frequency components that describe the major part of the signal (i.e. components that build some kind of structure). The model has essentially been based on psychophysical evidence, but has lately also found support by physiological data.

Basically, both theories suggest that the information is processed by a certain amount of spatial frequency analysis. The dispute is mainly as to whether the structure is detected already at this initial level or whether the mapping of frequency contents is only a pre-stage for an extraction of lines and edges at the next level. Both models however give perfectly acceptable suggestions of why systematic mottle will be easier to detect than random noise of the same physical RMS magnitude. It is interesting to note that, whereas low-pass filtering of the visual information already takes place immediately before and at the retinal level, narrowband frequency and orientation selective analysis chiefly take place at the cortical level, i.e. in the LGN and especially in the cortex.

The processed information is then transmitted from the striate to what is called the prestriate cortex, which includes several areas of the rear part of the brain. The transmission was first thought to be handled as a serial process, but empirical evidence now suggests that it is also made in parallel. A lot of the connections between the striate and prestriate cortex are here not forward projections but rather backward feedback connections to earlier stages in the chain from the prestriate to striate cortex.

Our knowledge of these and even later cortical processes is however still very limited, and it is basically on the hypothesis level. It is however interesting to recognize some theories of how, for example, we are able to visualize memories (and explanations of consciousness in general for that matter). Hesslow (1994) among others, for example suggests that the progression of visualizing memories or new virtual situations involves processes where activity in the frontal cortex projects back onto the visual areas of the cortex to simulate experiences. It may therefore be reasonable to think that the visual perception of reality is actually also a recursive process where visual stimuli are matched with previous experiences stored in the memory, which are in turn projected backwards. What we then end up with is a loop, suggesting that perceived experience is a mixture of visual stimuli, memories and perhaps also simulated virtual stimuli. What is really going on can perhaps best be described as a never-ending trial-and-error simulation where what Dennett (1991) calls “Multiple Drafts” are generated to cope with reality.

If we assume that the available memory is fairly constant over a short period of time, its influence on the perceived experience should then depend on the amount of visual stimuli available, which may vary heavily depending on the viewing conditions. One example of this could for example be that the risk of making a faulty identification is probably in most circumstances much lower in daylight than in moonlight. Another example could be that many persons probably agree that it is easier to remember the face of their first love if they close their eyes than if they recall the face while simultaneously watching a scene in an action movie that changes very rapidly.

So what has all this to do with print quality evaluation? Well, it suggests that the evaluation of print quality should be made under very stable and neutral light and context conditions, so that the influence of previous, and perhaps also virtually simulated, experiences during the evaluation is minimized.

To summarize, the HVS is designed to discriminate between relative rather than absolute levels of light. Its design also makes it more sensitive to variations within a rather limited spatial frequency range than to frequencies far outside this range. Later stages involved in the process of visual perception make the HVS more sensitive to systematic variations than to random variations, chiefly because it is valuable to be able to detect the boundaries of objects within natural scene images. These later processes also seem to interact heavily with other areas of the brain responsible for provoking memories and reasoning, which necessarily makes the quality evaluation of prints that convey comprehensible information, e.g. systematic mottle, more influenced by subjective factors such as previous experiences, than prints conveying nonsense information such as random mottle.

3.1.5. Colour Vision

The functionality of the HVS thus far, without considering the fact that the HVS can discriminate between different wavelengths of light, is quite impressive. The obvious question must thus be - why colour vision? Why spend an excessive amount of resources on discriminating between light of different wavelengths? And, in this particular context, how does this relate to print mottle?

Once again a reasonable explanation can be drawn from the conditions in which the HVS operates. Not only may the range of light intensities from the sun illuminating our terrestrial environment vary extensively. In addition, depending on whether an object is located in direct sunlight or in shade, the *local* intensities of illumination of different parts of an object may vary dramatically. This can make it very difficult to discriminate between object boundaries and boundaries of shadows, as well as between different objects with similar shapes (such as for example eatable and toxic berries). The spectral distribution of the reflected light however varies much less than its intensity if an object is located in shadow or under direct sunlight, and the spectral distribution may hence help to classify objects and the boundaries of objects. Although very expensive neurally, colour vision is thus very advantageous for many animals, such as e.g. predators, birds, and insects.

The cells ultimately responsible for the capability of the HVS to discriminate between light of different wavelengths are the cones located in the retina. The cones come in three types, L, M, and S, according to their sensitivity to light of different wavelengths. The L-cones respond mostly to longer wavelengths with peak sensitivity at 560nm. The M-cones responds to the middle wavelengths, although the peak sensitivity at about 530nm is very close to that of the L-cones. The S-cones are sensitive to short wavelength light and their peak response is at about 440nm.

The cones are mainly concentrated in the foveal region of the retina, especially the L and M cones, which are very sparsely located outside this area. The S-cones are however somewhat more uniformly distributed over the retina, with their highest concentration in the area just outside the fovea. In addition, the proportions of L, M, and S cones are far from being the same. The number of L-cones is about twice as high as the number of M-cones, which in turn are about five times as frequent as the S-cones. There are several reasons for this asymmetric architecture, of which the chromatic aberrations of the lens that makes it impossible to detect high frequent spatial variations of light of short wavelengths are the main reason why the S-cone structural sampling in particular differs considerably from that of the L and M cones (Wandell, 1995).

The fact that three different types of receptors are responsible for our perception of colour was actually predicted long before the cones themselves were physically discovered. A trichromatic theory of colour vision was initially proposed by Palmer (1777) and rediscovered by Young (1802). The theory proposed that three different receptors produce the psychological sensations of the colours red, green and blue. All other colours were explained as being combinations of these three primaries. The theory was extended by Grassman (1854), Maxwell (1855) and Helmholtz (1867) and is known as the Young-Helmholtz trichromatic theory.

Yet, in spite of its great success, the Young-Helmholtz theory cannot account for some of the facts and observations concerning people's subjective experience of colour. It does not explain why colour blindness always seems to come in pairs, either red and green or blue and yellow seem to vanish together – never alone. In addition, the theory accounts for three primary colours, red, green and blue, whereas the human perception of colour seems to include a fourth primary, yellow, which subjectively does not seem to be a mixture of red, green and blue.

Hering (1878) therefore launched another theory, the opponent process theory. His theory suggests that three types of receptors, green-red, blue-yellow, and black-white, can act in two opposite directions from a neutral level, and this remedies the deficiencies of the Young-Helmholtz theory. Merging them into one, the dual process theory (Hurvich & Jameson, 1957), elegantly solved the controversy between the two competing theories. In the Dual Process theory, a Helmholtzian trichromatic detection stage provides the input for a second Hering-like opponent process stage.

In the 1950's and 1960's techniques to reveal the physiological mechanisms behind colour perception were developed, and the existence of L, M, and S-cones was finally confirmed. Not long afterwards however, colour selective cells with a functionality resembling the mechanisms of Hering's opponent theory were discovered in the LGN of macaque monkeys (de Valois, 1965). Today we know that such colour selective cells exist in retinal bipolar and ganglion cells. Strikingly, most of the ganglion cells in macaque monkeys (and presumably in humans) actually show chromatically opponent responses (de Valois & de Valois, 1988). In other words, it seems that the Dual Process theory can to a great extent account for human perception of colour.

For the perception of colour mottle, three things are of particular interest. Firstly, considering the opponent character of early colour coding in the HVS, a three-dimensional representation of human discrimination of lights with different spectra, based on the three dimensions predicted by Hering's theory, i.e. black-white, green-red and blue-yellow seems very appealing. If mechanisms in the early parts of the HVS use these three opponent processes to code wavelength information, it is reasonable to assume that the sensitivity of the HVS to spatial chromatic variations is related to the three dimensions.

Secondly, concerning the shapes and relative magnitudes of luminance and chromatic contrast sensitivities, empirical evidence (Bradley, Switkes, & de Valois, 1985) supports the existence of multiple colour spatial frequency channels. There is however no physiological evidence for even moderately narrow spatial frequency band-pass mechanisms for isoluminant stimuli at the LGN level. The attenuation of low spatial frequency luminance patterns that is produced by centre-surround *antagonism* does not occur for colour because of the effective centre-surround *synergism* in this case. In striate cortex cells, however, the spatial filtering characteristics for colour and luminance are very similar (de Valois & de Valois, 1988).

Here, the concepts of antagonistic and synergistic centre-surround may require some explanation. Consider an opponent colour selective ganglion cell responding positively to an M-cone input (i.e. highest sensitivity to green light) in an arbitrary *central* position somewhere in the visual field and negatively to local *surrounding* L-cone inputs (i.e. highest sensitivity to red light). The central position and its local surrounding is called the *receptive field* of the ganglion cell. A cell with this kind of input structure, e.g. an excitatory centre and inhibitory surroundings, is said to have a centre-surround organisation. Now, assume that there is a *luminance* increment in the receptive field in relation to a darker surrounding. This will yield an antagonistic response for luminance in the centre (positive) compared to the surrounding (negative). Next, consider the shift in wavelength distribution of the light that hits the receptive field (say green light), compared to the background (red light). Now the positive centre will react positively to the green light, whereas the negative surrounding will react negatively to the green light, i.e. both reacting positively; hence a synergistic response.

Thus, while the centre-surround synergism in the colour case does not result in an attenuation of low frequency variation, it does not, on the other hand, as the centre-surround antagonism in the luminance case, emphasise high frequency variations. The aggregate result will therefore yield a more low-pass-like character of chromatic contrast sensitivity than that of the luminance contrast sensitivity. In other words, the HVS will emphasise local spatial *similitude* rather than contrast in the chromatic case. Overall, this implies a lower sensitivity to medium and high frequency spatial chromatic variations than to spatial luminance contrast variations of similar frequencies, but a similar or higher sensitivity to low frequency chromatic variations than to low frequency luminance variations.

In this chapter, chiefly due to the overall topic of the thesis, we have not considered similitude as much as contrast, but the fact is that in order to comprehend the spatial structure of the surrounding world the capability to perceive similitude is just as crucial as the ability to perceive contrast. Similitude in chromaticity between spatially nearby locations suggests that we are still within the boundaries of the same object. Emphasising chromaticity contrast between local positions would on the other hand eventually create nothing but noise, i.e. a complete inability to classify any objects. Consider for example the crown of a tree, the place from which we presumably originate. It would not easily be perceived as a single object if profound high frequency colour differences between its leaves were emphasised rather than neglected. Similitude in colour, or colour constancy, is therefore an important trait of the HVS. In general, the capabilities of the HVS can thus be said to be wisely designed as a trade-off between similitude and contrast.

Finally, with regard to the sizes of the red-green and yellow-blue sensitivities in relation to the size of contrast variations, the proportion, and the number of cone receptors on the retina reveal valuable clues to the sensitivity to spatial red-green and blue-yellow variations. Since S-cones reveal the proportion of light with wavelengths in the blue region, and the lack of light in the yellow region, and since the S-cones are fewer in number than the L and M cones, it can be expected that the sensitivity to spatial blue-yellow variations is lower than that to red-green variations. Further, since the S-cones are much more widely spaced than the L and M cones in the foveal region of retina, it can be expected that the sensitivity to spatial variations in the blue-yellow dimension is considerably lower at higher spatial frequencies than the sensitivity to red-green spatial variations. This standpoint is strongly supported by psychophysical evidence (e.g. Williams, 1993).

To summarize, since shadowing effects in many instances reduce the ability to create achromatic spatial similitude within objects that are illuminated differently, it seems that the HVS has been developed to attenuate low frequency spatial lightness variations. These shading effects do not take into consideration spatial low frequency chromatic variations. As a consequence, our achromatic map of the world gives us a middle to high frequency representation of the world, emphasizing fine details, whereas the colour map covers low and middle spatial frequencies and give us more information about large objects and extensive areas. This explains the shape of the contrast sensitivity functions applied throughout this thesis, lightness contrast sensitivity is typically band pass with a peak sensitivity around 3 cycles per degree of visual field, whereas the chromatic contrast sensitivity function is weaker and has a low pass or a very weak band pass tendency with a peak sensitivity of $\leq$ 1 cycle per degree of visual field.

3.2 Psychophysical Threshold Measurements – Fundamentals

The work presented in Paper I is to some extent based on classical psychophysics, such as the laws of Weber and Fechner. Although the remarkable work of these two pioneers still seems to be valid to some extent, it is important to remember a) that it represents rather rough approximations, b) that quite considerable deviations from their laws are observed in several situations, and c) that the laws may not be legitimate for use in many cases. This section will start by introducing these two fundamental laws of psychophysics, and then go on to consider the deviations that are important in the case of Print Mottle.

The notion of a sensory threshold is very central to the area of psychophysics. The concept originates from the early 19th century philosopher Herbart who introduced the idea of a threshold by assuming that mental events had to be stronger than some critical level in order to be consciously perceived.

When discussing threshold psychophysics, it is important to distinguish between two different types of thresholds, an absolute threshold (or stimulus threshold) and a difference threshold. The absolute threshold is, in terms of stimulus energy, the lowest stimulus level required to produce a detectable sensation. The concept is in other words closely related to the *absolute* magnitude of the stimulus.

The difference threshold is the magnitude of the change in a stimulus that is required to produce a just noticeable difference (jnd) in the sensation. This concept is in other words intimately related to the magnitude of *variation* of the stimulus. Since mottle can be defined as a spatial lightness variation in the print, difference thresholds are usually of concern in this thesis.

It is important however to point out that sensations can differ in other respects than intensity. At least three other dimensions of variation can be identified: duration, quality and extension. Of these, duration is not of concern as long as we assume that the print is viewed under a temporally homogeneous illumination. It may seem natural to incorporate a quality difference in the stimulus in our analysis of the magnitude of print mottle, but the concept does not here relate to quality as a degree of excellence, as in our definition of print quality in Chapter 2. Instead it refers to different kinds, sorts or classes of stimuli. Quality, in this sense, is not of interest if we consider the *magnitude* of mottle. If we attempt to distinguish *types* of mottle, e.g. random or systematic disturbances, it may however be relevant. Similarly, extension may be of interest if we wish to evaluate how the size of the sample in which the stimuli are observed influences mottle magnitude assessment.

Paper I concerns one of the first threshold relations that was investigated, the relationship between the difference threshold of intensity and the intensity level of the stimulus. In other words, if we have a difference threshold of X units at a mean intensity level of Y units, how large will the difference threshold be at a mean intensity level of 2Y units?

This type of question was considered by Weber, who adopted Herbart's threshold concept and used it in his investigations on the detection limits of the human senses. By using measurement techniques of physics and well-trained human observers, he was able to establish the threshold for the weakest detectable sensation difference.

Weber discovered that two heavy objects must differ in weight by a greater amount than two lighter objects for one to be perceived to be heavier than the other. Weber actually discovered not only that the size of the difference threshold was larger when the stimulus was heavier, but that it can be described by a linear function of the intensity of the stimulus. This relationship has since been found to apply surprisingly well, not only for perceived weight, but also for a whole range of different sensory stimuli. The simple relationship can be described by the equation:

$$c = \frac{\Delta\Phi}{\Phi} \;, \tag{1}$$

where the so-called Weber Fraction, c, differs for different types of sensory stimuli, Φ.

Weber's Fraction is not impeccable, and this is especially true (as Weber's own experiments indicated) when the level of the stimulus is very low. When the level of stimulus is low the Weber Fraction seems to grow rapidly towards very high values. Thus, a modification of the original equation that seems to agree better with empirical evidence has been suggested:

$$c = \frac{\Delta\Phi}{\Phi + \alpha}, \tag{2}$$

where the constant, α, compensates for the deviation at low stimulus levels. This compensation has not yet been related to any neurophysiological finding, but a plausible explanation is that it corresponds to a continuously fluctuating background noise level of the nervous system. When the expected value of this noise (i.e. α) is taken into account, Weber's Law seems to be essentially correct.

Unfortunately, in addition to the deviation at lower stimulus levels, disagreements at higher levels also have been reported in some situations, and other, more complex relationships have therefore been suggested for many types of sensory stimuli.

It was on the basis of Weber's work that Fechner founded the discipline of what is today known as psychophysics. Fechner was working mainly on the idea that mind and matter are the same - just two different perspectives of the universe. What Fechner realized from Weber's results was that they imply that it takes greater and greater changes in physical intensity to produce a mentally experienced noticeable difference in stimuli. By integrating Weber's Law, (1), over a series of physical values, Φ, Fechner arrived at what is today known as Fechner's law:

$$\Psi = k \log(\Phi), \tag{3}$$

i.e, the mental experience of the intensity, Ψ, is proportional to the logarithm of the physical level, Φ, which provides very elegant support for his own philosophical arguments concerning mind and matter.

Nevertheless, despite its beauty, it is important to keep in mind that Fechner's conclusion is founded on Weber's Law, and it is therefore valid only to the extent that Weber's Law, (1), is correct. In addition, experiments suggest that Fechner's Law is applicable only as an approximation of reality. It should thus be applied with more than some caution, but it is nonetheless often a good starting point in search for a relationship that agrees well with empirical results.

Regarding vision the perceived lightness, L^* in the CIELAB 1976 system, is proportional to the cube root of the physical luminance level, Y, except at very low physical luminance levels, i.e.:

$$L^* = \beta Y^{1/3} - \gamma \ , \tag{4}$$

where β and γ are constants. The equation $\Psi = k\Phi^{\alpha}$, known as Steven's Power Law (1957), has proven to be in better agreement with the results of psychophysical scaling experiments than Fechner's logarithmic relationship $\Psi = k \log(\Phi)$.

If we compare eq. (4) with Weber's and Fechner's laws we can identify two main similarities. Firstly, the relationship between the physical level and the perceived level is a concave non-linear function in both cases. In Fechner's Law, the perceived level is proportional to the logarithm of the physical level, and in the Lightness Equation, the perceived level is proportional to the cube root of the physical level. Secondly, in neither case does the relation hold for low physical values.

To summarize, although the basic laws of threshold psychophysics do not agree perfectly with empirical data, they provide an excellent foundation for an understanding of the relationships between physical and perceived stimuli, and much of the present understanding of threshold psychophysics is more or less, founded on these original declarations.

3.3 Frequency Analysis – A non-mathematical treatment

Many phenomena in our world can be conveniently described by waves (e.g. light, ocean waves and seasonal changes). The importance of the discovery made by Fourier (1822) that a periodic waveform of any complexity can be analysed into a linear sum of harmonically related sine and cosine waves can therefore hardly be overestimated. The method, now known as Fourier analysis and extended to non-periodic functions, has had a remarkable impact on virtually every field of modern science, and Vision Science is by no means an exception. Today, there is a lot of evidence suggesting that the HVS itself utilizes processes that are closely related to Fourier analysis.

To obtain a clear understanding of how the HVS works and, in the end, how print mottle and print quality are perceived, some basic understanding of frequency analysis is thus quite useful. The aim of this section is to try to explain briefly the basic concepts of frequency analysis without using any mathematical expressions. For a more comprehensive and rigorous mathematical explanation there are myriads of books on the subject.

The objective of frequency analysis is to break down a complicated signal into its components of different frequencies. Other methods than Fourier analysis can be used for this purpose, but since sine waves are conceptually fairly easy to grasp, we shall here confine ourselves to Fourier analysis. The word "components" in this case can be interpreted in several different ways, but the easiest way is to define it as the contribution to the whole integrated signal of each term in the sum of sine and cosine waves. The idea is illustrated in Figure 3.3.1 by a very basic signal.

When we make the change into the frequency domain, we have a finite or infinite series of sine and cosine components, each making a different contribution to the whole signal. One aim of frequency analysis is to visualize these contributions in some kind of graph or image and from this to draw certain conclusions concerning the characteristics of the signal. Another aim is to modify the contributions of the components in some specific manner, for example by attenuating or saturating some of them, and then to use the modified signal in some way when returning to the spatial domain.

The fact that the series is built up of both sine and cosine components make it somewhat difficult to both visualize and modify it. The components are therefore often mathematically written in a so-called exponential notation, and then divided into one Amplitude part and one Phase part. The amplitude part contains the information as to how great a contribution each frequency component makes to the whole signal, while the phase component describes where in the signal this contribution is located. Although phase information seems to dominate in the field of perception (Palmer, 1999), the amplitude seems to be most important for print mottle estimation. The reason is of course that we are more interested in the amount of variation in the print than where in the print the variation is located, and this is exactly what the amplitude of the frequency components describes; the magnitude of the variation in the print at different frequencies.

When we consider *systematic* print mottle, the amplitude seems to be more important than the phase component not only to describe the magnitude of the variations in the print but also to describe its textural characteristics (Eklundh, 1979). Overall, it is therefore fair to focus on the contributions to the perceptibility of print mottle of the amplitude components, and to ignore the contribution of the phase information, as long as the spatial location of the mottle in the print is not under consideration.

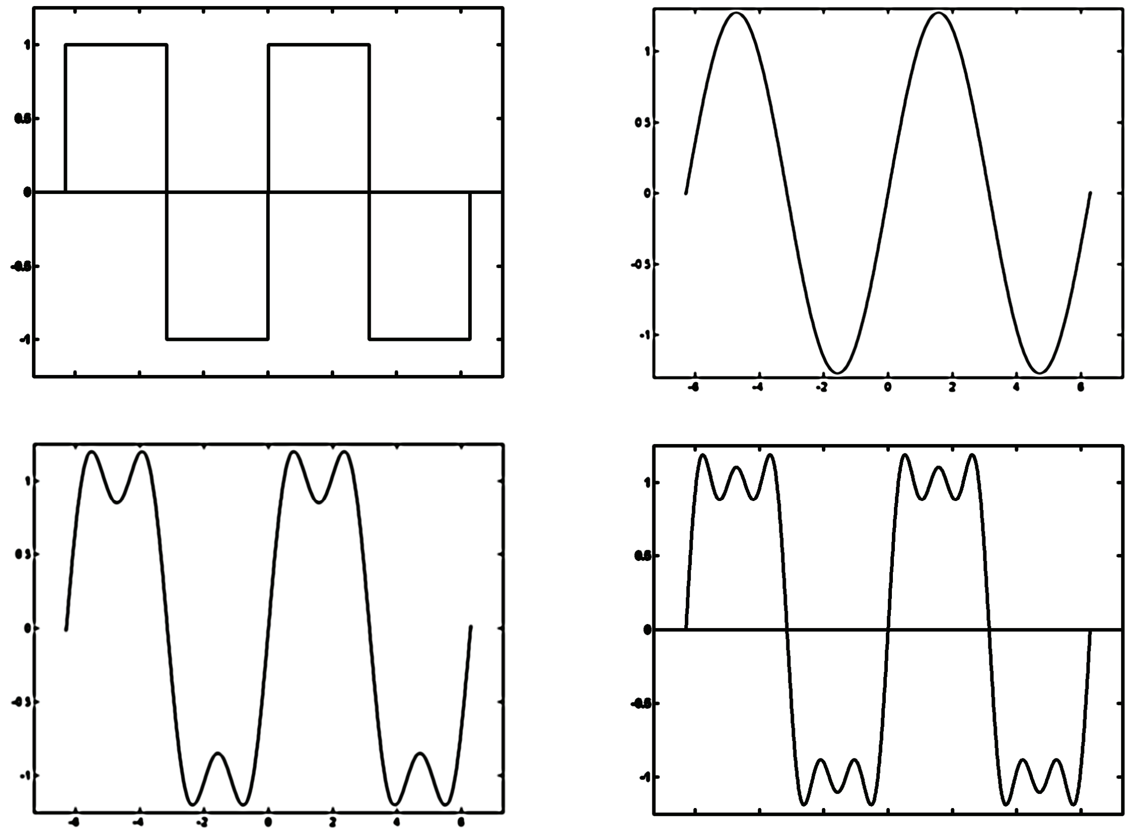

Figure 3.3.1. *A Basic Square Wave (top left) and its Fourier series approximation using 1 (top right), 3 (bottom left) and 5 (bottom right) of the terms in the sum of harmonics. As the number of terms in the series approaches infinity, the difference between the original signal and the approximation approaches zero.*

The amplitude component of a signal is commonly presented in what is called a Power Spectrum. The power spectrum is usually presented as two-sided, since due to symmetry, each peak occurs on both sides of the origin. The value in the middle of the graph represents the accumulated magnitude of the whole signal (and can therefore sometimes be rather large). One each side of this value the harmonic components are presented with increasing frequency, so that the further away from the centre of the graph the higher is the frequency of the component.

Since an image is a two-dimensional signal, it can vary in two dimensions. Image analysis in the frequency domain must therefore also necessarily be made in two dimensions. The power spectrum is in this case usually visualized as an intensity image, that is, the lightness of each position in the power spectrum image represents the magnitude of a specific component.

The two-dimensional power spectrum is also double sided, and again the origin of the spectrum presents the accumulated magnitude of the signal. Also here the frequency increases with increasing distance from the origin. The angle from the horizontal axis of the spectrum to a component reveals the orientation of the variation. For example, if the variation in the image is mainly along the horizontal direction, the components along the horizontal axis of the spectrum will be the main contributors to this variation, whereas if the variation is mainly along the vertical axis the components along the vertical axis of the spectrum will be the main contributors. Major variation at angles between the horizontal or vertical orientations will be represented in a corresponding way in the spectrum. An example of a print and its related power spectra are presented in Figure 3.3.2.

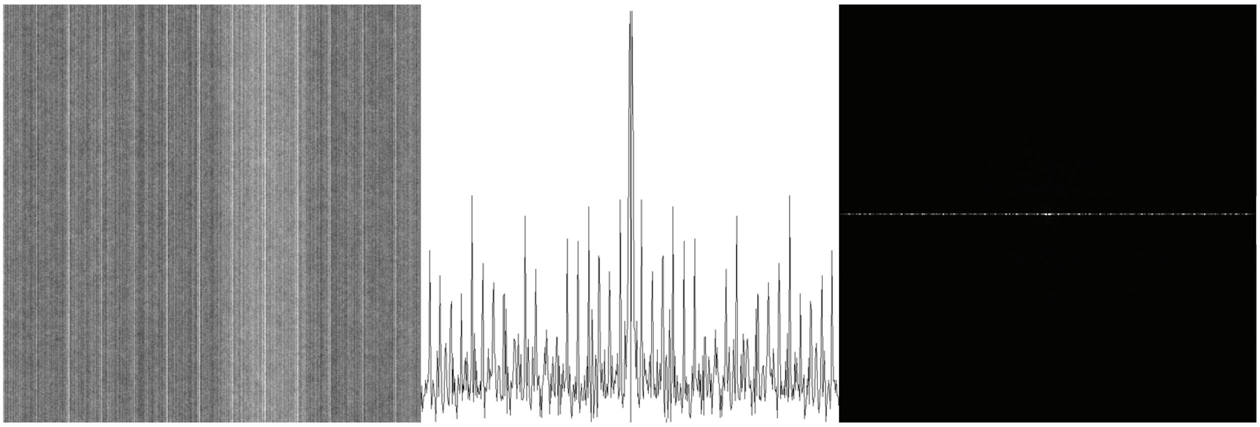

Figure 3.3.2. *Left– Example of Systematic Print Mottle (spatial domain). Centre – One Dimensional Power Spectrum (frequency domain, horizontal orientation) of the image to the left. The further away from the centre of the graph (the high peak in the middle of the graph), the higher is the frequency of that specific component. The magnitudes of the various components are the values of the y-coordinates in the graph. It is evident that the complex structure in the image is explained by a large number of components with various frequencies. Right – Two Dimensional Power Spectrum of the left-hand image (frequency domain). The distance from the centre of the right-hand image (the origin is marked as the white spot in the middle of the image) represents the frequency of each component. The direction (angle) from the x-axis represents the orientation of each component. The intensity (lightness) of the different positions in the right-hand image represents the square of the amplitude of the components at various frequencies and orientations. Notice that since the majority of the variation in the left-hand image is along the horizontal axis, most of the energy in the two-dimensional Power Spectrum is aligned along the x-axis (horizontal orientation, angle of zero degrees).*

A few other concepts and operations in the frequency domain are also useful. In many situations it is interesting to either examine or use signals above or below a certain frequency. To examine the frequencies above a certain frequency, the frequencies below this value are attenuated (more or less heavily) by what is called a *high-pass filter*, that is, a filter that allows frequencies above a certain value to pass through (hence the name high-pass).

By analogy, a *low-pass filter* attenuates frequencies above a certain level, and only allows frequencies below this level to pass through. If one combines a high-pass with a low-pass filter, one gets what is called a *band-pass filter*, i.e. a filter that only allow frequencies within a certain range to pass through, a pass band. The range of a band-pass filter, that is, the distance between the high-pass and the low-pass cut-off frequencies in the filter, is called the *bandwidth* of the filter. The different situations are further illustrated in Figure 3.3.3.

Fourier analysis is as mentioned very applicable, but it is also important to point out its limitations. What make Fourier analysis so useful are the linear operations applicable and its position invariance. If underlying assumptions of linearity and invariance not can be practically justified, use of Fourier analysis may very well lead to results that are inaccurate.

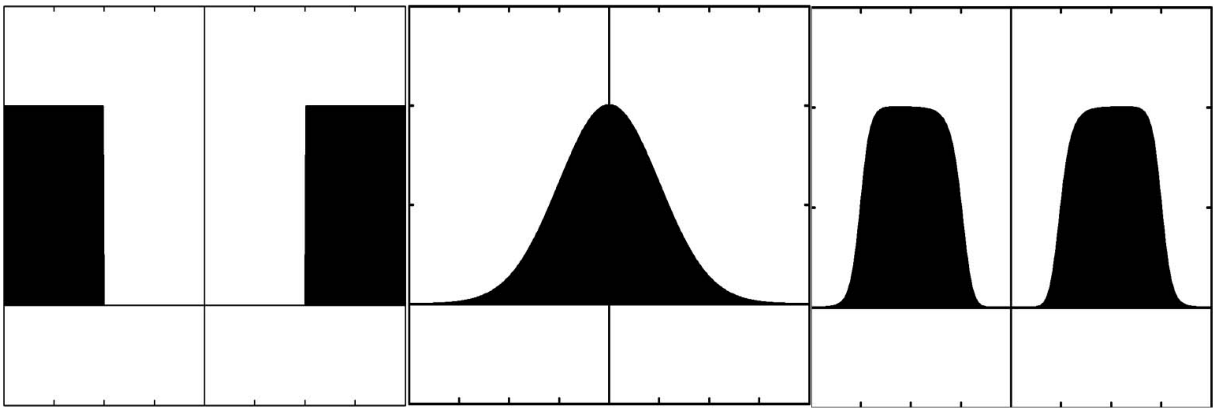

Figure 3.3.3. *Three types of one-dimensional frequency domain filters. The further away from the origin (cross) the higher is the frequency. Left – Ideal high-pass filter – Only the high frequencies are allowed to pass through the filter (black area), Centre – Gaussian low-pass Filter – Only low frequencies are primarily allowed to pass through the filter (black area), Butterworth band-pass filter – Only frequencies within a certain range are allowed to pass through the filter (black area). The bandwidth of the Butterworth filter is the width of the black hills in the graph. The three types of filters (or other combinations of Ideal, Gaussian and Butterworth filters) are all useful for various purposes in different circumstances (Gonzalez & Woods, 2002).*

3.4 Multidimensional Scaling

Things do not necessarily have to differ on a scale from good to bad; differences can for example, as with the colours in the visual spectrum, better be described by placing the items along a circle. In such cases ratings of the samples are of no value. What instead is required is an estimate of the inter-relationship between each sample, that is, an estimate of the similarity or dissimilarity among all samples.

There are several ways of doing this, but one popular way, partially because data can for example be collected with the subjective testing method of pairwise comparison, is Multidimensional Scaling. The idea is to ask each judge in the test panel to estimate the similarity (or dissimilarity) of each possible pair in the set of N samples. The average rating of all the judges for each similarity is then calculated and placed in an N x N proximity matrix.

By comparing the rated similarity between the pairs of samples in the proximity matrix with the distance between the samples in an $n < N$ dimensional space, an algorithm can be used to find the best fit minimizing the differences between the proximity matrix and the distances in the multidimensional space. When a best solution is found the researcher must from the final configuration find an appropriate set of orthogonal axes along which the samples are thought (or known) to vary.

The strength of multidimensional scaling methods is that they allow virtually any set of stimuli to be represented in a multidimensional space output. They are hence excellent alternatives to use in cases where other multidimensional methods may fail. There are however, as always, some limitations that it is important to keep in mind. The fact that the rotation of the axes in the final configuration must largely be done by hand makes it difficult, for practical reasons, to work with configurations in more than three dimensions. A more theoretical problem is the question as to whether human judgment of similarity is - like the distances in the multidimensional Euclidian output space - symmetrical, i.e. whether A must be just as similar to B as B is to A. In several situations, this has empirically been proven not to be the case.

To summarize, the multidimensional scaling methods are powerful and useful methods for the evaluation of samples that vary in a multitude of dimensions. It is however important that one initially has a fair grasp of what to look for before multidimensional scaling is applied, otherwise it may prove virtually impossible to interpret the output space in terms of stimuli. This is especially important if the samples vary in many different ways. The similarity objection is in cases of explorative research perhaps less important, but nevertheless it is always important to remember it, especially if the research is more towards the normative kind.

3.5 Texture Analysis

The need to take into account systematic print mottle makes texture a central issue in this thesis. This section aims to give a brief overview of texture analysis, and to relate the concepts used in the print mottle evaluation model to other approaches and findings in the field. It is written so as to be fairly independent of the material presented in the rest of the thesis, but at the same time it tries to explain why the particular approach to take into account the texture perception of print mottle suggested in Paper II was chosen.

Textures can be chiefly be divided into three classes: a) two-dimensional textures that are painted onto a surface, b) solid three-dimensional textures, for example carefully cut marble blocks with planar surfaces, and c) three-dimensional textures on materials with non-planar surfaces, for example fibre structures in paper and corrugated board. The methods of carrying out texture analysis described in Sections 3.5.1-3.5.4 generally assume class a), i.e. that the influence of the three-dimensional aspects of the texture are limited. Depending on the situation, these aspects must however be taken into account. As long as the printed surface can be assumed to be reasonable planar, print mottle can be treated as a two-dimensional texture, and this is done throughout this thesis. In other types of print and paper texture analysis, the assumption of a planar surface may however be completely inappropriate, and this may require a 3D model such as the ones presented in Section 3.5.5.

Texture, the feel, appearance, or consistency of a surface or a substance (Pearsall, 2001), is generally an important attribute in the fields of paper and printing. Understanding the textural components of the paper structure can be valuable not only to avoid problems linked to the mechanical properties of the paper but also to enhance the optical properties and visual appearance of the substrate. In printing, the interaction between the paper texture and the ink is crucial for the final printed result.

In paper, the formation, i.e. the local density and orientation of the fibres, strongly influences both the mechanical and the optical properties of the paper. Process-related marks in the paper web due to the wire, or stripes, harmonics, and banding phenomena due to imperfections in the movement of the web through the paper machine, can cause similar problems.

In the printing process, a texture pattern is created by the screening. The screen dot pattern of the print can vary in spacing (lines per inch), orientation (screen angle) and shape (e.g. round or diamond-shaped dots). The screening can be standard amplitude size modulated (AM), frequency distance modulated (FM), or hybrid involving a transition between the stochastic nature of the FM and the predetermined AM screening. Four-colour printing, i.e. the use of four colours with different screen angles, may give rise to a moiré pattern that can cause an undesirable visual appearance.

In the press, process-related problems, similar to those that occur in the papermaking process, can arise as a result of the interaction between web and rolls. Already in the Pre-press stage artefacts caused by improper treatment of the digital image may occur.

All these phenomena are in some way related to the concept of texture. The problem with texture is often that two repetitive patterns, interact in some undesirable way to cause a physical deficiency or an undesirable appearance (e.g. a systematic print mottle) in the paper or print.

Similar problems arise in many manufacturing processes and in many fields of engineering science. The area of texture analysis is vast, but the number of problems can however be narrowed down. Ehrich & Foith (1976) divide the task of texture analysis as follows:

1. Given a textured region, determine to which of a finite number of classes the region belongs.
2. Given a textured region, determine a description or model for it.
3. Given an image having many textured areas, determine the boundaries between the differently textured regions.

In the context of paper and printing, the relative importance of these issues is mainly in the order given, 1) detection and characterization are the most important issues, 2) to be able to describe and understand the region is secondary, 3) since paper and prints are generally relatively homogeneous in character, segmentation will be the least important aspect. This does not mean that the latter is irrelevant – there are several situations where it is of interest to be able to separate regions in a paper web with different physical characters, for example web borders from the middle section of the web.

3.5.1 Detection and Characterization

The textural character of an image depends on the spatial size of the texture primitives. Large primitives give rise to coarse texture and tiny primitives give a fine texture. To characterize texture we must typify the primitive grey level properties and the spatial relationship between them. Texture can thus be seen as a two-layered structure. The first layer concerns the local properties that reveal themselves in the grey level primitives. The second layer concerns to the specification of the organization among the grey level primitives. Several methods have been developed for this purpose, and we shall briefly consider a number of them.

Co-occurrence approaches

Co-occurrence statistics based on the idea of building the distribution of the probabilities p_{ij} that two neighbouring pixels separated by a distance d and with grey levels i and j respectively occur in the image, has a long history in the context of texture analysis. Julesz (1962) used the approach in human visual texture discrimination experiments. Darling & Joseph (1968) used statistics obtained from nearest neighbouring grey level transition probabilities in satellite images, and Haralick, Shanmuga & Dinstein (1973) suggested the use of spatial co-occurrence in the analysis of photomicrographs, aerial photographs and satellite images. Several features can be derived from the co-occurrence probabilities, e.g., a) uniformity of energy, b) entropy, c) maximum probability, d) contrast, e) inverse difference moment, f) correlation, g) probabilities of run-length, h) homogeneity, and i) cluster tendency.

The power of the grey level co-occurrence approach is that it characterizes the spatial interrelationship of the grey levels in a textural pattern and it can do so in a way that is invariant under monotonic grey level transformations. One of its weaknesses is that it does not capture the shape aspects of the grey level primitives. Hence it is not likely to work well for textures composed of large-area primitives. Also, it cannot immediately capture the spatial relationship between primitives that cover regions larger than a pixel (Haralick & Shapiro, 1991); in such a case a multi-resolution approach is required.

Cresson & Luner (1990 I; 1990 II; 1991) use spatial grey level dependence to characterise paper formation, based on beta-radiography maps of basis weight. The Co-occurrence approach can indeed be useful in many areas of the paper and printing context but, as Nguyen

& Jordan (1989) point out, the need to generate matrices for a multitude of separation vectors is slow and less practical than transform methods.

Auto-Correlation

An important feature of paper and printing texture is the spatial size of the grey level primitives, its so-called coarseness. A straightforward approach to describe the size of the grey level primitives is to use the standard autocorrelation function (ACF). In addition, if the primitives in the image are placed in a regular manner, the ACF will fall off and then rise again in a periodic way. As both coarseness and periodic structures (e.g. wave patterns in corrugated board) are important features of paper and printing textures, the autocorrelation concept is extremely important. The relationship between the ACF and the power spectral density function, being Fourier transforms of each other, means however that the ACF is less frequently used today since the Fast Fourier Transform (FFT) is ready available on any computer.

Transform Methods

The digital transform method of texture analysis is based on the idea that the digital N x N pixel image can be divided into a set of smaller, non-overlapping, square n x n sub-images. The n^2 grey levels in the sub image can be thought of as a number of directions with certain lengths in an n^2-dimensional space, i.e. as an n^2-dimensional vector. What the transform then does is that it transforms these sub-image vectors into a new coordinate system. The most commonly used transform is the standard, discrete Fourier transform, implemented by the FFT. During the last decade other transform methods based on the Wavelet idea (Daubechies, 1992) have been introduced.

The advantages of the global FFT are that it is easily available, fast, and, due to the power spectral density function's duality with the ACF, intuitively appealing to use. Its global character makes it suitable in cases where texture has a homogeneous character throughout the image, i.e. when primitives come in a regular manner. In cases where the texture is more random in character, or merely locally periodic, the global character of the transform makes it less attractive for texture recognition and classification. Features such as coarseness, directionality, and isotropy are in this case still available for a general characterization but, for classification purposes, the approach is less suitable.

The FFT is regularly used in paper and printing applications, often to detect periodic structure such as the waviness in corrugated board (Hallberg, Glasenapp, & Lestelius, 2004) or to estimate uniformity in paper and prints (Barros & Johansson, 2005). Wavelet-approaches have been used for similar purposes (Johansson, 1993), but few attempts have been made to use this approach to classify paper and print textures.

In this thesis, the FFT is used to transform the digital image of the print into frequency components. The approach is particularly useful since the perception of print mottle is very dependent on spatial frequency, and since it is generally fair to assume that the variation is distributed over the whole area of the print, i.e. has a global character. The use of the FFT allows straightforward implementation of the filtering operations that are carried out to emulate the human visual system's sensitivity to intensity variations of different types.

In a comparative study, Randen & Husöy (1999) compare several filtering approaches for texture feature extraction (classification), including several transform methods, Laws masks, ring/wedge filters, dyadic Gabor filter banks, wavelet transforms, wavelet packages, quadrature mirror filters, discrete cosine transform, eigenfilters, optimised Gabor filters, linear predictors, and optimised finite impulse response filters. They compute features as the local energy of the filter responses. For reference, comparisons with two classical non-filtering approaches, co-occurrence and autoregressive-based features, are given. Their results demonstrate that different approaches clearly yield different classification performance for different types of images, and that no single approach on an overall scale outperforms the others. The choice of approach is clearly dependent on the task.

Local Binary Patterns

Randen & Husöy (1999) also conclude that the degree of computational complexity of many filtering approaches is often very high. Some of the transform methods, such as the discrete cosine transform, may therefore due to their simplicity be very advantageous when computational speed is an issue.

Another simple but efficient approach is the multi-resolution grey-scale and rotational invariant texture classification with Local Binary Patterns approach of Ojala, Pietikäinen & Mäenpää (2002). The straightforward idea is to compare the grey-levels on a circle with radius R in a local neighbourhood around a mid-position to the centre grey level value C. The method simply considers the sign of the difference between the radius values and the centre value, hence the label: “binary” pattern. Despite the small spatial support of the method compared to many larger filters frequently used (e.g. some of those examined by Randen & Husöy, 1999), the authors claim excellent classification ability.

Recently, the approach has been successfully used to characterize paper texture, outperforming previous approaches in the field (Turtinen et. al., 2003; Turtinen, Mäenpää & Pietikäinen, 2003). It should however be noted that the other approaches considered in the comparison did not include to the most modern group of classifiers. It would therefore be of interest to compare it with some of the contemporary approaches described by for example Randen & Husöy (1999). In addition, application may be favourable only in those situations where rotational invariance is an advantage, i.e. when directionality is not a chief trait of the papers or prints.

Textural Energy

The Textural energy approach, or Law’s masks (Laws, 1980), is related to the transform approach but it generally uses smaller windows. First the image is convolved with a variety of kernels. Then each convolved image is processed with a non-linear operator to determine the total energy in the neighbourhood of each pixel. Laws (1980) showed that the approach performs significantly better than the basic grey-level co-occurrence approach. The greatest difficulty with the approach is that errors are introduced along boundaries between different textures. Extended approaches to avoid this deficiency have been made by introducing an additional step that better accounts for the boundaries (Hsiao & Sawchuk, 1989).

Similar approaches may be taken in the frequency domain. Jernigan & D’Astous (1984) compute the FFT on windows and then use the entropy in different-sized regions for the normalized power spectrum for textural features. Nguyen & Jordan (1989) apply this approach to prints and paper. In Papers II and VI of this thesis, we successfully use normalised entropy or Chi-Square measures in local regions of the FFT to filter in order to amplify the impact of systematic disturbances in prints compared to that of random noise.

Vector Dispersion
In this approach, the image texture is divided into mutually exclusive neighbourhoods, and a sloped plane fit is performed for each neighbourhood (Harris & Barrett, 1978; Fisher, 1953). A texture roughness measure is then calculated based on the variation of the unit normal vectors of the neighbourhood.

This elegant technique could be useful within the area of printing and paper, especially when the topography of the surface is important. Lindstrand (2002), for example, uses a related method, reflection vector maps, to characterize print gloss.

Morphology
Mathematical morphology can also be used for texture analysis. The granularity of an image can for example be estimated by using the opening operation on a binary image,

$$G(d) = 1 - \#F \circ H_d / \#F,$$

where #F is the number of elements in the image F ,$\circ$ the opening operation, and H_d a structuring element of length d. In this case $G(d)$ measures the proportion of pixels participating in grains of a size smaller than d.

Standard morphological operations are limited to binary images, which implies thresholding of an original intensity image. Sternberg & Sternberg (1983) however extended the morphological definition to grey level images. The importance of the morphological approach to texture analysis is that properties obtained by the application of operators can be related to physical three-dimensional shape properties of the material imaged (Haralick & Shapiro, 1991), including printing and paper textures.

3.5.2 Modelling

In addition to the need to be able to detect and characterize texture, the ability to model texture is of concern, especially if the desire is to create artificial patterns with characters similar to those of real prints or papers. A second reason why modelling of texture is interesting is that the ability to model texture is valuable from the perspective of classification and understanding of the visual perception of texture.

Auto-Regression Models
By exploiting the *linear* dependence that one pixel of an image has on another pixel, an autoregressive model for texture has been suggested (McCormick & Jayaramamurthy, 1974). The power of the auto-regression approach is that it is easy to use the estimator in a mode that synthesizes textures from any initially given linear estimator. Its main weakness is that the textures which the model can characterize are likely to consist mostly of micro-textures (Haralick & Shapiro, 1991).

Markov-Random Fields
A generalized approach similar to the Auto-Regressive Moving-Average concept is the idea of using Random Fields. The concept of Random Fields is however too general to admit an efficient description (Hassner & Sklansky, 1980), and it is thus more common to restrict it to stationary fields with the Markov property. Compared to the auto-regressive approach a Markov random field (MRF) defines a competent and potent framework for specifying *non-linear* interactions between features of the same or different nature.

Whereas Hassner & Sklansky (1980) consider synthetic examples, Cross & Jain (1983) examine real textures using MRFs with binomial conditional probabilities as a texture model. Overall, microtextures fit the model of Cross & Jain (1983) well. The synthetic *micro-textures* closely resemble their real counterparts, while the *regular and inhomogeneous* textures such as paper, wood and pebbles, do not. This casts doubt on the straightforward use of MRFs to model paper or print textures.

Structural Approaches
In contrast to the random approaches, the structural approach is based on the idea that textures are made up of primitives appearing in a practically regular repetitive manner. To describe the texture, we must describe the primitives and their spacing. In the printing and paper context, this approach is straightforward if we are to model repetitive patterns such as screening or wire marks.

Towards a Unified Theory for Texture Modelling
Zhu, Wu, & Mumford (1998) present a statistical theory for texture modelling. The theory combines a filtering stage and MRF modelling through the maximum entropy principle. The resulting model FRAME (Filters, Random Fields and Maximum Entropy) is an enhanced MRF model with a better descriptive ability than previous MRF models. The approach seems to be very promising in cases where texture has a random character. In cases where texture presents a more structural character, the results are still somewhat limited, although they are much better than those obtained by previous MRF modelling. The applicability to paper and printing may therefore be expected to be good in cases where texture is random in character; i.e. paper formation and print mottle can probably be modelled well, whereas the model may apply less well on highly structural elements such as gravure screening.

The models used to simulate various characters of print mottle in the papers presented in this thesis are generally more straightforward than the models suggested here. To simulate random mottle, we use low-pass filtered Gaussian noise to give it the low frequency character evident in prints. Systematic disturbances have been generated by repetitive patterns of different character (i.e. structural approaches) or by one-dimensional random walks. The patterns are described in detail in Paper III.

3.5.3 Texture Perception

Parallel to the development of machine vision texture analysis, the understanding of human texture perception has also been explored, and, since human texture perception still generally outperforms the most sophisticated machine approaches, nearly all ideas on how to improve machine texture analysis originate from human perception.

Serious studies of human texture perception were first made by the Gestalt psychologists in the early 20th century (Wertheimer, 1922; 1923). Julesz (1962) carried out pioneering visual pattern discrimination experiments on a computer screen, and already here suggested the embryo to the concept of Textons.

On the physiological side, much of the findings based on psychophysics were confirmed but also revised by the findings of Hubel & Wiesel (1959; 1968). They were the first to successfully apply the receptive field mapping techniques pioneered by Kuffler (1953) and Barlow (1953) to the striate cortex. Of primary importance here are the findings of a) Simple cells that respond to swift spatial changes in luminance, i.e. edge, line or bar detectors, and b)

Hyper-complex, end-stop simple, cells that respond less to a line or edge that is extended beyond a certain length than to a shorter line or edge.

Based on these findings and further psychophysical experiments, Julesz (1981) presented a texture perception theory. Findings suggest that pre-attentive texture discrimination cannot globally process third- and higher-order statistics. The central concept in his theory is the Texton, a local feature element with distinctive line terminators, connectivity and closure properties. Julesz suggests that only first-order statistics of these textons have perceptual significance, and that no relative phase between the textons can be perceived without detailed inspection by focal attention.

The findings that second-order statistics per se are of limited importance to human texture perception cast serious doubt on the usefulness of Fourier decompositions to describe supra-threshold visual-texture perception (Julesz & Caelli, 1979). This is of particular interest here, since autocorrelation-related approaches are frequently used in the paper and printing field.

The results must however be interpreted depending on the context within which they are applied. Several workers, for example, Jernigan & D´Astous (1984), reported positive results using Fourier-related approaches. As in so many other cases, the applicability of Fourier approaches must be judged in relation to the task at hand. If the task is to model human visual texture discrimination ability, the results presented by Julesz (1981, Figure 7b, for example), vividly demonstrate the limitations of using approaches based on second-order statistics. In many other situations, however, these exceptions must be weighed against the convenience of applying a straightforward modelling approach based on Fourier decomposition. In the paper and printing field, the results of Julesz (1981, Figure 7) suggest, for example, that if highly repetitive patterns such as wire marks and screening are masked by random noise, such as mottle, Fourier-based methods should be applied with caution. It should in particular be recognized that the model presented in this thesis is based on Fourier decompositions, and that because of possible screening influence the model only slightly amplifies the impact of high frequency systematic variations compared to systematic variations of lower frequencies (eq. (12) Paper II; eq. (10), Paper VI).

Despite its overall success, there is still an argument concerning precise whereabouts of the texton elements as such or, as Li, Wang, & Shum, (2002) put it, the concept of texton was first proposed by Julesz some twenty years ago, although a clear definition is still in debate.

Based on the texton approach, Bergen & Landy (1991) outline a computational model of visual texture segregation. Generally, without entering into details, the model is very simple and straightforward in structure and it is designed to follow the main findings of Julesz and Hubel & Wiesel. The reasonable success of this simple model in predicting human performance is somewhat surprising, but it is also clear that improvements are necessary, especially concerning model parameters, before a generic model can be achieved.

Malik & Perona (1990) present a similar but rather more sophisticated approach; particularly in their way of modelling the non-linear properties thought to be involved. Their results are however somewhat more convincing than those of Bergen & Landy, at the expense of a more complex model. The authors claim that the explanatory power of their model suggests that many of the essential aspects of texture perception have been captured in their theory. This may be the case, but the causal link between texture perception and their model is still rather tentative, and it is conceivable that other, rather different, models could perform just as well.

It appears that much remains to be done before a corroborated model that truly describes the mechanisms involved in human texture perception will emerge.

3.5.4 Segmentation

Most work in image texture analysis concerns the global analysis of the entire image. This is quite natural since it is often perfectly reasonable to assume that the texture of, for example, an image of a material such as paper is the same throughout the whole image. In many other cases however, finding such a difference in texture may be the chief task, e.g. as a means of extracting an object from a background.

Image segmentation techniques can be classified into two broad families, a) region-based, and b) contour-based approaches. Region-based approaches try to find partitions of the image pixels into sets corresponding to coherent image properties such as brightness, colour and texture (Malik et. al, 2001).

Early techniques, in both contour-based and region-based frameworks, made local decisions, whereas later frameworks on region-based approaches, MRFs and onward (Geman & Geman, 1984), are often based on global objective functions. The advantage of having a global objective function, rather than using local decisions, is that decisions are then made only when information from the whole image is considered at the same time.

Malik et. al. (2001) successfully combine contour analysis with texture analysis based on textons in image segmentation. In some cases, the results correspond well with the segmentation expected to be made by a human observer. If colour information could be better considered in this kind of approach, the performance would probably be even more impressive. Mossfeldt & Tillander (2005) successfully applied the method of Principal Component Hue (Ranefall, Östlund & Bengtsson, 1998) to define areas of interests for the analysis of eye-tracking data. Combining the method of Malik et. al. with this kind of technique would probably lead to a powerful approach whenever colour information is available.

Throughout this thesis, print mottle is assumed to be homogeneously distributed over the whole sample. This is not however necessarily the case. The reflectance variations can in particular cases be clustered in one or several parts of the sample, which would probably mean that the visual appearance of the mottle would be worse than if the distribution were uniform. A feasible way to identify these mottle areas and subsequently account for the impact of the clustering on visual appearance could be to use segmentation methods to identify mottle clustering tendencies.

3.5.5 3D Texture

Traditional texture analysis is based on 2D representations of 3D physical objects, e.g. materials such as paper or prints. It is well known that the reason why humans are able to create a proper 3D understanding of the surrounding environment is that the visual system uses a vast number of visual cues to back up the 2D spatial information on the retina. Many of these cues are linked to the fact that the 2D images on the retina are slightly displaced for several reasons such as binocular vision, eye-movements etc. Illumination conditions in reality also present strong cues such as shape-from-shading direction (Palmer, 1999).

Recent approaches to texture analysis have therefore moved towards models that attempt to incorporate information similar to that coming from the cues used by the visual system. The most straightforward approach is to use several images of the object, taken from different angles and with the incoming light illuminating the object from different angles.

Leung & Malik (2001) extend the concept of 2D textons to 3D by representing images with varying lighting and viewing conditions. They study the recognition of surfaces from different materials, including rough paper. From a large collection of images of different materials they create a 3D texton vocabulary. Given a small number of images, typically 1 to 4 of each material, they are then able to characterize the material using the 3D texton vocabulary. A similar technique is successfully applied by, for example, Cula & Dana (2004). Generally the 3D approaches to texture classification can be said to outperform 2D analysis when texture has a clear 3D character.

Hanson & Johansson (1999) describe a photometric stereo method where light from two directions is used to acquire two images of the paper surface to determine the surface topography (shape-from-shading). The approach has been further developed by Barros & Johansson (2005).

3.5.6 Overview

The theories presented above are divided into five sections, a) detection and characterization, b) modelling, c) texture perception, d) segmentation, and e) 3D texture. This division should not however be seen as five separate areas, but rather as five heavily overlapping regions. Most of the approaches presented actually either originate or have straightforward applications in some of the other areas.

The history of texture analysis as such is strongly coupled to the development of computers. It chiefly took off in the early sixties when computers were a novelty, and grew more and more sophisticated as the computational power of readily available computers evolved. Texture analysis is today therefore a wide research area with applications in a variety of fields, paper and printing being merely two of them.

The development of computational capacity has been influential not only in the area of texture analysis but also in the whole fields of computer science, numerical analysis and neuro-physiology. Most approaches, whether they are the core element or act as a support in the approaches of texture analysis originate in one or several of these related fields. Examples of such methods are Monte Carlo simulations and neural networks. The development of texture analysis is therefore intimately related to the overall advancement in the field of computer science. All considered this has led to an impressive development of the models that are presently available for texture analysis.

It is nonetheless important to remember that more sophisticated models do not necessarily mean a better performance. Randen & Husöy (1999) vividly demonstrate this in their comparative study of filtering approaches. The fact that filters such as the discrete cosine transform, despite their conceptual intuitivism and computational simplicity, sometimes outperforms much more intricate filters should act as a warning towards modelling-fetishism; Occam’s razor still seems to apply.

The lack of performing approaches does not necessarily mean that more complex models must be developed. On the contrary, the general trend seems to be that models that can be thought of as being a combination of several primitive approaches are more successful than one-stage approaches that are complex by origin. Examples of this are the Modelling approach FRAME of Zhu, Wu, & Mumford (1998), the texture perception model of Bergen & Landy (1991), image segmentation of Malik et. al. (2001), and 3D texture of Leung & Malik (2001). This is not however very surprising. By applying comparably simple, *separable*, stages in the models, the approaches become not only intuitively more comprehensible but also reasonable to test empirically. Intrinsically complex models are not only more difficult to overview but also practically much more demanding to corroborate empirically, since the number of degrees of freedom involved tends to explode. The work presented in this thesis is to a large extent based on similar judgments.

3.6 Inhomogeneities in Prints and Paper

This section considers the relationship between print mottle and other inhomogeneities in printed and unprinted papers.

3.6.1 Definitions

Optical Properties
The optical properties of paper and prints refer to their mode of interactions with light; how the light is reflected, scattered, and absorbed in the paper or print.

Mechanical Properties
The mechanical properties of unprinted and printed paper refer to the strength and stiffness of the paper, its capability to handle stresses by strain and compression.

Printability
The printability of paper is the combination of paper-related factors that contribute to the achievement of a desired quality level (Oittinen & Saarelma, 1998). Printability parameters are measured as optical, surface, structural and mechanical properties. Some of the printability parameters refer to inhomogeneities in the optical and mechanical properties.

Optical Inhomogeneities
Optical inhomogeneities are spatial variations of the optical properties in the printed or unprinted paper. The most obvious form of optical inhomogeneity stems from variations in light absorption over the printed surface. This is seen as print mottle in diffuse or directed illumination or as gloss variation in specular viewing (Johansson, 1993).

Mechanical Inhomogeneities
Mechanical inhomogeneities are spatial variations in the mechanical properties. It is possible that the methodology presented in this thesis may in a general sense be applicable also to mechanical inhomogeneities but, since the approach taken here is based on the capabilities of the HVS, which not are of concern in the case of mechanical inhomogeneities, the applicability must be assumed to be very limited. We shall thus in 3.6.2 only consider optical inhomogeneities.

3.6.2. Relationship to other optical inhomogeneities in paper and prints

Depending on the illumination conditions and whether the paper is printed or unprinted, other inhomogeneities related to print mottle may occur. Of these, the one that may be regarded as the closest relative to print mottle is paper mottle, i.e. variations in light absorption over the *unprinted* surface seen in diffuse or directed illumination, but not at the specular angle where gloss effects dominate. The most commonly measured form of mottle in the unprinted paper is probably white top mottle, i.e. mottle in paperboard having a bright layer on top of a darker middle layer.

The most obvious difference between print mottle and white top mottle is that, whereas print mottle is generally measured in half-tone black or full-tone cyan prints with a low to medium mean reflectance factor level (10-50%), white top mottle is measured in white paperboard with a high mean reflectance factor level (85-95%). The fact that the perceived magnitude of lightness according to the CIELAB metric is proportional to the cubic root of the luminance factor level implies that the perceived lightness level difference between different samples of unprinted white top paperboard is generally insignificant. The importance of the mean reflectance factor normalization examined in Paper I is hence small. The other features of print mottle considered in this thesis, the amplitude of the variation, the coarseness of the variation, the textural character and to some extent chromatic variations, are however also important in the case of white top mottle. Differences in coarseness of the variation and artefacts such as streaking may occur as white top variations, depending on e.g. the coating technique that has been applied. Chromatic variations are hopefully less frequent but could theoretically occur. An inhomogeneity in the distribution of e.g. fluorescent whitening agents may under some illumination conditions create phenomena closely related to colour variations, and since the lightness level is very high and the surface almost homogeneous in lightness level, colour variations in these cases can probably be very close to purely light blue – light yellow in character. Overall, it is thus quite reasonable to assume that the facets of mottle considered in this thesis are also applicable in the case of white top mottle.

Together with variations in the light flux diffusely reflected from printed or unprinted paper surfaces, paper formation is probably the inhomogeneity in paper that has been investigated most thoroughly, which is not surprising since it generally has such a huge impact on the final quality of the print. Paper formation can be defined as spatial variations in the grammage of the paper.

Traditionally, formation has been evaluated by beta-radiographic recordings (Johansson & Norman, 1996). The evaluation procedure is analogous to the method presented in Paper VII for instrumental print mottle evaluation, except that longer wavelengths are emphasised by increasing the bandwidth in proportion to the wavelength, hence achieving a number of steps with a constant logarithmic increase in band width; an operation very similar to the logarithmic integration proposed in the print mottle evaluation model presented in this thesis. The findings concerning print mottle presented here are, except for the colour variations, thus presumably also useful for the evaluation of paper formation. The optical evaluation of formation is sometimes seen as an alternative to beta-radiographic recordings. Here a flat bed scanner is used but the data acquisition is based on light transmitted through rather than reflected from the paper. The value of optical formation analysis is however limited, since it is related to the visual character rather than to the physical structure of the sheet.

If a printed sample is viewed so that specular reflections become visible, gloss mottle may appear. Gloss is a very complex concept, both physically and visually. The angle of the maximum magnitude of the reflected light (the peak angle) is for example generally not quite equal to the specular angle. The directed reflectance may be considerably lower at the specular angle than at the peak angle, which is sometimes as much as 5-10 degrees from the specular angle (Lindstrand, 2002). In the present work, we have seen that the physical magnitude of non-specular spatial reflectance variations in prints, i.e. density mottle, is visually not considered to be a one-dimensional metric of non-print quality. A similar statement can to an even greater extent be said to hold regarding gloss and gloss variations. Visually perceived gloss quality is indeed a multidimensional concept.

Attempts to evaluate gloss and gloss variation have nevertheless been made on both unprinted, and printed, paper surfaces. MacGregor & Johansson (1991) use the coefficient of variation of the specular light reflection to estimate the gloss mottle in prints. The method of evaluation is identical to the one presented for print density mottle in Paper VII, with the important distinction that a different range of wavelengths was found to correspond to subjective gloss quality; 0.4-3.2mm compared to the 1-8mm in the case of print density mottle.

Despite the differences and complex concepts of gloss variation and gloss quality in general, it is reasonable to assume that some of the findings presented in this thesis may find also application regarding gloss. It is at the same time important to emphasis that there are indeed huge differences between print density mottle and gloss mottle. Print gloss variation is generally evaluated in black surfaces, a situation where the level of reflected light may differ dramatically, from highlight glare to very dark, from one spatial location to another, i.e. the gloss contrast differences are in general considerably larger than in print density mottle.

Another case of dramatic spatial differences in the level of reflected light is when a solid tone printed surface, intended to be homogeneous in print density, completely lacks ink in some spatial positions. These regions of exposed substrate are generally referred to as Uncovered areas. If the intended colour is dark and the substrate is white, the differences in magnitude of reflected light between the areas that are covered with ink and those that are not would resemble the case of gloss mottle. Since the contrast is higher in the case of uncovered areas than in the case of ordinary print density mottle and since the perceived variations are thus further above the threshold of detection, spatial variations with shorter wavelengths than in the case of print mottle will visually contribute to the perceived impression of non-print quality.

Uncovered area is hence often evaluated differently from print mottle. Barros, Fahlcrantz & Johansson (2005) obtained excellent correlation between the simple instrumentally measured percentage uncovered area and the visually estimated percentage uncovered area in flexographic prints. A cumbersome predicament when uncovered regions are visible is if and where to draw the line between print mottle and uncovered area. It is evident that perceived contrast differs between typical print mottle and uncovered area, but when the density variations are a mixture of mottle and uncovered area the situation is less clear. In those cases, the instrumental evaluation may require that print mottle and uncovered area are evaluated separately.

A related phenomenon is missing dots occurring in halftone prints. If one, or more, of the halftone dots are not transferred to the substrate surface during printing, the final print will include outstanding bright dots similar to the uncovered areas in full-tone prints. Since half-tone prints are generally lighter than full tone prints, the contrast is however lower and hence the effect less detrimental. Instrumental evaluation is often made as in the case of uncovered area, as an estimation of the percentage of missing dots.

ISO 13660:2001 distinguishes two types of print noise: Graininess - aperiodic fluctuations of density at a spatial frequency greater than 0.4 cycles per millimetre in all directions; and Mottle - aperiodic fluctuations of density at a spatial frequency of less than 0.4 cycles per millimetre in all directions corresponding to a wavelength of 2.5 mm. The model for predicting the visual assessment of print mottle presented in this thesis does not make such a distinction. The impact of high frequency variations on the predicted visual assessment is however attenuated considerably in the model. This may give the false impression that it is assumed that high frequency spatial variations are insignificant for print quality. This is not the case. The correct interpretation is that it is assumed that high frequency spatial variations are insignificant for perceived *mottle*, not for perceived print *quality*. Print quality is often greatly influenced by high frequency print noise because, whereas print mottle leads to a deterioration in the interpretation of the information content in image areas with a low to moderate original contrast, graininess is unfavourable for the perception of image information in areas with a high contrast, e.g. in areas that contain edges. Print sharpness, and especially edge sharpness, can thus be expected to be greatly influenced by high frequency print noise.

3.7 A short overview of the causes of print mottle

Although the opposite is sometimes claimed, mottle will *physically* always be present in a print. The reflectance inhomogeneities creating print mottle are caused by the inevitable fact that the amount of ink that is transferred to the substrate during printing will always vary to some extent. The variation may be low, but it will nevertheless always exist. Visually however it may be possible to eliminate it. If the print density variations are reduced below the threshold of detection, they will no longer be visually present. The ultimate reason why we evaluate print mottle is, of course, to remove it. This however requires an understanding of why it occurs.

This section gives a brief introduction to the causes of print mottle by presenting some examples where mottle can occur when ink is applied to a substrate under some particular conditions. It does not enter into any detail, but attempts to exemplify how the different components involved in the printing chain, alone or by interaction, can cause print mottle. Since printing is an interaction between three main components, substrate, ink and press, the causes of mottle can be related to properties of the substrate or of ink or to the press, or to some interaction between the three components:

1. Interaction between press and ink
2. Interaction between press and substrate
3. Interaction between substrate and ink
4. Interaction between substrate, ink and press

The discussion is from the point of print mottle, but since many attributes other than the absence of print mottle are necessary to produce a pleasant print, other aspects are mentioned here to explain why some ways of reducing the amount of mottle in the print may not be feasible is practice.

In many of the cases where print mottle may be of concern for the quality of the printed product, the substrate is a combination of a base paper and a coating layer. The properties of the substrate will therefore be dealt with in two sections, the first considering the base paper, and the second the coating layer.

3.7.1 Print Mottle caused by inhomogeneities in the base paper formation

Paper is a general label for materials manufactured in comparatively thin sheets from fibrous substances, mainly from wood pulp. Compared to many other non-fibrous materials, the main building blocks, the fibres, are relatively large. The way in which the fibres are bonded during the papermaking process results in a structure with a typical distribution and orientation of the fibres. If there are large spatial inhomogeneities in the structure, the reflectance properties of different spatial positions of the sheet after printing will vary. The variation can be caused by an inhomogeneous distribution of ink and ink penetration and/or by the fact that the background of the ink varies in thickness and/or lightness. Visually this inhomogeneity may be perceived as print mottle.

Johansson & Norman (1996) suggested that paper formation should be evaluated by the coefficient of variation, i.e. as the percentage grammage variation divided by the mean grammage. This means that formation is more severe if the grammage is low as in newsprint than if the grammage is high as in paperboard.

A paper that is rough, i.e. has large topographical variations can be made smoother by calendering; a finishing process by which paper, plastics, rubber and textiles are smoothed, glazed, polished, or given embossed surface. The material is passed through a series of rollers, and the resulting surface depends on the pressure exerted by the rollers, on their temperature, composition, and surface designs, and on the type of coating previously applied to the material to be calendered (Columbia Encyclopedia, 2005).

Calendering of a rough base paper will not however necessary lead to a lower level of print mottle. Since, while the topographical differences in the paper may be smoothen out in the calendering process, the local mass density variations will increase, i.e. the formation is not necessarily reduced, and the local variations in absorption characteristics can increase.

3.7.2 Print Mottle caused by inhomogeneities in the coating layer

The most straightforward way to improve the optical properties of a surface is to apply a makeup, and paper is no exception. The coating of paper is in fact nothing less than applying a base makeup that consists mainly of pigments and binders, to increase the light scattering of the surface and to fill in the macro-structure deficiencies. In addition to smoothening the surface, the coating typically gives: a) a more homogeneous ink absorption that decreases mottle, b) a higher opacity that reduces the risk of print through, and c) an enhancement of the paper brightness and gloss level.

Unfortunately coating is no guarantee that print mottle will be avoided. If, for example, the coating layer is applied with a blade, so-called “blade coating”, the coated surface will be smoother than the base paper. The amount of spatially distributed coating will however be inhomogeneous to compensate for topographical variations in the base paper. This may lead to an inhomogeneity in the optical properties of the surface and, compared to the base paper, a reduced but still significant variation in the absorption properties of the coated surface. Hence, print mottle may nevertheless occur.

In contrast, spray or airbrush coating applies a more evenly distributed contour coating on the surface, avoiding inhomogeneities in optical properties and absorption due to variations in the coating layer. In this case, however the macro-roughness may still be on the same scale as in the base paper and mottle may therefore occur here also, due to uneven ink transfer to the substrate during printing. To minimize mottle, a proper combination of base paper, coating composition and coating technique must be matched with the intended technique for applying the ink to the substrate, i.e. with the intended printing process.

3.7.3 Print Mottle caused by inhomogeneities in the ink

Compared to the surface, fluid ink can generally be considered to be homogeneous. Any heterogeneity in concentrations of the ink ingredients does not generally apply at the spatial distances relevant for print mottle. If the ink is non-fluid, e.g. dry toner, other considerations may apply.

In offset printing, both ink and dampening solution are applied to the printing form in the lithographic process. However, if the ink is emulsified with an excess of dampening solution, small drops of dampening solution can cause white dots in the print and a general appearance of a pale print.

3.7.4 Print Mottle caused by imperfections in the printing form

If the printing form used to transfer the information to the substrate is deficient, disturbances in the print may occur. Deficiencies and limitations in the printing form can have different causes. Firstly, the digital prepress handling of the information, before it is transferred to the print form, may induce errors. Disturbing patterns may e.g. occur if the screening is created in a faulty way. Secondly, errors can present themselves when the screened image is transferred to the printing form, either because of direct transfer errors or because of limitations in the plates, gravure cylinder etc.

Some digital printing techniques such as ink-jet or xerography do not have a static physical printing form. The printing form is here created momentarily just before the ink is transferred to the substrate. The temporary character of these printing forms makes digital printing more vulnerable to artefacts in the printing form. Clogging of nozzles in inkjet heads may for instance lead to striped prints.

3.7.5 Print Mottle caused by imperfections in the press and pressroom

A four-colour printing press is a grand and complex device and there are thus many parts of it that can malfunction. Eventually many of the parts become worn out and require replacement. Things can get damaged due to the often demanding condition under which a printing press is operating etc. There are hence a myriad of potential imperfections in the press itself that can cause print mottle.

Next to the press itself, the way the press is run may lead to disturbances in the print, i.e. the human factor. Speed fluctuations in a web-offset press can e.g. create fluctuations in the draw that in turn cause misregister and fine-scale print noise. Humidity fluctuations in the pressroom can create shrinkage/expansion of the substrate that in turn can create similar artefacts etc.

3.7.6 Print mottle caused by interaction press-ink

Most printing techniques are based on the idea that the ink is first transferred to a printing form, such as a plate, before it is transferred to the substrate. There is thus an important phase where the press interacts with the ink to form the image to be printed. If an unintended pattern is produced already on the printing form, the final result will inevitably reveal mottle. Depending on the printing technique, different factors can cause this undesirable interaction.

In the offset press, the ink interacts with the press in several stages before it is finally transferred to the substrate. Firstly, the amount of ink that is to be transferred to the substrate in one revolution of the plate is regulated and limited by the ink knives. If the form demands more ink than is feasible, undesirable density variations will unavoidably reveal themselves in the print. A ghosting effect where homogeneous areas in the print reveal signs of other parts of the print form can sometimes be seen. The knives must thus be adjusted properly to distribute the ink suitably over the print form, and, perhaps even more important, the prepress job must be designed so that the different amounts of ink required in different parts of the print is practically feasible (Nordström, 1999).

Secondly, the dampening solution must be distributed correctly to ensure that the ink transfers only to the plate in those areas where it is intended. If the required amount of wetting agent, e.g. isopropyl alcohol, to ensure that the dampening solution forms a thin coverage of the plate is not met, the areas that are intended to be uncovered will attract ink. If the water is too hard and/or the pH-value is unfavourable, the dampening solution may dissolve pigments and a mottled toning effect may occur in the non-image areas of the final print.

Thirdly, the ink must be transferred correctly from the plate to the blanket. If the blanket's acceptance of ink is not homogeneous, e.g. due to build up of material from the paper, density variations in the print may occur. In addition, it is important that the blanket is undamaged; otherwise disturbances in the print may also present themselves.

In the gravure process, the ink is transferred directly from the printing form, the engraved cylinder, to the substrate. The ink must however first be correctly distributed in the cells of the cylinder. Not only must the cells be filled with the ink but, all the surplus ink must also be removed from the non-image parts of the cylinder. Gravure printing is intended for large volume printing, i.e. many copies. Eventually the doctor blade whose task it is to distribute the ink in the cells and remove the surplus ink from the cylinder may become worn. This can result in several undesirable artefacts. Firstly the surplus ink will not be totally removed from the cylinder, which may create streaks in the print at the position where the blade was damaged. Secondly, it can in turn damage the cylinder, and this may create similar or related disturbances in the final transfer of ink to substrate.

As in lithography, flexographic printing involves two steps of press-ink interaction before the final transfer to the substrate takes place. The low-viscosity flexographic ink must, as in the gravure case, first be distributed homogeneously in the cells of the anilox roller. If the doctor blade is damaged or worn out, surplus ink may however not be wiped off properly and this may cause inhomogeneities, similar to those in gravure, in the anilox distribution of ink. The ink is then transferred from the anilox roller to the printing form. In this step, the ink should be spatially equally transferred to all the parts of the form that are intended to bear ink, but only to those parts. If the ink film is uneven or if areas of the form that are not intended to carry ink do so, print noise will occur. It is thus important that speed, pressures, and surface properties of the anilox roller, ink and form are correctly matched.

In digital printing, the printing form is not pre-made; it is created *during* printing or it exists, as in ink-jet, only as a virtual concept. This puts high demands on the presses that are used because they must swiftly mimic the situation which, in the conventional printing techniques, can carefully be prepared *before* actual printing takes place. In the xerographic techniques, electrostatic forces are used to create the temporary printing form. It is hence crucial that the voltages that are applied are precise, and that they are not influenced by external electrostatic interactions. If for example, a voltage intended to be constant to create a printed area with equal density varies spatially, a mottled pattern will be produced.

3.7.7 Print mottle caused by press-ink-substrate interaction

Despite the fact that there are several components and interactions in the printing chain that can cause print mottle, the pivotal point is still when the ink is transferred from the press to the substrate. This because the substrate is normally the spatially most inhomogeneous component in the chain. Compared to the metal plate, the rubber blanket, steel cylinders, plastic forms etc., the substrate, chiefly paper, varies from grade to grade, roll to roll, and region to region. Pre-made printing form or not, all components are generally tailored to suit for the specific printing process, and their interactions are thus less likely to be the cause of artefacts than those where the substrate is involved. This does not however imply that the substrate itself is the faulty component. It is the *interaction* between press, ink and substrate that is crucial. The process where the press, ink and substrate interacts is also generally the most complex part of the printing chain and therefore probably the most difficult to understand.

In offset printing, for example, the rubber blanket transfers the ink to the substrate. When the ink interacts with the paper, the tack properties of the ink become very important. It is vital that the printing nip does not find it difficult to split and release ink to the substrate. Otherwise, small parts of the substrate can be detached from its surface and stick to the blanket. This will cause disturbances in the subsequent revolutions of the blanket. If, on the other hand, the binding capability is not sufficient, the ink will not bond to the paper as required, and density inhomogeneities will occur because of the variability in the substrate's capacity to attract the ink. This effect can be promoted by extensive wetting of the substrate in earlier printing nips. To minimize disturbances in the print, it is thus desirable to achieve a good split, a so-called 50/50 split, where about 50% of the ink on the blanket is transferred to the substrate. This can be obtained by running a sufficiently thick film of ink (Ryan, 2004). In general it can be said that the offset press-ink-substrate interface is a very complex interaction and that many factors influence the transfer of ink, i.e. a sufficiently thick film does not unfortunately always mean the same thing.

In gravure printing it is important that the ink is not too viscous to transfer properly from the cylinder to the substrate. In a multi-colour gravure press, the ink also needs to dry between the colour stations because gravure cannot print wet-on-wet. These two issues require liquid ink with a proper amount of toluene and sufficient hot air drying between the stations to avoid mottle problems.

The flexographic process also uses a low viscosity ink, but in contrast to gravure, the printing surfaces of the printing form are peaks covered with ink rather than cells filled with ink. The pressure between the form and the substrate is here very important. If the pressure is too low, the ink on the form may not reach to the bottom of the topographical valleys on the substrate, hence leaving uncovered areas in the print. If, on the other hand, the pressure is too high, the low viscosity flexographic ink will splash sideways off the elevated screen dots of the form, creating tone shifts and print mottle. The interaction in the printing nip is also greatly influenced by the speed of the press. To avoid density variations in flexographic prints it is thus imperative to maintain a proper combination of press speed, nip pressure, and ink properties.

3.7.8 Print mottle caused by post-press ink-substrate interaction

Unfortunately transferring the ink from the printing form to the paper in a proper manner is not sufficient. After transfer has been achieved, the ink must dry and fix to the substrate without causing spatial density variations. Components of the ink must penetrate the surface homogeneously without passing too far into the sheet and thus causing print-through and/or print-through mottle. In a multi-colour press it is important that the ink has set (increased its viscosity) sufficiently before the next printing station, and that the substrate has not been wetted too much by water, which can otherwise cause so-called trapping mottle. If the ink has not dried sufficiently before the finishing and folding operations take place, density variations can still be induced in the print. It is therefore important that short-term and long-term interactions between the substrate and the ink, both chemically and physically, are favourable.

To summarize, this section has, without entering deeply into any detail, given a very brief overview of causes of print mottle. It should therefore be clear that mottle and related density disturbances in the print can be caused by a myriad of factors. By analysing the character of the print mottle and matching it with previous knowledge of the results of unfavourable combinations or interactions of press, ink and substrate, it may nevertheless be possible to identify the cause of the problem.

4. Summary of the Papers

“Brakenbury: What, so brief? 2nd Murderer: ‘Tis better, sir, than to be tedious.”

William Shakespeare, 1564–1616, Richard III.

4.1 The influence of mean reflectance on perceived print mottle (Paper I)

This paper considers how to normalize an instrumental mottle estimate based on the variation in the print, due the fact that the perceived magnitude of a stimulus detected by the human visual system is not the same as its physical intensity. Classical psychophysics, based on Fechner’s law (Gescheider, 1997), suggests that the perceived magnitude should be proportional to the logarithm of the physical stimulus. If this is the case, the perceived variation of a stimulus should, through differentiation of Fechner’s law, be described as the physical variation of the stimulus divided by the mean level of the stimulus, i.e. as the relative measure, the Weber Fraction, of the stimulus.

The traditional STFI print mottle evaluation technique, calculating the Coefficient of Variation, by band-pass (1-8 mm) image analysis (Johansson, 1993), is based on this assumption. An estimate of the amount of mottle in the print is given by dividing the standard deviation of the reflectance factor by the mean reflectance factor level of the analyzed print.

This estimate works quite well as long as the difference in mean reflectance between the analyzed prints is moderate, but when the mean reflectance level differs greatly between different samples, instrumental evaluation correlates less well with visual evaluation of the same samples, suggesting that a more complex function of the mean reflectance factor level should be used as an appropriate normalization.

The paper examines several alternatives to the model derived from Weber’s Law. The first main alternative is based on psychophysical evidence that suggests that Weber’s Law does not hold for low stimulus values. Instead, models that normalize with respect to a combination of the mean level of the stimulus plus a correction factor seem to be a better choice. The second main alternative is based on the CIELAB color metric (Wyscecki & Stiles, 1982), which suggests that we should normalize by division with the mean reflectance factor level raised to a power of two thirds, rather than with the simple mean reflectance factor level. In addition to these main candidates, a large range of models combining various power functions of the stimulus with different correction factors were examined.

A set of 54 half-tone patches was, for the purpose of the evaluation, constructed by simulation. Random noise images with 6 different levels of noise and with 9 different mean reflectance factor levels, were created digitally and then filtered in the Fourier domain to produce a general appearance similar to the mottle occurring in conventional prints. The set was then printed on the same substrate with a high-resolution ink-jet printer and evaluated both visually and by the instrument.

Results suggest that several candidates for the normalization are possible, but that the original model using the simple mean reflectance factor level seems to be less appropriate. Instead, models with a lower power of the mean reflectance factor level appear to be more suitable. A model using the square root of the mean reflectance factor level, instead of the simple mean reflectance factor level, seems to be a good candidate for practical application, but a model based on the CIELAB color metric also seems plausible.

4.2 Evaluating Systematic Print Mottle (Paper II)

In this paper, a model of evaluating systematic print mottle with an instrument is proposed. A theoretical model based on psychophysical evidence is outlined, implemented and tested in two different evaluations. The human visual system is very good at recognizing patterns. This capacity to detect order and texture, is very important when we interpret our surrounding environment, but it unfortunately makes systematic noise much more vivid than random disturbances in prints.

Lately, the introduction of digital printing techniques has raised interest in the problem of stripes and patterns in prints. Digital printing is to a large extent based on discrete techniques such as LED-voltages and ink-jet heads; techniques that often lead to discrete disturbances. Typical examples of systematic print mottle are therefore gratings, bandings and streaks of various kinds, although more complex textures such as oriented stochastic noise may also be considered to belong to this type of mottle.

Another factor, often ignored in instrumental print mottle evaluation, is the contrast sensitivity of the Human Visual System. The fact that the detection ability of the HVS depends on the frequency contents of the perceived visual information (Barten, 1999) brings up the necessity to evaluate print mottle with this, otherwise often neglected, consideration in mind.

A new method, based on frequency analysis, which considers both contrast sensitivity and texture, is therefore proposed for the purpose of evaluating systematic print mottle. The idea is to construct an easily-implemented model, from which one single print mottle estimate can be extracted for straightforward use in the printing industry without neglecting recent research on the HVS.

The model is best explained as a four-step chain. First, a digital image of the print is acquired with a scanner (or a camera). The digital image is then transformed into the frequency domain with the Fourier Transform and the Power Spectrum is calculated. The Power Spectrum is thereafter first filtered with a mathematical approximation of the Contrast Sensitivity Function of the human eye (Jacobson, 1995) and then filtered a second time with a texture enhancement filter which is based on a local calculation of a Chi Square Measure (Jernigan & D’Astous, 1984; Liu & Jernigan, 1990; Nguyen & Jordan, 1989) in the Power Spectrum. The energy within the visually detectable area of this twice filtered Power Spectrum is then finally integrated to obtain a single print mottle estimate.

To test the model, printed samples from both a simulated set of prints with various degrees of systematic mottle and a second set of prints from various conventional presses (offset, flexography, digital liquid toner and dry toner; Eidenvall et al., 2001) were analysed visually, with the traditional STFI print mottle evaluation model, and with the new model.

The new model was found to be superior to the traditional STFI print mottle evaluation model when results from the two approaches were compared with the visual evaluation of the two sets of prints. The difference in performance of the two instrumental evaluations was especially clear when the mottle present in the prints had distinct textural characteristics, such as artefacts frequently occurring in digital prints.

4.3 Perceptual Assessment of Simulated Print Noise with Random and Periodic Structure (Paper III)

Whereas the second paper mainly describes the proposed method for evaluating systematic print mottle with an instrument, this third paper focuses more on visual evaluation. Three main issues are addressed, (a) how observers assess systematic noise compared to random noise of a similar rms magnitude, (b) how consistent such assessments are in general, and (c) the merit of direct magnitude scaling in two dimensions compared with the standard method of pairwise comparison. Because of the approach taken, the paper also addresses the problem of how to minimize the influence of external variables in print quality evaluation by using digital simulation.

A set of 12 digitally simulated samples with various amounts of stochastic and systematic noise were printed using a high quality ink-jet printer and evaluated by a panel of observers. Two different evaluation methods were used. The first evaluation method was a standard pairwise comparison where each of the 66 possible combinations of pairs was presented to the observer in a random order. For each pair, the observer was asked to rate (a) the dissimilarity between the samples, and (b) the degree to which one sample was preferred to the other. The results of the assessments were then analyzed by a multidimensional scaling technique (Ramsay, 1982). The second evaluation was carried out using a digitizing tablet. By positioning the 12 samples in both a horizontal and a vertical direction, the observers rated the two different aspects of the samples that, due to the digital simulation, were thought to influence the visual perception most, (a) the general “Perceived Noise Level”, and (b) the amount of “Perceived Order”.

The results show that different observers rate the samples in a very consistent way and that systematic noise is perceived to be more annoying than random noise of a similar magnitude (rms value). To address the merit of direct magnitude scaling in two dimensions as compared to the method of pairwise comparison, the results of the Multidimensional Scaling and of the two-dimensional rating obtained by the digitizing tablet were compared. The correlation between the distances of the samples in the two configurations was 0.85, which suggests that two-dimensional rating on a digitizing tablet is a viable method for grouping samples in a plane.

It is also interesting that the results demonstrate the potential value of using simulation techniques to evaluate the interaction between different aspects of a print quality parameter such as print mottle, or the interaction between different print quality parameters, by minimizing the influence of external sources of variation.

4.4 A Comparison of Different Print Mottle Evaluation Models (Paper IV)

Since, print mottle probably is among the most central aspects of general print quality, the ability to interpret print mottle with a reliable instrumental evaluation is important in most printing trials. Several models for evaluating print mottle instrumentally have therefore been introduced, and an ISO Standard for the evaluation of reflectance inhomogeneities in prints was recently published (ISO 13660:2001, Joint Technical Committee of ISO/IEC working in the general field of Information Technology). The theoretical foundation of this standard is not however entirely reassuring.

A number of other instrumental print mottle evaluation models flourish both in the research community and in the printing industry. These models are sometimes very similar, but they also often differ quite extensively from each other in principle, and this is probably one reason why there is little consensus as to how print mottle evaluation should be carried out. The fact that several of the models exist only as commercial software and are not always well documented in the literature merely enhances the mystification.

This paper attempts to illustrate, both by conceptual examination and by empirical comparison with visual assessment, the underlying reasons why a given print mottle evaluation model is successful or not. By carrying out this comparison for a number of different evaluation models, the paper also attempts to pin down what is important to consider when evaluating stochastic monochrome print mottle instrumentally and what is presumably less crucial.

Results suggest that the characteristics that unite the models which do correlate well, and in some cases very well, with visual assessment all consider three important aspects of stochastic monochrome print mottle: a) the magnitude of the variation, b) the coarseness of the variation, and c) the mean reflectance factor level of the print. Their degree of success depends chiefly on the way in which this is carried out. The opposite is true for the models that perform poorly, i.e. they all lack a proper consideration of at least one of these three important aspects. The ISO 13660 Mottle model performs well in this evaluation, but it is nevertheless outperformed by several other approaches. We therefore question whether an ISO standard on print mottle should really be based on a specific model such as the one specified in ISO 13660. A standard based on a rigorous visual assessment of artificially created mottle would perhaps serve a better purpose.

Technical models could then easily be assessed by their correlation with the results of this standard visual evaluation. This would not only promote the development towards better models for evaluating print mottle instrumentally; it would also make it much easier for the industry to choose which model to use. Whenever someone confronts the paper and printing industry with a new and presumably better model, this model could easily be appraised by assessing how well measurements correlate with the standard visual evaluation.

Agreement on the way to evaluate stochastic monochrome print mottle would be beneficial for everyone. If some kind of consensus could be achieved, we could more easily move on to the more cumbersome mottle problems of colour variation, systematic disturbances and local variations, which are all still much less explored.

4.5 Evaluating Colour Print Mottle (Paper V)

In this paper, we acknowledge the fact that the ability of the Human Visual System (HVS) to perceive colour makes its receptive not only to lightness variations but also to chromatic variations. The print mottle evaluation model presented in Paper II is therefore generalized to colour variations. We restrict the model to stochastic mottle and therefore detach the texture enhancement filter applied in Paper II but generalize the model to incorporate not only lightness variations but also chromatic variations, by carrying out the analysis in the CIELAB space. To be able to carry out the analysis not only in the L^* channel but also in the a^* and b^* channels, relative colour contrast sensitivity functions for the a^* and b^* channels are introduced. A single estimate of the colour mottle in a printed sample is obtained as the combined variation estimate from the L^*, a^* and b^* channels. To test the generalized colour mottle evaluation model, four separate evaluations were made. In each evaluation, the samples were evaluated visually, with the new colour version of the model, and with the grey-scale version.

The first of the evaluations, which considered a set of 29 simulated grey samples with colour mottle, illustrates the potential merits of using a colour mottle evaluation model instead of a grey-scale model. The correlation coefficient between visual assessment and instrument was 0.97. Of the samples, 14 were contaminated with variations solely in the a^* and b^* channels. These samples show a correlation coefficient of 0.06 with the grey scale version but 0.95 with the model that acknowledges colour variations.

The second evaluation considered 12 artificial samples created to emulate colour mottle in duplex solid tones. The correlation coefficients between visual assessment and instrument were in this case 0.98 for the colour mottle model and 0.70 for the grey-scale model. The results of these two evaluations suggest that the new colour mottle model is an important improvement if mottle is highly chromatic in character.

Both the third and fourth evaluations consider samples printed in real printing presses. The correlations between the visual assessment and the colour mottle and the grey-scale models were very similar. The immediate conclusion is that little is to be gained by using the colour mottle model rather than the grey-scale model for real prints. However, in both the third and the fourth evaluations, the correlation coefficient between the grey-scale model and the colour mottle model was virtually 1, i.e. although the samples in these two evaluations reveal chromatic variations, these variations correlate almost perfectly with the lightness variation in the samples. In such a case, the new colour version of the model can never outperform the grey-scale version.

If this explanation accounts for most printing situations and, based on the wide range of prints evaluated here there are good reasons to believe that this may be so, little will be gained by carrying out a colour print mottle evaluation. When human observers perceive large-scale colour variations in prints, they are in fact almost entirely based on a detection of lightness variations. In addition, one must keep in mind that the colour calibration of a scanner is a far more complex and cumbersome operation than grey-scale calibration, and it may even fail in some cases (Sokolowski, 2003). The most rational recommendation must therefore be not to perform colour print mottle evaluation except in cases where it may be expected that the variation is mainly in the a^* and b^* coordinates. In such cases, Evaluations 1 and 2 decisively demonstrate the need for a colour mottle model.

*4.*6 *Print Mottle Evaluation – A Unified Approach* (Paper VI)

The sixth paper presents a compiled model for the evaluation of print mottle. The unified model is based on the work presented in the first five papers of this thesis. The integrated model considers all the important attributes of reflectance disturbances in prints, a) the amplitude of the variation, b) the coarseness of the variation, c) the mean lightness level of the print, d) the degree of systematic character of the variation, and e) colour variations. The performance of the model is evaluated by comparing its correlation with the visual assessment of disturbances in prints that have a wide range of different characteristics with the performance of two of the most commonly used print mottle evaluation models, Johansson's model (1993) and the ISO 13660:2001 Mottle model; both discussed in Paper IV.

The approach presented is based on the notion that the perception of the magnitude of print mottle can be approximately predicted by a linear model, where the original information that strikes the retina passes through a number of filters and is, in the end, integrated to yield a single estimate of the magnitude of mottle in the print. The colour intensities of the image are described by the CIELAB colour metrics, $L^*(x,y)$, $a^*(x,y)$ and $b^*(x,y)$. By using the Fourier transform, the three image components are transformed into the frequency domain, $N_{L^*}(u,\varphi)$, $N_{a^*}(u,\varphi)$, and $N_{b^*}(u,\varphi)$, which represent the amplitudes of the variation in the different colour components L^*, a^* and b^*. To emulate the visual system's sensitivity to lightness contrasts at different frequencies, the L^* power spectrum is filtered with the mathematical approximation of the contrast sensitivity by Barten (1999). To estimate the contrast sensitivity of the a^* and b^* channels, the relationships between the L^* a^* and b^* contrast sensitivity for different frequencies presented in paper V are applied, and the a^* and b^* spectra are filtered with their relative contrast sensitivity functions. The influence of stimuli texture on contrast sensitivity is taken into account by texture enhancement filters that are based on local calculations of Chi-Square Measures in the power spectra. The filtered power of each of the colour channels is then integrated to yield an estimate of the variation in each channel. A single mottle estimate is given as the square root of the sum of the squared variation measures of the three components. To acknowledge the influence of mean lightness level on perceived print mottle in a way that agrees with the results presented in Paper I, the mottle estimate obtained is multiplied with the sixth-root of the mean reflectance factor level.

A set of 24 different half-tone grey test patches, reflectance level 38%, was created by digital simulation and then printed on the same substrate with a high quality inkjet printer. The patches are all of the same reflectance level, but contain noise varying both in magnitude and in character. 11 persons ranging from individuals with no earlier experience of print mottle evaluation to expert judges assessed the samples visually. The printed samples were scanned in RGB at 300 ppi with a flatbed scanner. The colour evaluation starts by transforming the RGB image of the scanned prints into the $L^*a^*b^*$ space. This procedure involves a colour calibration. The evaluation is then carried out according to the new model. The greyscale evaluation was carried out by first transforming the RGB images into a grey-scale using the standard NTSC transformation and then applying the evaluated grey-scale measurement models (Fahlcrantz, 2003; Johansson, 1993; ISO 13660:2001, Mottle).

When the performance of the new model was compared with the performance of the traditional models, the results clearly suggested that the new model provides a considerable improvement in print mottle prediction in this general case. The correlation with visual assessment, 0.91, compared to the second best model, 0.59, suggests that the new model is a first-rate candidate for the evaluation of print mottle in the general case.

4.7 Print Mottle Evaluation of Flexographic Prints – Using a Scanner-based Measurement System (Paper VII)

This paper may act as a first reading on print mottle. It presents a context and a background to the new model presented in Papers I to VI by demonstrating the applicability and also the limitations of the traditional STFI Mottling model. The driving forces behind the new print mottle evaluation model presented can be derived from the shortcomings of the traditional model.

The intent of the paper is however to investigate the applicability of the STFI Mottling model to flexographic prints. The model is evaluated by analysing the print mottle in flexographic full-tone cyan prints printed on a wide range of different boards, using both visual assessment and the STFI Mottling Analysis System.

In flexography, mottle may occur when the ink is applied to the substrate in an unclean printing press, or if the substrate, the ink or the combination of substrate and ink are inappropriate for the printing conditions prevailing. Typical problems may be unsuitable viscosity of the ink, high substrate roughness, uneven thickness, unevenly absorbing substrate, inhomogeneous printing form surface, improper anilox roller, or a bad combination of printing speed and pressure.

As described in Paper IV, several models have been developed to measure print mottle, and a substantial number are also available as evaluation systems. Many of these systems do not, however, consider all the important aspects that influence the visual impression of the spatial reflectance variations of the print, and they may thus not always correspond well to visual print quality.

The flat bed scanner-based analysis system, STFI Mottling, based on the theoretical approach presented by Johansson (1993), estimates the Mottle in a printed area, the Coefficient of Variation, as: $CV_R = \sigma / R$, where σ is the Standard Deviation of the Reflectance, and R the mean reflectance level of the print. σ is usually taken as the Standard Deviation of Reflectance within the range of wavelengths to which the HVS is most sensitive at a normal viewing distance (1-8 mm), but other pass bands could also be considered.

Full-tone cyan prints were prepared on 14 different boards (PPS roughness values 2-10μm) using an IGT-F1 flexographic laboratory press (IGT-F1, 2004). 10 judges carried out a visual assessment of the print mottle magnitude of the samples. The printed samples were scanned in greyscale at 300 ppi with an Epson 1680 Pro scanner, and the scanned images were analysed by the STFI Mottling analysis system.

In this report, Paper VII, samples with print mottle that can be considered to be random in nature and which had very similar mean reflectance levels were evaluated. The correlation, 0.93, between the visual assessment and the instrumental measurement suggests that the STFI Mottling Analysis System, based on the Coefficient of Variation, presents a good estimate of the magnitude of mottle in a full-tone flexographic print in this generic case. The authors however also point out that in other circumstances such as if the mottle includes ordered disturbances, a wide range of mean lightness levels or colour hue variations, other solutions, such as those presented in Papers I to VI of this thesis, may be required to yield a good agreement between visual and instrumental evaluations.

5. Discussion

"If we had had more time for discussion we should probably have made a great many more mistakes."

Leon Trotsky, 1879–1940.

This chapter attempts to identify the contributions of the new print mottle evaluation model, in comparison with the previous models available. The findings in each of the seven papers are first examined separately to give a critical perspective of the results and to evaluate the firmness of the conclusions. This is followed by a general discussion of the new model. We shall pay specific attention to questions such as: What are the additional benefits of using the new model? What are the performance-improvements using the new model compared to previous candidates? Secondly, since the new model contains several parameters, we discuss the accuracy of the magnitudes of these parameters. Thirdly, we address the limitations of the model. Is any component missing? How general is the model? Under what circumstances will it fail? Finally, we summarize the work.

Paper I - The influence of mean reflectance on perceived print mottle

The first paper considers a discrepancy between the traditional STFI print mottle evaluation instrument (presented in Paper VII) and visual assessment, in that there are empirical indications that the instrument may overestimate the amount of mottle in dark samples and underestimate it in light ones. In the traditional model, the amount of mottle is estimated as the Coefficient of Variation, i.e. by dividing the standard deviation of the reflectance factor by the mean reflectance factor level of the analysed print.

Paper I considers a number of alternatives to this model and the results suggest that the traditional model should be replaced in favour of a new model where the standard deviation of the reflectance instead of being divided by the mean reflectance level, should be divided by a power function of the mean reflectance level. The empirical results suggest that the most promising alternative could be to use the square-root of the mean reflectance (i.e. a power of 0.50) but other alternatives such as a dL^*-model based on the CIELAB lightness equation (yielding a power of 2/3) seems to be feasible.

The main limitation of the empirical results presented in the paper is the fact that, since the correlation between visual and instrumental evaluation is very high and almost constant for a wide range of alternative models with power functions between 0.40 and 0.80, it is very difficult to make any decisive conclusions concerning the optimal power function. Because of the biased visual assessment technique used, we can thus not conclude that the square-root model actually performs better than the dL^*-model. It seems however safe to accept the hypothesis that there does exist a model, with a power between 0.40 and 0.80, that performs better than the original model.

Studies on the human contrast sensitivity function are generally based on the Michelson Contrast $(L_{\max}-L_{\min})/(L_{\max}+L_{\min})$, where $L_{\max}$ is the maximum luminance level and $L_{\min}$ the minimum level in a sinusoidal stimulus grating. Compared to the random disturbances that we investigate this would closely correspond to our concept of dR/R. It has been shown by van Nes & Bouman (1967) that the human contrast sensitivity varies with mean field luminance, especially for high frequency variations. From the theoretical perspective, visual threshold modulation at a given frequency increases in proportion to the inverse square-root of the mean field luminance (de Vries – Rose law) until a region is reached where the contrast sensitivity is constant, i.e. where the law of Weber, dR/R holds. This would be in agreement with our suggestion to use the square-root of the mean reflectance level to normalize the measurement of print mottle but, since the relationship eventually will approach the law of Weber at high luminance levels, other power functions between 0.5 and 1 are, depending on the observation conditions, feasible.

Strictly speaking we should filter our estimate of the reflectance variation with a contrast sensitivity function whose magnitude depends on the field luminance. In practical print mottle evaluation situations it will however be difficult to measure the mean field luminance level every time we confront the observer with a new sample, and then apply this level in our instrumental evaluation of the particular sample. Our suggestion to normalize with a power function of the mean reflectance level ought therefore to be considered to be a more practical solution.

The fact that the calculation of the variation is made by Fourier analysis introduces another curiosity. The mathematical properties of the Coefficient of Variation and its relatives makes it theoretically vague to use the current method where the Fourier transform of the reflectance levels is calculated to obtain the variation and then to divide this obtained variation with a power function of the mean reflectance level.

Strictly, one should instead first calculate the perceived lightness level, P, based on the *L** equation or similar candidate (i.e. $P(x,y) = const*R(x,y)^q$) and then, subsequently, make a Fourier transformation of the perceived lightness level image; in mathematical terms to using:

$$\mathbf{F}\big(P(x,y)\big), \text{ instead of } \frac{\mathbf{F}(R(x,y))}{\left(\mathbf{E}[R]\right)^q},$$

where **F** denotes the Fourier transform, **E**[R] the mean reflectance factor level, R(x,y) reflectance factor level at position (x,y), and q the power used in the instrumental model. In practice, however, the mean difference in the final value between the two procedures is small, and the correlation coefficient between the two procedures is higher than 0.999, i.e. it is perfectly safe to use the calculation approximation of the model.

Paper II - Evaluating Systematic Print Mottle

The second article, which constitutes a major part of the work, considers one of the main objectives, that is, to investigate the possibilities of developing a print mottle evaluation model that correlates well with visual evaluation not only when the mottle is random but also when the mottle includes systematic components, such as bands, streaks or more complex textures.

The occurrence of systematic components, which may come in a wide range of different forms, implies that frequencies outside the range in which the HVS is most sensitive have to be taken into account for. The new model therefore considers frequencies between 0.25 and 16mm by weighing the impact of different frequencies using the contrast sensitivity function presented by Barten (1999). In addition, the model has to acknowledge the fact that ordered variations are perceived as being more disturbing than random variations at the same amplitude level and coarseness. The solution was therefore to let the new model analyse the frequency distribution of the variation, and then amplify the variation in a certain octave band and orientation if it appeared to be ordered. A higher mottle estimate is thus given if the mottle appears to be ordered, and this corresponds better with the visual appraisal.

A number of objections need to be addressed here: a) the use of a contrast sensitivity function that is based on the evaluation of sinusoidal variations whereas print variations may take a wide range of different forms, b) the use of a contrast sensitivity function based on modulation *threshold* experiments, and c) the use of a local power spectral character to account for the visual experience of texture.

From a theoretical point all these three objections are reasonable – the shape of the contrast sensitivity function of e.g. random variations will not be exactly the same as the shape of the sensitivity function to sinus patterns, threshold perception deviates from supra-threshold perception, and several workers (e.g. Julesz, 1981, Figure 7b) have demonstrated that the human pre-attentive textural discrimination system cannot process global differences in second-order statistics.

From the practical standpoint, the objections are however less convincing. Mapping the contrast sensitivity of a wide range of broadband disturbances at a wide range of supra-threshold levels would currently be a monumental task. The same applies to the development of a complete model of texture perception. Attempts have been made to develop such a model (e.g. Malik & Perona, 1990), but it is very uncertain if the precision of such a model would contribute much to the accuracy of the print mottle evaluation model presented here. From this perspective, the choices made in the model that is presented in this thesis appear very sensible.

Paper III - Perceptual assessment of simulated print noise with random and periodic structure

Within this framework the third paper should mainly be seen as an attempt to verify that the visual evaluation method used in the first visual evaluation of Paper II is indeed a valid one, and to justify the use of simulated prints to evaluate print mottle evaluation methods. In addition however, it draws attention to several other interesting aspects. First, the high correlation between observers in the visual evaluations suggests that we humans, despite all possible subjective influences, do indeed agree fairly well on how disturbing systematic print mottle of different magnitudes and characters actually is. This strengthens the belief that we can eventually construct an instrument that can assess perceived magnitude of print mottle in a way that is almost identical to an average assessment by visual observers. Secondly, the results not only justify the use of simulation in this context but they also indicate that simulation is a very potent tool in the area of print quality research. By using simulation we were able to minimize the impact of external variables on the samples that are to be assessed; something that otherwise is often a major problem in the area of print quality research, since so many factors along the long chain of producing a print influence the final result. Thirdly, the excellent agreement between the two-dimensional evaluation on the digitising tablet and the pairwise comparison suggests that magnitude estimation in two dimensions may be an interesting alternative to the demanding and time-consuming pairwise comparison.

Paper IV - A Comparison of Different Print Mottle Evaluation Models

Paper IV was written with three purposes. Firstly to compare the model presented in this thesis with other existing print mottle evaluation models. To make the comparison fair, the new model did not include the suggested filters for systematic disturbances and colour variations, i.e. it only considered the amplitude, the coarseness and the mean reflectance factor level of the print. Secondly the paper was written to illustrate that print mottle evaluation in the achromatic stochastic case can be made in somewhat different ways as long as the important factors are considered in a proper way, i.e. with respect to human perception of stochastic achromatic print mottle. Thirdly it was written to discuss the ISO Standard on print mottle, and how such a standard can be designed.

It is important to emphasize that the paper was written as a *comparison* not a benchmarking of different print mottle evaluation models. We wished only to demonstrate what type of model is adequate for the task, and what types of model fail because they do not consider all the important factors. We did not attempt to rank models that work well.

The ISO Mottle standard performed well in this study where the variation was random in nature, and should thus be adequate for the general evaluation of print mottle. As is demonstrated in Paper VI, this is not however always the case. To avoid such predicaments in the future and to promote the development of better evaluation models, we therefore put forward the idea that an ISO Standard on Print Mottle perhaps should be based on a standard set of reference samples rather than on a mathematical algorithm.

Paper V - Evaluating Colour Print Mottle

The fifth paper attempts to acknowledge the fact that the perception of mottle needs to be founded not only on lightness variations in the print but also on variations in hue and saturation. The model is thus extended from a grey scale to colour by applying the CIELAB metric.

When extending the model to colour, it is first and foremost important to distinguish between the common colour measurement situation where we measure the *average deviation* from an intended colour in the original image and the physical colour that appear in print, and our situation where we attempt to measure the *spatial* colour *variation* in an area intended to be homogeneous in colour, i.e. the size and shape of a particle cloud in the $L^*a^*b^*$ space. Since we are interested in the *variation* around a colour coordinate in colour space it is not essential to know the exact position in colour space. What is essential is that any *deformation* of the colour space due to an imperfect colour calibration is limited in magnitude. Colour calibration is thus a less severe problem here than it would be if we attempted to measure an absolute average colour deviation by using a scanner, but it is nevertheless essential since we cannot allow the $L^*a^*b^*$ metric to be *heavily* deformed.

Of the obstacles to constructing a colour mottle evaluation model, the choice of colour contrast sensitivity functions is the most challenging. Since there are no mathematical approximations of the colour contrast sensitivity functions, we derived relationships between the lightness contrast sensitivity function and empirical data on colour contrast sensitivity, i.e. relative contrast sensitivity functions for the a^* and b^* channels. These relationships are far from being precise but they do on average account for the difference in shape between the contrast sensitivity functions for lightness and those for the red-green and blue-yellow dimensions.

Four sets of prints with colour variations were evaluated; two of which were simulated samples printed with a high quality ink-jet printer and two sets that were prints from conventional presses. The colour mottle model showed a significantly better correspondence with the visual appraisal of print mottle than the colour-blind model in the two cases where variation was simulated and intended to be highly chromatic in character. The results from the evaluations of the conventional sets of prints suggest however that the extension from grey-scale to colour adds little to the general capability of predicting visual assessment of print mottle. The reason seems to be that the chromatic variation is highly correlated with the pure lightness variation in most prints.

The results may at first appear somewhat disappointing and surprising, but the opposite would in fact be even more surprising. If variations in prints, and objects in general for that matter, were to a considerable extent based on red-green and yellow-blue variations, colour-blind people would have difficulty in comprehending many impressions, and experience says that this is not generally the case. Being colour blind is generally a severe handicap only in very specific situations where the chromatic variations no longer correlate strongly with the lightness variations in the visual stimuli. We tend to relate to colour as a two dimensional concept consisting of hue and saturation, but what we actually refer to, in physical terms, when we speak of colour variations in prints is in fact a three dimensional concept, which is based mainly on variations in lightness.

Paper VI - Print Mottle Evaluation – A Unified Approach

The sixth paper investigates how the compiled version of the new model performs in the general case of disturbances in prints, compared to two of the traditional print mottle evaluation models, the coefficient of variation by band pass image analysis of Johansson (1993) and the ISO 13660 Mottle model.

In the unified approach, we make use of our compiled knowledge about the evaluation of print mottle given by Papers I to V, i.e. we consider a) the influence of mean lightness level, b) the frequency dependence of the contrast sensitivity function, c) the influence of texture on contrast sensitivity, and d) sensitivity to colour variations.

To test whether the unified model can predict the visual appraisal of disturbances in prints in a very general situation, we evaluated a set of 24 simulated samples with a wide range of different variation characters, i.e. samples showing distinct colour and/or systematic disturbances. The amplitude range of the variation was similar to a range that occurs in real commercial prints of normal to good quality (Coefficient of variation, 1-8 mm, in the range of 0.5-2%).

The results vividly illustrate the potential advantages of using the new model instead of the traditional models in the general case. Where the traditional models fail to acknowledge the colour and systematic character of the disturbances, the new model recognizes their importance for the perception of mottle and yields a good correlation, 0.92, with the visual assessment. We thus come to the conclusion that, compared to the traditional models, the new model is a considerable improvement in the general case of print mottle evaluation.

Paper VII - Print Mottle Evaluation of Flexographic Prints – Using a Scanner-based Measurement System

Whereas the first six papers concern the design of a new print mottle evaluation model, this last paper considers the traditional print mottle evaluation model used by STFI-Packforsk and many of its clients. The paper illustrates the fact that the traditional model is indeed a good predictor of visual appraisal of print mottle in most common cases where considerable mean reflectance differences between the evaluated samples are absent, and where the prints show little or no signs of colour variations and/or systematic disturbances.

It thus provides a good background reading on the basis on which the new model is founded, and why the emphasis in this work has been mainly towards colour variations, ordered mottle, and the influence of the mean reflectance level on perceived print mottle, and, except for Paper IV, has not been concerned with the fundaments of print mottle evaluation (amplitude and coarseness). Since Paper VII mainly concerns the basic factors, amplitude, coarseness and mean reflectance level, it may also act as an introductory reading to print mottle.

General Remarks

From the first six papers, it is clear that the new model considers new aspects that previous print mottle evaluation models did not take into account; especially colour variations and systematic disturbances. Nevertheless, the perception of print mottle is a very complex process, and there are thus many aspects that are still quite open.

Among those, the most important may be the locality of print mottle, i.e. the distribution of the variations on the surface. Currently, print mottle is treated as a homogeneous stimulus, spread out fairly uniformly over the spatial extension of the print. It is clear that there are situations where this is not the case, where the variations in the sample are clustered in one or more areas of the sample. In such cases it is reasonable to assume that the variation will be perceived as more detrimental than if it were evenly distributed. If we have a clustered variation, we shall thus, as in the case of systematic disturbances, need to amplify the estimated magnitude of visible mottle in the print.

A feasible way to do this would be to use a method similar to that used in the case of systematic mottle, but with the essential difference that the Chi-Square Measure or Entropy evaluation should be carried out in the spatial domain, rather than in the frequency domain. Tentative attempts were made in this direction with promising results, but when an additional filter is incorporated into the model to consider the locality of the mottle, the systematic filter will probably also have to be adjusted, since systematic components may also yield a lower entropy value in the spatial domain (e.g. banding and streaking).

Orientation dependency of systematic disturbances is another aspect that could be considered. The model that has been presented acknowledges findings that the HVS anatomically consists of orientation channels (Hubel & Wiesel, 1959), i.e. units which selectively respond to contrast patterns of specific orientations, and that the median width of the orientation channels is around 35-42° (de Valois, Yund & Hepler, 1982). In addition, it is however expected that vertical disturbances may be somewhat more visually prominent than horizontal, which in turn are more visible than diagonal disturbances. It would thus be appropriate to put different amplification factors on different components of systematic disturbances depending on their orientation. Another very complex aspect that may have an important impact on the perception of print mottle is visual masking. We refer to the work by Breitmeyer (1984).

Additional issues, that have been partly investigated here but may require further consideration, are the integration with respect to $d(\log_2(u))$ rather than du, and the choice of integration limits, wavelengths of 0.25-16 mm. Previous workers have reported that logarithmic integration shows a better correlation with perceived image quality than plain frequency integration in one dimensional image quality evaluation (Granger & Cupery, 1972; Barten, 1999). This suggests that the longer wavelengths play a more prominent role in the *magnitude* evaluation of variations than could be expected from the modulation *threshold* experiments of contrast sensitivity. It appears that fine scale variations disturb us less than coarser variations at a similar magnitude when fine scale and coarse variations are presented aggregated as a broadband noise.

Theoretically the phenomenon may be linked to the notion of multiple spatial frequency channels in the HVS (Campbell & Robson, 1968), i.e. that the sensitivity of the HVS to contrast variations is based on a group of pseudo-independent, quasi-linear, band-pass filters of octave character. The experience of a broadband spatial noise is in such case, ignoring masking effects, related to the superposition of the detected noise in each of the frequency channels. The concept resembles the commonly accepted manner in which the auditory system operates (Moore, 2003, pp. 89-147).

The model presented in this thesis acknowledges this by a logarithmic integration in a two dimensional analysis. This will however put less emphasis on longer wavelengths than is suggested by one-dimensional logarithmic integration. Compared to the one-dimensional models we should integrate with respect to $\mathrm{d}u/u^2$ rather than $\mathrm{d}u/u$ to put the same emphasis on the longer wavelengths (from white to 'pink' noise). Based on our empirical findings, Table 5.1 suggests however that the accentuation of low frequency variation by $\mathrm{d}u/u^2$ rather than by $\mathrm{d}u/u$ integration seems to give a poorer correlation with visual assessment. It appears that $\mathrm{d}u/u^2$, which together with the contrast sensitivity filter actually results in a low pass rather than a band pass filtering of the variation, puts too much emphasis on coarse and too little on fine scale variations.

There may be several practical reasons for this difference. Granger & Cupery (1972) consider variations between 3 and 12 cycles/degree whereas our model considers much lower frequencies, down to about 0.5 cycles per degree. In addition, print mottle is generally more long-wave in character than pure white noise. The frequency distribution of the print mottle we evaluate in areas intended to have a homogeneous density is thus likely to differ considerably from the short wave grainy variations in photographic prints studied by Granger & Cupery (1972), and may hence be another reason why we achieve better results with $\mathrm{d}u/u$ rather than with $\mathrm{d}u/u^2$.

Table 5.1. *Correlation between visual assessment and instrumental evaluation, integration with respect to du/u and* du/u^2 *respectively. The evaluation formulas are the same as in the Papers respectively, except that the order gain factor (eq. (12) Paper II; eq. (10), Paper VI) is put to ½ in the 8-16 mm wavelength band in the* $\mathrm{d}u/u^2$ *evaluations of Paper 2 and 6 to avoid over compensation of coarse variations due to systematic components (the original 0.625 gives lower correlations for* $\mathrm{d}u/u^2$ *than those presented here). Negative correlations indicate that the visual assessment were made for print quality rather than assessed magnitude of print mottle.*

	du/u	du/u^2
Evaluation 1, Paper 2	0.97	0.76
Evaluation 2, Paper 2	-0.90	-0.86
Evaluation 2, Paper 2, 12 worst samples excl.	-0.79	-0.67
Evaluation in Paper 4	0.97	0.96
Evaluation in Paper 6, (Grey Scale Evaluation)	0.85	0.82

Hypothetically there are, at least, three reasonable explanations of this: a) the bandwidth of the spatial frequency channels, b) threshold effects, and c) masking effects. Blakemore & Campbell (1969) concluded that channel bandwidths were somewhat narrower at high than at low spatial frequencies, and physiological data from units in monkey striate cortex by de Valois, Albrecht & Thorell (1982) support this standpoint. Superposition of several channels would then imply more emphasis on high than on low frequencies compared to the pure logarithmic integration, i.e. with du/u^2. Another feasible explanation would be that the low frequency components of the mottle patterns must eventually fall below the threshold level due to the shape of the CSF and hence cannot contribute to the aggregate experience of the mottle phenomenon. A third, perhaps more tentative, reason may be that the assumptions of independency and linearity are inappropriate, e.g. that masking effects do not allow straightforward superposition of the different spatial frequency channels, and hence invalidate pure logarithmic integration.

The precise choice of integration measure in the case of print mottle evaluation must therefore be considered open. A choice somewhere between du/u and du/u^2, say $du/u^{1.5}$ which, together with the CSF, would still result in a band pass filter may very well be the optimal choice (Figure 5.1). It should however be acknowledged that, compared to the STFI 1-8 mm band pass image analysis, all these three alternatives, du/u, $du/u^{1.5}$, and du/u^2 combined with CSF filtering, put more emphasis on longer wavelengths than the traditional model presented in Paper VII.

The choice of integration limits is to some extent arbitrary. The shorter limit, 0.25 mm, was chosen because the sensitivity to variations with a shorter wavelength is very low, and hence contributes negligibly to the overall impression. The longer limit, 16mm, was mainly chosen for practical reasons; test patches are generally not large enough to consider variation all the way up to the next octave limit, 32mm. However if available, this band, 16-32 mm, could also be considered in the estimation of print mottle.

A few remarks may be appropriate regarding the scope of the model. First, we need to address validity issues concerning the use of simulations to investigate how several of the key factors influence the perception of print mottle. Two main questions are interesting here: a) does the choice of samples simulated to study print mottle introduce any considerable investigator bias? and b) can the conclusions drawn from the empirical studies of simulated samples be generalized to real printed samples?

The answer to the first question is, of course, yes. From the beginning, attempts have been made to take this into account. In several of the studies we have chosen to use simulated samples to maximize our control over the stimuli. By using simulation, we have been able to forcefully attenuate the influence of other, external, variables on the results. This is suggested by the results in several of the papers, in particular by those of Papers III and V. If we had used real prints, external variables such as paper quality and gloss character would have influenced our results considerably and made our conclusions much weaker.

To avoid considerable choice-of-stimuli bias and a low external validity, we have made an effort to create simulated samples with a character that as far as possible resembles the mottle that may occur in prints (Paper III, Section 2.1). We have low-pass filtered the random noise introduced so that it better corresponds to print mottle. The systematic variations introduced were chosen to resemble patterns that we have found in real prints, and the colour variations applied were chosen in a similar manner. In addition we have complemented the studies using simulated samples with studies based on real prints to confirm that they yield results in a similar direction, and none of these studies yielded results that were in disagreement with the results given by the studies using simulated samples. It should also be recognized that using real prints instead of simulated samples by no means guarantees that the choice-of-stimuli bias is minimized. Our conclusions are thus that the use of simulated samples has been much more of an advantage than a disadvantage.

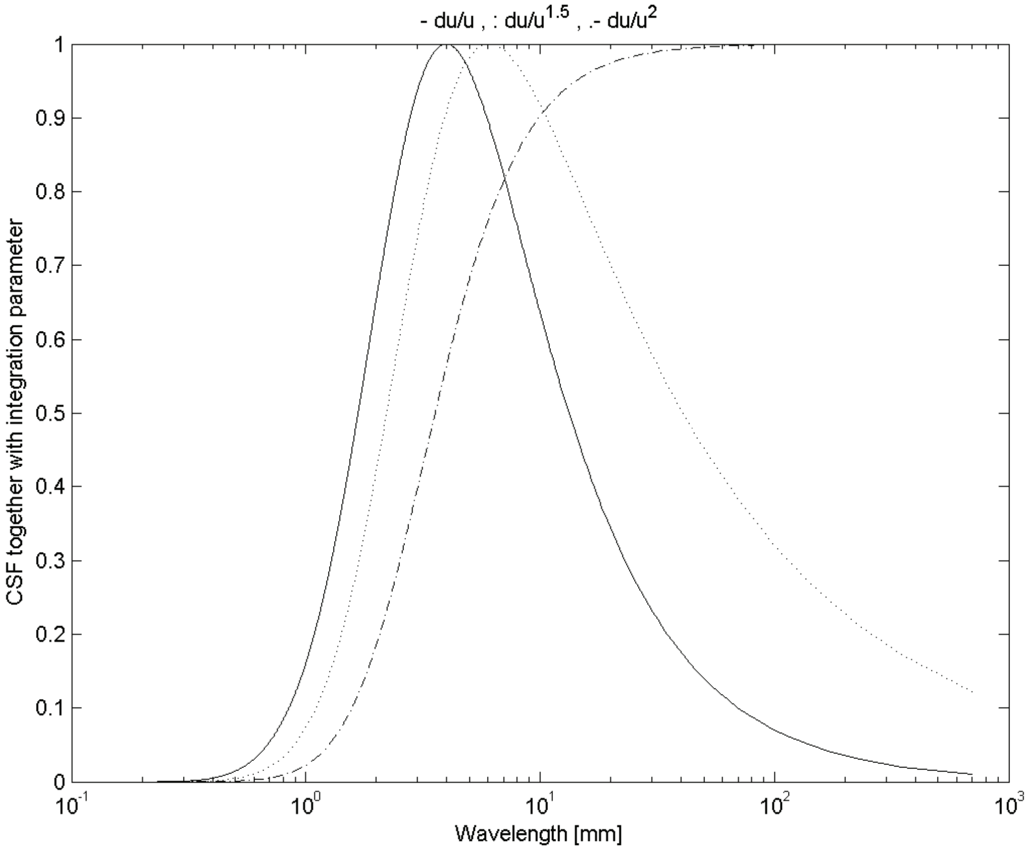

Figure 5.1. *The combined filtering operation of the CSF and the integration parameter on the variation at different wavelengths. The model presented in this thesis uses du/u (-). The du/u*^{2} *(.-) integration gives a pure low pass filter. The compromise du/u*$^{1.5}$ *(··) is also presented.*

The image acquisition process is a just as important a part in computer vision as the optics of the eye in human visual system. If you have bad eye optics and/or bad glasses, the visual cortex will not be of much use. It should be noted that this thesis has presented a model building approach to print mottle evaluation, and the assumption that the image acquisition is made in an appropriate way has been present from the beginning. In practice, this is of course far from always being true. The modular transfer function of the image-acquisition system together with, for example, moiré artefacts may introduce considerable distortion to the digital images that are to be evaluated. These problems have not been considered here. We have however, in each study, used the same image-acquisition device with the same settings for all samples in the study, and we have carefully attempted to avoid moiré effects where they could occur (since the simulated samples are printed with ink-jet printers with a very high frequency FM-screening the problem very rarely arises). It is thus reasonable to assume that the artefacts introduced by image acquisition are similar for all samples in each specific study.

Concerning the advantages of the new model over the previous models available, the most important contribution is probably the introduction of an amplification filter that in a reasonable way accounts for the enhanced sensitivity of the human visual system to ordered noise. No serious attempt to account for systematic noise has, to our knowledge, been made before in the photographic and print quality field, and all our results do in fact indicate that the rather straightforward method that we suggest works surprisingly well in many circumstances.

The second advantage, from a practical standpoint, should be the suggestion to apply a contrast sensitivity function in combination with a logarithmic integration. Based both on the theoretical foundations concerning the HVS and also on the empirical results presented in this thesis, this approach appears to be a better choice than previous suggestions for how to account for the perception of print mottle variations of different wavelengths.

The third advantage is the square-root compensation for mean reflectance factor level and the taking into account of colour variations. In practical terms, these compensations are generally less important. The original coefficient of variation, i.e. normalization with respect to the mean reflectance factor level, and grey scale evaluation, are often sufficient. Generally, comparison of the magnitude of mottle in prints is made in such a way that the samples have very similar mean reflectance factor levels. In these cases, the mean reflectance factor level compensation plays a minor role. The results in Paper V suggest that the colour components of the mottle in colour prints normally correlate very well with the lightness variations in the prints. Adding the information obtained by a colour print mottle evaluation thus has hardly any influence on the accuracy of the instrumental evaluation. However, from a theoretical completeness perspective, both an appropriate mean reflectance factor level compensation and colour mottle evaluation are interesting.

There are, unfortunately, also limitations and disadvantages of the new model. The new model is more complex than previously suggested models, and this introduces new obstacles. Firstly, it is somewhat more complicated to implement than most other approaches. This is not however a very serious concern with modern computer technology. Being a linear model, it is still very straightforward and does not require unreasonable computational capacity.

More cumbersome may be the fact that, since it is more complex, it necessarily introduces more degrees of freedom, which implies a lower robustness. This is particularly the case with the filter introduced to account for systematic variations; based on amplification it becomes somewhat sensitive, especially at low frequencies where the standard, discrete, FFT power spectrum provides limited accuracy. Several measurements may therefore be required to obtain an accurate estimate if a sample shows systematic disturbances at a low frequency such as banding.

The new model may be more complex than previous models, but it is still a linear approach. It thus does not account for the non-linearities in the HVS. In very specific situations it is therefore reasonable to assume that it will not yield an appropriate prediction of perceived print mottle.

To round up, the theoretical approach proposed was intentionally made in such a way that many parameters can be adjusted or replaced. It would be more than naïve to claim that one could present a solid model of how to evaluate print mottle in an optimal way, merely by correlating data from a few series of visual assessments. What is required is more testing. Not to confirm that the newly proposed model correlates well with visual assessment, but to find out where it does not function. Only by finding the limitations of the model will it be possible to suggest better parameter values or the replacement of certain parts of the model with better alternatives. The proposed new model appears to be a promising candidate for the instrumental evaluation of print mottle, since empirical evidence strongly supports the conclusion that the new model outperforms previous print mottle evaluation models. Details concerning parameters in the model are indeed still open, but in general the approach appears to be solid. Its success or failure is written in the stars.

6. Conclusions

"We are not certain, we are never certain. If we were, we could reach some conclusions, and we could, at last, make others take us seriously. In this world, nothing can be said to be certain, except death and taxes"

Benjamin Franklin, 1706–1790.

A new model for the evaluation of print mottle was step by step developed in the first five papers of this thesis and then integrated in the sixth paper. The model accounts for a) the amplitude of the mottle, b) the coarseness of the mottle, c) the mean reflectance factor level of the print, d) the texture of the mottle, and e) variations not only in grey-scale but also in colour. The empirical results presented suggest that the new model predicts the perceived magnitude of print mottle better than all the models with which it has been compared in the thesis.

The following conclusions are of particular interest:

- To properly account for the influence of mean reflectance factor level on perceived print mottle, the estimated reflectance variation in the print should be normalised with a power function of the mean reflectance factor. The power coefficient should be lower than 1. We propose a power coefficient of 0.5.
- To account for the human visual system's greater sensitivity to systematic than random lightness variations, a texture amplification filter based on a local Chi-square measure in the frequency domain can be applied.
- A combination of contrast sensitivity filtering and logarithmic integration of the reflectance variations at different frequencies can successfully account for human perception of lightness variations of different coarseness levels.
- Three factors are of primary importance in the instrumental evaluation of achromatic stochastic print mottle, a) the amplitude of the variations, b) the coarseness level of the variations, and c) the mean reflectance factor level of the print. If any of these factors is neglected, the evaluation will not correspond well to the visual assessment of print mottle.
- To account not only for variations in lightness but also for chromatic variations in prints, a grey-scale model can be extended to the colour space, i.e. by estimating the variation in each of the three colour channels L^*, a^* and b^*. A single mottle estimate is given as the square root of the sum of the squared variation measures of the three components.
- The visual assessment of print mottle can with success be predicted by integration of the spatial reflectance variations at different frequencies, if these variations have been pre-filtered properly to account for i) contrast sensitivity of different spatial frequencies, ii) texture, iii) colour and iv) mean reflectance factor level.

7. References

” Whatever is well said by another is mine.”

Lucius Annaeus Seneca, BC. 4 - AD 65.

Aspler, J. (2004). Print Quality Test Methods for Linerboard, *Taga Proceedings*, 2004.

Barlow, H. B. (1953). Summation and inhibition in the frog’s retina, *Journal of Physiology, 119,* 69-88.

Barros, G. G., & Johansson, P-Å. (2005). The OptiTopo Technique for Fast Assessment of Paper Topography: Limitations, Applications and Improvements, *Journal of Imaging Science & Technology*, *49*, 2, 170-178.

Barros, G. G., Johansson, P-Å., & Fahlcrantz, C-M. (2005). Topographic Distribution of UnCovered Areas (UCA) in Full Tone Flexographic Prints, *TAGA Journal, 2*, 2, , 43-57.

Barten, P. G. (1999). *Contrast Sensitivity of the Human Eye and Its Effects on Image Quality,* Bellingham: SPIE Optical Engineering Press.

Bartleson, C. J. (1982). The combined influence of sharpness and graininess on the quality of colour prints, *J Photographic Science, 30,* 33-38.

Behe, M. J. (1996). *Darwin’s Black Box*, New York: Free Press, ISBN 0028741013.

Bergen, J. R., & Landy, M. S. (1991). Computational modelling of visual texture segregation, In Landy, M. S. & Movshon, J. A. (Eds.), *Computational Models of Visual Processing*, 253-271, Cambridge, MA: MIT Press.

Blakemore, C., & Campbell, F. W. (1969). On the existence of neurons in the human visual system selectivity to the orientation and size of retinal images*, J. Physiology, 203*, 237-260.

Bradley, A. Swikes, E., & De Valois, K. K. (1985). Orientation and spatial frequency selectivity of adaptation to color and luminance gratings, *Vision Reseach, 28,* 841-856.

Breitmeyer, B. G. (1984). *Visual Masking: An Integrative Approach*, New York: Oxford University Press, 1984:133.

Burningham, N., & Bouk, T. (1994). Threshold visibility and objectionability of banding in reflection prints, *Paper presented at the IS&T Tenth International Congress on Advances in Non-Impact Printing Technologies.*

Campbell, F. W., & Robson, J. G. (1968). Application of Fourier analysis to the visibility of gratings, *J. Physiology, 197*, 551-566.

Columbia Encyclopedia, (2005). Sixth Edition, Copyright (c) 2005.

Cresson, T., Tomimasu, H. &, Luner, P. (1990). Characterization of paper formation, part 1: Sensing paper formation, *Tappi Journal 73(7),* 153–159.

Cresson, T., &, Luner, P. (1990). Characterization of paper formation, part 2: The texture analysis of paper formation, *Tappi Journal 73(12),* 175–184.

Cresson, T., &, Luner, P. (1991). Characterization of paper formation, part 3: The use of texture maps to describe paper formation, *Tappi Journal 74(2),* 167–175.

Cross G., & Jain, A. (1983). Markov Random Field Texture Models, *PAMI, 5*, 1, 25-39.

Cula, O. G., & Dana, K. J. (2004). 3D Texture Recognition Using Bidirectional Feature Histogram, *IJCV*, *59*, 1.

Daly, S. (1992). The visible differences predictor: an algorithm for the assessment of image fidelity, *SPIE,* Vol. 1666*,* Human Vision, Visual Processing , and Digital Display III.

Darling, E. M., & Joseph, R. D. (1968). Pattern Recognition from Satellite Altitudes, *IEEE Trans. On Syst. Man and Cybernetics*, *Vol. SMC-4*, 38-47.

Daubechies, I. (1992). *Ten Lectures on Wavelets*, Philadelphia: S.I.A.M.

Dembski, W. A. (2001). *No Free Lunch*, Lanham, Maryland: Rowman & Littlefield Publishers, Inc, ISBN 0742512975.

Dembski, W. A. & Orr, A. H. (2002). Darwin and Design, *Boston Review, Vol XXVII, No.5.*

Dennett, D. C. (1991). *Consciousness Explained,* Little Brown & Company, ISBN 0316180661.

De Valois, R. L., Yund E. W., & Hepler, N. (1982). The orientation and direction selectivity of cells in macque visual cortex, *Vision research, 22*, 531-544.

De Valois, R. L. (1965). Analysis and coding of color in the primate visual system, *Cold Spring Harbour Symposium on Quantitative Biology, 30*, 567-579.

De Valios. R. L., Albrecht, D. G., & Thorell, L. G. (1982). Spatial frequency selectivity of cells in macaque visual cortex, *Vision Research, 22,* 545-559.

De Valois, R. L. & De Valois, K. K. (1988). *Spatial Vision*, Oxford Psychology Series 14, New York: Oxford University Press.

Dow, N. W. (1964). Visual Response to Gradients of Varying Colour and Equal Luminance, *Nature*, 203, 215.

Duda, R. O., Hart, P. E., & Stork, D. G. (2001). *Pattern Classification* (p.1, 2nd ed.), New York: John Wiley & Sons Inc.

Ehrich, R. W., & Foith, J. P. (1976). Representation of Random Waveforms by Relational Trees, *IEEE Transactions on Computers*, *Vol. C-25*, 725-735.

Eidenvall, L., Eriksson, L., Fahlcrantz, C-M., Johansson, P-Å., Klaman, M., Lindberg, S., Norberg, O., Pauler, N., & Westin, P., (2001). *Digital Printing Evaluation 2000/2001*, Stockholm: Framkom, ISSN 1650-687.

Eklundh, J. O. (1979). On the Use of Phase Features for Texture Discrimination, *Computer Graphics and Image Processing, 9*, 199-201.

Engeldrum, P. G. (2000). *Pshycometric Scaling: Atoolkit for Imaging Systems Development*, Imcotec Press, Winchester, MA, 2000.

Fairchild, M. D. (1997). *Color Appearance Models,* Addison Wesley Longman, Inc.

Field, D. J. (1994). What is the goal of sensory coding? *Neural Computation, 6*, 559-601.

Fisher, R. A. (1924). On a Distribution Yielding the Error Functions of Several Well Known Statistics, *Proceedings of the International Congress of Mathematics*, Toronto, *2*: 805-813.

Fisher, R. A. (1953). Dispersion of a Sphere, *Proceedings of the Royal Society of London, Vol. A217,* 295-305.

Fourier, J. (1822). *Théorie analytique de la chaleur,* Paris: Firmin Didot, Père et Fils.

Geman, S., & Geman, D. (1984). Stochastic Relaxation, Gibbs Distributions, and the Bayesian Restoration of Images, *PAMI* ,*6*, 6, 721-741.

Gescheider, G. A. (1997). *Psychophysics: The Fundamentals*, Third Edition, Lawrence Erlbaum Associates, Publishers, Mahwah, New Jersey.

Gonzalez, R. C. & Woods, R.E. (2002). *Digital Image Processing*, Upper Saddle River, New Jersey: Prentice-Hall Inc.

Granger E. M., & Cupery, K. N. (1972). An optical merit function (SQF), which correlates with subjective image judgements, *Photgraphic Science and Engineering, 16:3*, 221-230.

Grassman, H. (1854). On the theory of compound colors, *Phil. Mag. (Ser. 4.), 7,* 254-264.

Guilford, J. P. (1954). *Psychometric Methods*, Second Ed. McGraw-Hill, New York, 1954.

Gurnsey, R, & Fleet, D. J. (2001). Texture Spaces, *Vis. Res. 41*, 745-757.

Guth, S. L. (1997). The Chromatic Contrast Sensitivity Myth, *Proceedings of the 5th Color Imaging Conference*, 23-26.

Hallberg, E., Odenberg Glasenapp, A., & Lestelius, M. (2004). Quantification of banding on printed corrugated board using spatial frequency analysis, Submitted to Packaging Technology & Science.

Hansson, P. & Johansson, P-Å. (1999). A new method for the simultaeous measurement of surface topography and ink, *Nordic Pulp and Paper Research Journal, 14(4).*

Haralick, R. M., Shanmugam, K., & Dinstein, I. (1973). Textural Features for Image Classification, *IEEE Trans. On Syst. Man and Cybernetics*, *Vol. SMC-3*, 6.

Haralick, R. M., & Shapiro, L. G. (1991). *Computer & Robot Vision*, Chapter 9 Texture, Addison-Wesley.

Hardeberg, J. Y. (1999). Desktop Scanning to sRGB, *SPIE Proceedings*, *Color Imaging: Device-Independent Color, 3963*, 47–57.

Harris, R., & Barrett, R. C., (1978). Towards an Objective Nephanalysis, *Journal of Applied Meteorology*, *17*, 1258-66.

Hassner, M., & Sklansky, J. (1980). The Use of Markov Random fields as Models of Texture, *Computer Graphics and Image Processing*, *12*, 357-370.

Heaps, C., & Handel, S. (1999). Similarity and features of natural textures, *J. Exp. Psychol. Hum. Percept. Perform, 25*, 299-320.

Helmholtz, H. von. (1867/1925). Treatise on physiological optics (from 3rd German edition, Trans.) (3rd ed., Vol III). New York: Dover Publications.

Hering, E. (1878/1964). *Outlines of a theory of the light sense*, (L. M Hurvich & D. J. Jameson, Trans.), Cambridge, MA: Harvard University Press.

Hesslow, G. (1994). Will neuroscience explain consciousness? *Journal of Theoretical Biology 171,* 29-39.

Hirose, Y. (1993). Percetual Characteristics of Image Noise in Color Hardcopy Images, *SPIE Vol. 1912, Color Hard Copy and Graphic Arts II.*

Hubel, D. H. and Wiesel, T. N. (1959). Receptive fields of single neurons in the cat's striate cortex, *J. Physiol. (Lond.)*, *148*, 574-591.

Hubel, D.H., & Wiesel, T.N. (1968). Receptive fields and functional architecture of monkey striate cortex, *J. Physiol.*, *195*, 215-24.

Hurvich, L. M., & Jameson, D. (1957). An opponent process theory of colour vision, *Psychological Review, 64*, 384-404.

Hsiao, J. Y., & Sawchuk, A. A. (1989). Unsupervised Image Segmentation Using Feature Smoothing and Probabilistic Relaxation Techniques, *Computer Vision, Graphics and Image Processing, 48*, 1-21.

Ishihara, (1984). *Ishihara's test for Colour Blindness*, *38 Plates Edition*, Tokyo: Kanehara & Co.

IGT-F1 (2003). Specifications: http://www.igt.nl/uk/specs/specf1.html, Hompage: http://www.igt.nl .

ISO 13660:2001 (2001). *Information technology – Office equipment – Measurement of image quality attributes for hardcopy output – Binary monochrome text and graphic images*.

Jacobson, R. E. (1995). An Evaluation of Image Quality Metrics. *The Journal of Photographic Science, 43*, 7-16.

Jernigan, M. E., & D`Astous, F. (1984). Entropy-Based Texture Analysis in the Spatial Frequency Domain, *IEEE Transactions on Pattern Analysis and Machine Intelligence*, *Vol. PAMI-6*, 237-243.

Johansson, P-Å. (1993). Print mottle evaluation by band-pass image analysis. *Advances in Printing Science and Technology, 22*, 403. Pentech Press.

Johansson, P-Å., Lundby, H., Lindberg, S. & Nyström, S. (1999). Optical homogeneity of traditional and digital prints, *Advances in Printing Science and Technology, 26*, 137-149, PIRA Int.

Johansson, P-Å., & Norman, B. (1996). Methods for evaluating formation, print unevenness and gloss variation, *Proc. TAPPI 1996 Process and Product Quality Control Conference*, Cincinnati, TAPPI Press, Atalanta, 139.

Jordan, B. D. & Nguyen, N. G. (1986). Specific Perimeter – A Graininess Parameter for Formation and Print-Mottle Textures, *Paperi ja Puu*, *67:6-7*, 476-482.

Julesz, B. (1962). Visual pattern discrimination, *IRE Trans. Inf. Theory IT-8*, 84-92.

Julesz, B., & Caelli, T. (1979). On the limits of Fourier decompositions in visual texture perception, *Perception*, *8*, 69-73.

Julesz, B. (1981). Textons, the elements of texture perception, and their interactions, *Nature*, *290*, 91-97.

Kelly, D. H. (1975). Luminous and Chromatic Flickering patterns Have Opposite Effects, *Science*, *188*, 371-372.

Klassen, R. V., & Goodman, N. (2000). Human Chromatic Contrast Contrast Sensitivity Function: Exploration of Dependence on Mean Color, *IS&T 8th Color Imaging Conference, IS&T, Springfield, VA, 2000*.

Kuffler, S. W. (1953). Discharge patterns and functional organization of mammalian retina, *Journal of Neurophysiology, 16*, 37-68.

Laws, K. I. (1980). Rapid Texture Identification, *SPIE Conf. Image Processing for Missile Guidance*, 376-380.

Leung, T., & Malik, J. (2001). Representing and Recognizing the Visual Appearance of Materials using Three-dimensional Textons, *IJCV*, *43*, 1, 29-44.

Li, Y., Wang, T., & Shum, H-Y. (2002). Motion texture: A two-level statistical model for character motion synthesis, *Proceedings of ACM SIGGRAPH 2*.

.

Lindstrand, M., (2002). *Gloss: measurement, characterization and visualization – in the light of visual evaluation.* Licentiate Thesis, Linköping: LiU-TEK-LIC-2002:48.

Liu, S. & Jernigan, M. E. (1990). Texture Analysis and Discrimination in Additive Noise, *Computer Vision, Graphics, and Image Processing*, *52-67*.

MacGregor, M. & Johansson, P-Å. (1991). Gloss uniformity in coated paper – Measurements of commercial papers*, Proc. TAPPI 1991 Coating Conference, Montreal TAPPI Press, Atalanta*, 495.

Malik, J., Belongie, S., Leung, T., & Shi, J. (2001). Contour and Texture Analysis for Image Segmentation, *IJCV*, *43*, 1, 7-27.

Malik, J., & Perona, P. (1990). Preattentive Texture Discrimination with Early Vision Mechanism, *JOSA-A(7), 5*, 923-932.

Maxwell, J. C. (1855). Experiments on colour, as perceived by the eye, with remarks in colour-blindness, *Transactions of the Royal Society, Edingbourogh, 21*, 275-298.

McCormick, B. H., & Jayaramamurthy, S. N. (1974). Time Series Model for Texture Synthesis, *International Journal of Computer and Information Sciences*, *3*, 1411-20.

Melara, R. D. (1992). The concept of perceptual similarity: from psychophysics to cognitive psychology, in: D. Algom (Ed.), *Psychophysical Approaches to Cognition*, North-Holland and Elsevier, Amsterdam, 285-312.

Mizes, H. (2000). Graininess of Color Halftones, *IS&Ts NIP16 International Conference on Digital Printing Technologies*.

Mizes, H., Goodman, N., & Butterfield, P. (2000). The Perceptibility of Random Streaking, *IS&T's 2000 PICS Conference*.

Moore, B. (2003). *An Introduction to the Psychology of Hearing,* 5th Ed., Academic Press.

Mossfeldt, L., & Tillander, J. (2005). *Design and Implementation of a Region of Interest Analysis System of Eye-Tracking Studies*, Master's Thesis, Lund, Sweden.

Mullen, K. T. (1985). The Contrast Sensitivity of Human Colour Vision to Red-Green and Blue-Yellow Chromatic Gratings, *Journal of Physiology*, *359*, 381-400.

Nguyen, N. G. & Jordan, B. D. (1989). Overview of texture analysis of print and paper. *Paperi ja Puu, 70(8),* 933-944.

Nordström, J-E. (1999). STFI-JEP, STFI-Justified and Enhanced Print*, Swedish patent 9903174-2.*

Oittinen, P., & Saarelma, H. (1998). *Papermaking Science & Technology, Book 13 – Printing,* Helsinki: Fapet Oy.

Ojala, T., Pietikäinen, M., Mäenpää, T. (2002). Multiresolution Gray-Scale and Rotation Invariant Texture Classification with Local Binary Patterns, *PAMI*, *24*, 7, 971-987.

Orloff, D. I., Challas, J., Rudman, I. (1995). Flexographic Printing of Linerboard, *Taga Proceeedings*, *1*, 1995.

Orr, A. H. (1997). Is Darwin in the Details? - H. Allen Orr Responds, *Boston Review*, *XXII,* No.1.

Owens, H. C., Westland, S.. Van de Velde, K., Delabastita, P. , & Jung, J. (2002). Contrast Sensitivity for Lime-Purple and Cyan-Orange Gratings. *IS&T/SID 10th Color Imaging Conference*.

Palmer, G. (1777). *Theory of Light*, London: Leacroft.

Palmer, S. E. (1999). *Vision Science,* MIT Press.

Patel, A. S., (1965). Spatial Resolution by the Human Visual System, The Effect of Mean Retinal Illuminance, *Journal of the Optical Society of America*, *56*, 5.

Pearsall, J. (2001). *New Oxford Dictionary of English*, Oxford University Press.

Popper, K. R. (1963). *Conjectures and Refutations*, Routledge and Keagan Paul.

Poirson, A. B., & Wandell, B. A. (1993). The appearance of colored patterns: pattern-color separability, *J. Opt. Soc. A.*, *10*, 2458-2470.

Ramsay, J. O. (1982). Some statistical approaches to multidimensional scaling data, *Journal of the royal statistical society, A 145*, 285-312.

Ramsay, J. O. (1991). Multiscale manual. *Unpublished manuscript, Mc Gill University, Department of Psychology, Montreal Canada.*

Randen, T. & Husöy, J. (1999)., Filtering for Texture Classification: A Comparative Study, *PAMI*, *21, 4*, 291-310.

Ranefall, P., Östlund, C., & Bengtsson, E. (1998). Principal Component Hue, *Proceedings of SSAB Symposium on Image Analysis,* Uppsala, Sweden.

Rao, A. R., & Lohse, G. L. (1993). Identifying high level features of texture perception, *CVGIP: Graph. Models Image Process. 55*, 218-233.

Rao, A. R., & Lohse, G. L. (1996). Towards a texture anming system: identifying relevant dimensions of texture, *Vis. Res. 36*, 1649-1669.

Rosenberg, R. R. (2002). Stochastic Frequency Distribution Analysis as Applied to Mottle Measurement, *10th IPGAC 2002 Bordeaux.*

Ryan, J. (2004). Ink Film Thickness and its Relationship to Quality, Productivity and Waste in the Sheetfed Litho Pressroom, *TAGA Proceedings 2004*.

Sakata, H., & Isono, H. (1977) Chromatic Spatial Frequency Characteristics of Human Visual System (Color Difference Discrimination), *The Journal of ITE of Japan*, *31*, No.1, 29-35, Jan. 1977.

Scavone, G. P., Lakatos, S., & Harbke, C. R. (2002). The sonic mapper: an interactive program for obtaining similarity ratings with auditory stimuli, *Paper presented at the 2002 International Conference on Auditory Display, Kyoto, Japan.*

Schade, O. H. (1958). On the Quality of Color-Television images and the Perception of Color Detail, *Journal of the Society of Motion Picture and Television Engineers*, *67*, 801.

Sokolowski, K. (2003). *Colour scanner calibration – A Comparison of Different Methods*, Master's Thesis, Stockholm: Royal Institute of Technology, Department of Numerical Analysis and Computing Science.

Steiger, J. H. (1980). Tests for comparing elements of a correlation matrix, *Psychological Bulletin*, *87*, 245-251.

Sternberg, S. R., & Sternberg, E. S. (1983). Industrial Inspection by Morphological Virtual Gauging, *IEEE Workshop on Computer Architecture, Pattern Analysis, and Image Database Management*, Pasadena, CA.

Stevens, S. S. (1957). On the psychophysical law, *Psychological Review, 64*, 153-181.

Stevens, S. S. (1975). Psychophysics: Introduction toits perceptual, enural and social prospects, New York: John Wiley & Sons Inc.

Turtinen, M., Mäenpää, T., & Pietikäinen, M. (2003). Texture Classification of Combining Local Binary Features and a Self-Organizing, Map, *Image Analysis, SCIA 2003 Proceedings, Lecture Notes in Computer Science 2749*, Springer, 1162-1169.

Turtinen, M., Pietikäinen, M., Silven, O., Mäenpää, T., & Niskanen, M. (2003). Texture-based paper characterization using non-supervised clustering, *Proc. 6th International Conference on Quality Control by Artificial Vision (SPIE 5132), May 19-23, Gatlinburg, Tennesse*e, 350-358.

Van der Horst J. C., & Bouman, M. A. (1967). On searching for "Mach Band Type" Phenomena in Colour Vision, *Vision Research, 7*, 1027-1029.

Van der Horst J. C., & Bouman, M. A. (1969). Spatiotemporal Chromaticity Discrimination, *JOSA*, *59*, 11.

Van Nes, F. L., & Bouman, M. A. (1967). Spatial Modulation Transfer in the Human Eye, *JOSA*, *57*, 3, 401-406.

Verity IA. (2003). *Verity IA Uniformity Number*, www.verityia.com .

Wandell, B. A. (1995). *Foundations of Vision*, Sunderland, Massachusetts: Sinauer Associates, Inc.

Watanabe, A., Sakata, H., Isono, H. (1976). Chromatic spatial sine-wave response of the human visual system, *NHK Lab. Note., 198*, 1-10.

Wertheimer, M. (1922). Untersuchungen zur Lehre von der Gestalt. I, Prinzipielle Bemerkungen, *Psychologische Forschung, 1*, 47-58.

Wertheimer, M. (1923). Untersuchungen zur Lehre von der Gestalt. II, *Psychologische Forschung, 4*, 301-350.

Williams, D., Sekiguchi, N., & Brainard, D. (1993). Color, Contrast Sensitivity, and cone mosaic, *Proc. Natl. Acad. Sci. USA, 90*, 9770-9777.

Wyscecki, G. & Stiles, W. S. (1982). *Color Science – Concepts and Methods, quantitative data and formulae*, 2nd ed., John Wiley & Sons, New York.

Yee, S. N. (1996). Visual tolerance study of one-dimensional periodic (sinusoidal) noise in various spatial frequency binary and gray halftones, *Paper presented at the IS&T's NIP 12: international conference on digital printing technologies, San Antonio TX.*

Young, T. (1802). *On the theory of light and colors,* London: The Society.

Zang, Y. H., & Aspler, J.S. (1995). Factors that affect the flexographic printability of linerboards, *Tappi Journal*, *78*, 10, 24023-24033.

Zhang, X. M., & Wandell, B. A. (1996). A spatial extension to CIELAB for digital color image reproduction, *Soc. for Info Disp. Symp .Tech. Digest*, *27*, 731-734.

Zhu, S. C., Wu, Y. N., & Mumford, D. (1998). Filters, Random-Fields and Maximum-Entropy (Frame): Towards a Unified Theory for Texture Modelling, *IJCV*, *2*, 107-126.

8. Appendix – Notations & Glossary

"Ask yourself whether our language is complete—whether it was so before the symbolism of chemistry and the notation of the infinitesimal calculus were incorporated in it; for these are, so to speak, suburbs of our language. (And how many houses or streets does it take before a town begins to be a town?) Our language can be seen as an ancient city: a maze of little streets and squares, of old and new houses, and of houses with additions from various periods; and this surrounded by a multitude of new boroughs with straight regular streets and uniform houses."

Ludwig Wittgenstein, 1889–1951.

8.1 Physical and Psychophysical Notation:

a* – green-red colour coordinate in the CIELAB space
b* – blue-yellow colour coordinate in the CIELAB space
CSF – Contrast Sensitivity Function
jnd – just noticeable difference
D – print density
L*– perceived lightness level
M – Predicted Perceived Mottle
MTF – Modular Transfer Function
P – perceived intensity of stimulus
R – mean reflectance factor
R(x,y) – reflectance factor at coordinate (x,y)
dR – reflectance factor variation
VTF – Visual Transfer Function
w – relative contrast sensitivity
Y – absolute (physical) luminance level
Φ – stimulus level
$d\Phi$ – stimulus variation
Ψ – mental experience level

8.2 Mathematical Notation:

c, k, α, β, γ – various constants
CV_R – coefficient of variation
f – a function
h – convolution function
i – original grey level in image
j – detected grey level
n – noise component
p – power exponent function, or in some cases probability density function
r – correlation coefficient
u – frequency, frequency coordinate
w – weight function
x – spatial coordinate
y – spatial coordinate

$E[\cdot]$ – expected value, mean value

F – Fourier transform of f
G_{eye} – contrast sensitivity transfer function
$G_{texture}$ – texture compensation transfer function
I – Fourier transform of original grey level
J – Fourier transform of detected grey level
H – transfer function
m – mean value
N – Fourier transform of the noise function
Q – texture estimation in the frequency domain
T – texture estimation in the frequency domain
φ – orientation
ρ – power function
σ – standard deviation

8.3 Mathematical Definitions:

Definition: A system S is **linear** if the principle of superposition,

$$S\{af+bg\} = aS\{f\} + bS\{g\},$$

holds for all valid insignals f and g, and all constants a and b.

Definition: A system is said to be **shift invariant** if the only effect of a shift in the position of the input is an equal shift in the position of the output, i.e.:

$$S\{f(x-u)\} = g(x-u).$$

8.4 Glossary:

achromatic colour – a colour lacking hue; thus being white or grey or black
axon – the long threadlike part of the nerve cell along which impulses from the cell body are conducted to other cells
chromatic – generally referring to polychromatic, here sometimes loosely used to refer to a spatial distribution of light with varying hue and chroma
chromatic aberrations – the failure of the lens to produce an exact point-to-point correspondence between an object and an image because the light that passes through the lens gets dispersed, or split, into many colours.
contrast sensitivity function – the HVS sensitivity to spatial reflectance variations at different frequencies, or the ratio of perceived spatial reflectance variation to the physical spatial reflectance variation of the stimulus as a function of spatial frequency.
cortex – the outer layer of the cerebrum, the brain
dendrite – projection of a nerve cell, which conducts the electrical stimulation received from other cells to the body of the cell from which it projects.
diffraction of light – change in the direction and intensity of a light wave after passing by an obstacle or through an aperture whose size is of the order of the wavelength of the wave.
diffuse illumination – in an instrument: light coming from all directions, no shadow.
first-order statistics – probability distribution of the intensity levels of the image without consideration of pixel positions
HVS – human visual system

isochromatic – having the same wavelength, sometimes loosely used to refer to a spatial distribution of light with the same hue and chroma
illumination – lighting condition in the environment
isoluminant – having the same luminance level
jnd – the smallest change in stimulus that an observer can detect
LED-voltage – voltage of the light emitting diodes in some xerographic printing processes
lens aberration – a failure of a lens to behave according to the ideal laws of lenses
luminance – number of photons falling on a given surface per unit of time
magnitude – chiefly referring to either perceived or measured rms magnitude of the noise in a sample. In some cases when systematic noise is compared to random noise, not only is the rms magnitude at pixel level assumed to be similar but also the proportions of variation in each octave within the visual detectable range (between 0.25 and 16 mm, i.e. between about 28 and 0.44 cycles per degree at a viewing distance of 0.4 m).
metamers – surfaces that look the same in a given illumination but have different physical spectra
modulation – the addition of information to an optical signal carrier
modulation transfer function – the ratio of the output signal variation to the input signal variation as a function of frequency (MTF)
monochromatic – having a single wavelength
point source – all the light comes from one single point, distinct shadow
polychromatic – having several wavelengths
ppi – pixels per inch
rms – root mean square, referring to the root mean square magnitude of the noise in the print at pixel level. The resolution used in the image acquiring process is throughout the thesis always 300 pixels per inch, i.e. 118 pixels per centimeter.
second-order statistics – joint probability distribution that two points, at given distances in the image, have two particular intensity levels (e.g. both being black)
spatial – of or relating to space
spherical aberration – the failure of the lens to produce an exact point-to-point correspondence between an object and an image because its shape deviates from the hyperbolic.
supra – above
temporal – of or referring to time
visual transfer function – the ratio of the output image variation to the input image variation as a function of spatial frequency (VTF)