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A Review of Methods of Analysis for White Top Mottling

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VUORI, VEIKKO:
Katsaus painamattoman pinnan heijasteen variaatioiden analyysi menetelmiin

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Pakkauskartonkien laatuvaatimukset kasvavat jatkuvasti. Tämä asettaa paineita niin valmistus- kuin mittaustavoille. Valkopintainen WTL (White Top Linerboard) koostuu valkaistusta pintakerroksesta ja valkaisemattomasta runkorakenteesta. Pintakerros on huomattavasti kalliimpi kuin runkomateriaali, joten sen määrä pyritään minimoimaan. Liian ohuesta ja epätasaisesta pintakerroksesta läpi näkyvä valkaisematon kuitu aiheuttaa pinnalle laikukkaan vaikutelman. Tätä ilmiötä kutsutaan nimellä White Top Mottling eli valkoisen pinnan heijasteen ei-haluttu variaatio homogeenisessa valaistuksessa.

Opinnäytetyössä kerättiin tietoa white top mottlingin analysointiin liittyvistä fysikaalisista ja fysiologisista tekijöistä sekä käytössä olevista menetelmistä. Ulkopakkauskartonkilajien valmistuksen ja tuoteperheen esittelyn jälkeen käsitellään mottlingin optiseen mittaukseen liittyviä termejä ja käsitteitä. Seuraavaksi on katsaus ihmisen näköjärjestelmän toiminnasta ja havainnoinnin rajoitteista. Mottlingin mallintaminen ja analyysimenetelmien rakentaminen perustuvat ihmisen näköjärjestelmän kykyyn havainnoida valon aallonpituuden ja intensiteetin variaatioita. Lopuksi esitellään yleisesti mottling-analyysiin käytettyjä menetelmiä, kuten Fourier (taajuus-)analyysi, myötäesiintymä (co-occurence), FFT, aallokekuvan kohinan vaimennuksen (wavelet image denoising) teoria ja moniulotteinen skaalaus. Liitteenä on muutama kaupallisesti tarjolla oleva mottling-analyysimenetelmä.

Käytössä olevat menetelmät, kuten STFI mottling expert, antavat yksiköttömän, painotetun vaihtelukertoimen arvioina mottlingista. Nämä menetelmät ovat tehty ensisijaisesti painojäljen mottlingin mittaamiseen, mutta soveltuvat myös painamattoman pinnan analysointiin. Analyysia voidaan kuitenkin parantaa ottamalla huomioon, että läheltä tarkasteltuna valkaisemattoman taustan heijasteet voivat jäädä havaitsematta valkaistun pinnan korkean heijastekertoimen takia, mutta voivat tulla näkyviin suuremmalta etäisyydeltä tarkasteltuna. Tämä voi vaatia taajuusanalyysin laajentamista ottamaan huomioon variaatioiden sijainnin.

Asiasanat: valkopäällystelaineri, heijasteen variaatiot, mottling, Fourier-analyysi

ABSTRACT

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White Top Linerboard (WTL) consists of a bleached top layer and unbleached structural layer. The top layer is considerably more expensive than the unbleached layer and there is a drive towards minimizing the thickness of the top layer. Too thin a top layer allows light reflection from the unbleached layer to affect whiteness of the top layer. This effect is known as white top mottling or unwanted lightness variation of the surface.

This thesis strives to collect information of the physical and physiological factors related to analysis of white top mottling including currently utilized methods for mottling analysis. After introducing the containerboard production process and products, terms related to optical qualities of mottling are discussed. This is followed by a review into human visual system (HVS) and its properties related to mottling analysis. A general view is provided of methods currently used for mottling analysis such as frequency analysis.

In conclusion, currently available methods such as STFI mottling expert, produce a unitless and weighted coefficient of variance as a result for the scale of mottling. These methods are primarily created for analysis of print mottling but are sufficient at creating comparable results for white top mottling. The analysis can be improved by allowing for different viewing distances. High reflectance factor of the white top layer can attenuate perception of reflections from the unbleached layer when viewed from close but can become visible at longer distances. This may require expansion of frequency analysis to consider the location of the lightness variation.

Key words: white top liner, mottling, lightness variation, Fourier-analysis

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ABBREVIATIONS

CIE	Commission Internationale de l'Eclairage (International Commission of Illumination)
FFT	Fast Fourier Transform
FWA	Fluorescent Whitening Agent
ISO	International Organization for Standardization
FBB	Folding Boxboard
WLC	White Lined Chipboard
LPB	Liquid Packaging Board
SBS	Solid Bleached Sulphate
HVS	Human Visual System
EMS	Electromagnetic Spectrum
LGN	Lateral Geniculate Nucleus (LGN)
CSF	Contrast Sensitivity Function (CSF)
JND	Just Noticeable Difference
ACF	Auto Correlation Function

1 INTRODUCTION

The subject of this thesis was provided by a paper industry manufacturer with an interest into current methods and systems for white top mottling measurement. Mottling is a major concern for the paper manufacturers, particularly with the growing market for sustainable packaging materials placing more demands on the quality of packaging boards.

Mottling is described as unwanted variation of perceived lightness on an otherwise uniform surface. White top mottling is a type of paper mottle that occurs when a thin layer of bleached pulp is applied to an unbleached structural layer, resulting in an uneven diffuse reflection of light combined from both the top and underlying surfaces.

The thesis begins with a short introduction to general linerboard production process, as well as the current market for packaging boards and the need for improved methods of mottle measurement. Afterwards it delves into theoretical background of mottling measurements and human visual perception. And finally, the thesis presents a few image analysis methods that can be used for white top mottle measurement and analysis.

The goal of this thesis is to provide information on the basics of mottle measurement and analysis, such as optical properties, capabilities and limitations of human visual system, and image and sample analysis methods.

2 CONTAINERBOARDS

2.1 Production process

The most common paper and paperboard production process is based on wet web forming where the appropriately selected paper components are mixed with water to form a suspension. Water acts as conveyor material that enables homogenous distribution of the raw material onto a thin web. In the continuous process water is removed from the web through drainage, pressing and evaporation. The end-product is ready for appropriate finishing processes. Important difference between paper and paperboard production processes is that the board is usually a multi-layer web with higher basis weight. A typical linerboard machine schematic is presented below in figure 1.

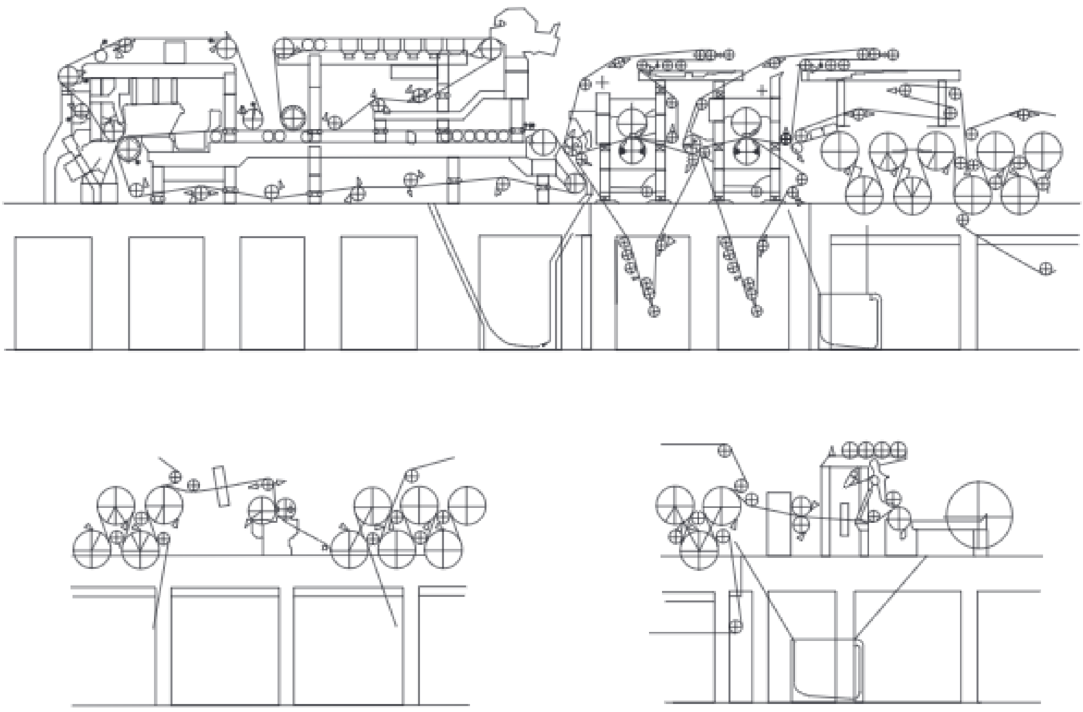

FIGURE 1. Linerboard machine with a gap former and a fourdrinier in the forming section. (Kiviranta 2000, 69)

For packaging boxboard the basis weight ranges from 170 to 450 g/m2 and velocity between 300 to 600 m/min and width of machine between 3 and 6 m. For linerboard the machine velocity ranges from 500 to 900 m/min and width of the machine up to 9 m. New machines can be over 10m wide (Valmet 2023). (KnowPap version 24.0, 2023, a)

2.1.1 Wet end and Headbox

The most important component of paper and board raw materials are fibers. Since properties of wood fibers in different pulps vary greatly, the use of mechanical, chemical, chemi-mechanical and recycled pulps is subject to changes between paper and board grades. Other raw materials include fillers, adhesives, chemical additives and different coating agents. (KnowPap version 24.0, 2023, a) Raw materials and their treatments are selected as economically as possible for each paper and board grade. For most board grades different furnish types are not only utilized as compositions but also for forming in layers. Selected treatment methods have significant effect on the properties of the end-product. Grinding and refining improve e.g. fibre bonding and formation of chemically separated fibres but impair opacity of the end product. (KnowPap version 24.0, 2023, b)

Pulp is diluted to appropriate consistency with filtrate water passing through the wire at part of the process called short circulation. It is located between pulp dosing and the board machine. Multilayer board machines have a short circulation for each layer. In addition to dilution, removal of impurities with hydrocyclones and screens, deaeration of dissolved gasses and optimization of particle size distribution and fibre and filler economy are achieved during short circulation. Another aim is also minimize pressure fluctuations before headbox. (KnowPap version 24.0, 2023, c)

Headbox is located between short circulation and the wire section. Short circulation piping delivers the stock suspension at desired consistency, usually 0,5 % to 1,0 %, into the headbox. The task of the headbox and short circulation piping is to distribute the stock suspension uniformly in the cross direction of the paper machine. (KnowPap version 24.0, 2023, a)

2.1.2 Forming, pressing and drying sections

There are various designs for forming sections for modern linerboard machine. Basic design for linerboard has two plies which can be done with two fourdriniers, a fourdrinier and a gap former, or with a single gapformer with a multichannel headbox. Separate forming sections are required for mottled, white-top and coated white top linerboards. (Kiviranta 2000, 68)

Tasks of the forming section include removing water from stock suspension through the forming fabric, prevent floc generation and their dispersal, maintain uniform retention of fiber and filler, and bring web to high enough dry content to enable runnability through press nips. Important structural properties such as basis weight variation, formation, opacity, and fiber orientation are determined during the forming section. (KnowPap version 24.0, 2023, a)

The water removal is continued at the press section where pressure is applied through roll nips to remove water while maintaining sufficient bulk and whole web structure. Pressing has strong effect on smoothness and symmetry, bulk and porosity and moisture profile. (KnowPap version 24.0, 2023, a)

In the drying section, water is removed through evaporation. Three common methods are: contact or cylinder drying, air-drying and radiation drying. Surface and strength properties as well as moisture profile are affected by the drying process. (KnowPap version 24.0, 2023, a)

2.1.3 Finishing

Finishing methods depend upon the grade requirements but typical for paperboard grades are winding and reelings. In addition, the product can be surface sized, coated, calendered or extrusion coated. Coating can be divided into three categories depending on the weight and consistency of the finishing agent applied: surface sizing, pigmentation, or coating. The target of surface sizing is to improve paper board strength. It reinforces bonds between fibers with a water-soluble binding agent, usually starch. Pigments can be added to surface size.

The purpose of coating of paper and board is to improve the appearance and printability. The goal is to affect optical properties such as opacity, brightness and gloss as well as surface smoothness, strength and ink absorption that affect printability. (KnowPap version 24.0, 2023, d)

Calendering serves three main purposes: improving surface properties such as smoothness and gloss and improve printing properties, adjusting paper thickness, and levelling the paper profile to obtain even rolls at the winder. Reeling is done to render paper and paperboard into a form that easier to handle. Reeling is first done at machine reel and may be reeled several times before it is a finished product. Purpose of rereeling is to secure that the product is flawless before going to further processing. Reeling is closely linked to maximum smoothness, with an effort to not waste work already done. Winding is done to collect paper or paperboard around a reel spool. The parent reel is cut into suitable width and length and wound up around cores before sending out from the mill. (KnowPap version 24.0, 2023, d)

2.1.4 Corrugating and gluing

Production of corrugated board starts with the corrugation process. As shown in figure 2, corrugating medium is first preheated to soften lignin and hemicellulose. The medium is then presteamed to add extra moisture and increase temperature close to 100 ^{o}C before corrugation.

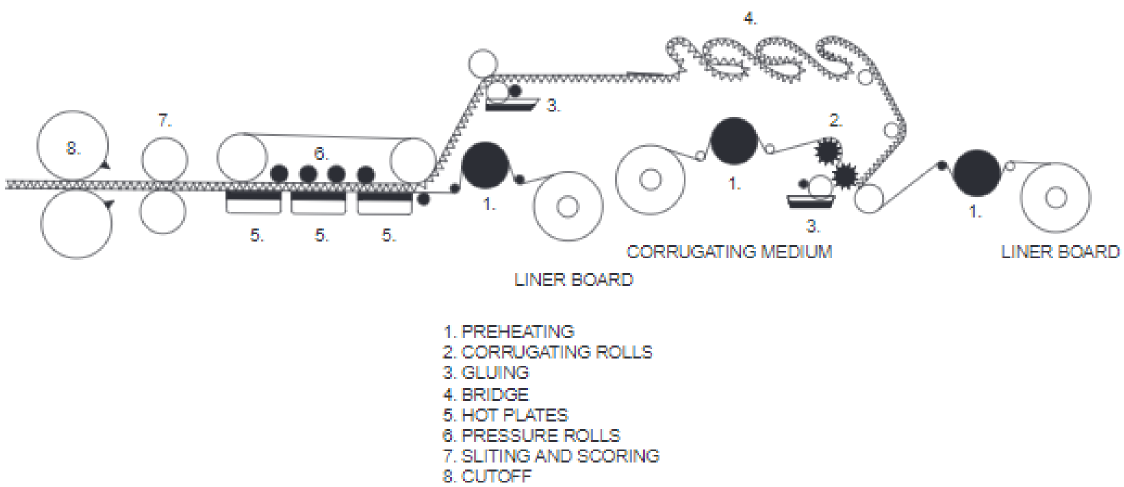

FIGURE 2. Corrugating machine (Kiviranta 2000, 65)

In corrugation, web is run between two heated corrugating rolls that are steam heated up to 190 °C. Afterward the glue is applied on the tips of flutes and liner is pressed against the corrugating medium to form single-faced corrugating board. This is followed by buffer stock called bridge acting as preparation before glue is applied to the other side of the fluting and second liner is added. Heating is used to dry the glue. Corrugated board is creased and cut on the machine. Some cracking may appear close to the location of crease or cut which is correlated to the strength of linerboard. Therefore, virgin fibers have clear advantage over recycled fiber in this respect. (Kiviranta 2000, 65)

2.2 Paperboard products

The wide variety of paperboards can be classified into three categories: cartonboards, containerboards and specialty boards. Most paperboard grades are multi-ply products and are used for packaging with some exceptions like plasterboard. Cartonboards are mainly used for consumer products such as food, cigarettes, and pharmaceuticals. Containerboards are a very big and growing market in paperboard industry. Corrugated boxes are used in many packaging applications ranging from simple transportation containers to multicolor printed display containers for stores. (Kiviranta 2000, 55)

The most important packing board grades are packaging boards: folding boxboard (FBB), white lined chipboard (WLC), liquid packaging board (LPB), solid bleached sulphate (SBS), carrier board and container boards: kraftliner, testliner and fluting or corrugated medium. Variety of specialty board grades is high, but production volumes compared to previously mentioned are low.

Containerboards, consisting of linerboard and corrugated medium, are used to produce corrugated board and corrugated containers. As such, corrugated board is an old packaging material but still very competitive with growing demand due to new environmental legislations and growing market awareness on sustainable development and disposable packaging. Corrugated boards can be divided into four groups: single-faced, single-wall, double-wall and triple-wall corrugated boards. Single-faced corrugated board has just one liner and one corrugated medium glued together. This is not used for boxes but as protective material. Single-wall corrugated board is the most common raw material for corrugated boxes. It has a single corrugated medium glued between two liners. Double-wall corrugated board has two layers of corrugated medium and three liners, and triple-wall corrugated board has three layers of corrugated medium and four liners. Basis weight and type are depended on the end use and protection needed. Triple corrugated board with high basis weight liners is used for high strength applications, while micro-flute corrugated board is on the other end of spectrum competing with FBB and SBS markets. (Kiviranta 2000, 64)

Linerboard is used as liner for corrugated board and their typical basis weight range is 100-350 g/m^2. Linerboard is manufactured with various top plies and raw materials. Both softwood and hardwood are used as well as virgin and recycled fibers. When mostly virgin fibers are used, linerboard is called kraftliner, and linerboard containing recycled fibers is called testliner. If virgin softwood kraft pulp is used, the pulp for base ply is cooked for high yield and then refined slightly. Top ply is cooked to lower kappa number and refined more than base ply. Linerboard is also resin sized for moisture resistance. Recycled fibers may require surface sizing to produce sufficient strength properties. (Kiviranta 2000, 66)

Brown linerboard consists of unbleached top and base plies, and it is the simplest linerboard product since requirements for printing properties are not high. Typical basis weight split between top and base plies is typically 30/70 depending on machine design. Mottled linerboard has a top ply made of bleached pulp. Top ply basis weight is typically low, roughly 40 g/m^2, to give the linerboard a flocky appearance. The appearance is further enhanced by increasing headbox consistency and by increasing jet-wire speed, compared to other linerboards, to make formation worse. White top linerboard, figure 3, is used for more demanding printing jobs, and therefore smoothness and appearance of the top ply are very important.

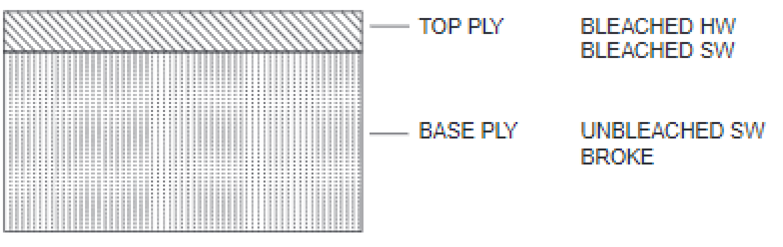

FIGURE 3. Structure of a white (kraft) linerboard. (Kiviranta 2000, 67)

Bleached chemical pulp is used for top ply which typically has basis weight of 70-80 g/m^2. Hardwood is required for excellent formation and visual appearance. Opacity and therefore visual appearance are further improved by use of fillers. For most demanding applications, white top linerboard can be further coated on or off machine. These applications include containers that are used to display products in stores. Testliner (figure 4) is usually produced with four plies compared to the usual two layers for kraftliner.

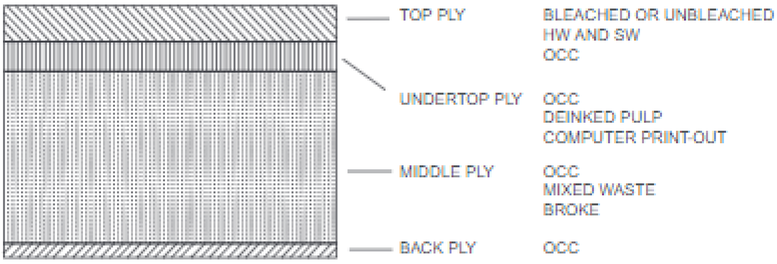

FIGURE 4. Structure of a test linerboard. (Kiviranta 2000, 67)

Due to used recycled fiber, linerboard properties can be better optimized with four-ply structure and drainage of high resistance fiber is easier when base ply is split into multiple lighter plies. (Kiviranta 2000, 67)

2.3 Economical and environmental aspects

According to Fortune Business Insights market research report the global containerboard market size was USD 126.66 billion in 2021. The market size is projected to grow to USD 153.51 billion in 2029. Increasing demand for sustainable packaging solutions point toward bright future for containerboard grades. The board was one of the most recycled packaging materials (approximately 88.8

%) in 2017. The production of corrugated boxes from recycled material help manufacturers reduce environmental impact. (Fortune Business Insights 2022)

The Demand for low basis weight products is growing and microflute-based corrugated board is gaining ground in consumer packaging. Increasing amount of point-to-sale and display applications for consumer containerboard sets increasing demands for print and packaging requirements. Production lines may need to be upgraded to produce quality lighter-weight grades economically including upgrading on-line measurement systems. (KnowPap versio 24.0, 2023, e)

The perceived value of paper and paperboard products depends on both the performance and their visual appearance. (Farnood, 2009) Raw material of linerboard top layer is, however, far more expensive that of the body layer and should therefore be minimized. If top layer is too thin, the board will appear uneven due to the body layer. This phenomenon is referred to as white-top mottling.

3 OPTICAL PROPERTIES AND MOTTLING

3.1 Optical properties

Optical properties of paper refer to how light is reflected, scattered, and absorbed by it. Light that penetrates paper surface to certain depth, reflects from the boundary surfaces of particles, and is finally emitted back to entry side is called scattered or diffusively reflected light. Our perception of lightness, brightness or color is formed by observing diffusively reflected light. Optical inhomogeneities are spatial variations of these properties. Some incident light absorbs into the paper and is released as heat. Absorption is wavelength specific and therefore most materials have color under ‘white’ light. Variation in light absorption over the printed surfaces is particularly easy to see type of inhomogeneity. (Vaarasalo 1999, 163-164)

3.1.1 Basic concepts

Reflectance factor, R, is the ratio of radiation reflected by a body to that reflected by the perfect reflecting diffuser. Measurement of reflectance factors uses an absolute scale. This means that reflectance factor of an ideal diffuser is 1 or 100% and zero (0) for a black body. Intrinsic reflectance factor is a measure of reflectance factor when no light is transmitted through the object. The measurement uses a sufficiently thick stack of paper that no light penetrates. On-line measurement uses a single sheet of paper with white background. Intrinsic reflectance factor is used in determination of brightness, whiteness, and color in laboratory conditions. (Vaarasalo 1999, 165)

Opacity is the measure of paper attribute that makes it impermeable to light. Depending on paper thickness and its light scattering properties, some incident light may transmit through the paper. There is an economic drive towards lower basis weights while maintaining adequate opacity. In layered products, such as white-top liners, light transmitted through to the unbleached layer and then reflected back toward an observer may be perceived as mottling. (Vaarasalo 1999, 175)

Gloss refers to paper's 'shininess' and it is the ability of the paper to reflect light in specular direction. If sample is viewed from specular angle, gloss mottle may appear. Gloss is a psychophysical property that influences the perception of the human observer. Important distinction between print mottle and gloss mottle is the difference in wavelength for subjective quality; 0,4-3,2 mm for gloss compared to 1-8 mm for print density. (Fahlcrantz, 2005) When determining lightness and reflectance, gloss component is eliminated as much as possible. (Vaarasalo 1999, 163)

CIE defines brightness as "the reflectance of blue light with a specified spectral distribution peaking at 457 nm compared to that of a perfectly reflecting, perfectly diffusing surface". Historically, brightness was used as a measurement of whiteness but difference in illumination conditions and the use of OBAs have lead into better whiteness quantification methods. (Farnood, 2009)

"Whiteness is a colorimetric property. The impression of whiteness consists of the perceived lightness and hue." (Vaarasalo 1999, 174) The estimation of commonly perceived whiteness is done with CIE whiteness equation and it is done under a specific illumination and viewing geometry (D65/10°). Colour appearance, and thus perceived whiteness, can additionally depend upon the immediate environment of the colour stimulus. This is of particular interest when the compared paper samples affect each other's perceived appearance. All color models are only valid in well-defined visual environments including the viewing geometry. Whiteness is a commercially important property for paper and board products. The use of FWAs and violet-blue shading dyes in paper has increase due the strive toward a higher degree of pulp bleaching and whiter papers. FWAs are dyes that work by absorbing UV light and radiating out a longer wavelength from the blue region of the spectrum. Perceived whiteness is thus increased due to increased lightness and blueness (Coppel 2012) There is an ISO standard for indoor whiteness (ISO 11476) which stipulates the use of the CIE illuminant C/2°, which has a much lower UV content than CIE illuminant D65/10° specified for outdoor whiteness (ISO 11475).

3.1.2 CIE systems for lightness and colour

The stimulus of an eye or test result of an instrument is the product of an energy distribution of the illuminant, S(λ), the reflectance of the object, R(λ), and the spectral response of the detector, y(λ). Repeatable and comparable test results are possible only if the properties of the illumination and the response of the instrument have been standardized. This requires standard illuminant and standard observer. The characteristics of an illuminant can be unambiguously described by the energy spectrum of the light source. The spectral energy distributions of CIE standard illuminants are available in CIE publication. The standard observer is a numerical description of relative sensitivity of HVS to different wavelengths of light. (Vaarasalo 1999, 166-167)

The two most popular colour systems in the paper industry are CIE's system from 1931 and CIELAB system. In the CIE 1931 system the tristimulus values X, Y, and Z describe the amount of stimulus caused by red, green, and blue light respectively. CIE 1931 colour system is based on additive mixing of lights. Placing colour coordinates x (=X/(X+Y+Z)) and y (=Y/(X+Y+Z)) into a perpendicular x, y -coordinate system gives a horseshoe shaped plot that represents all real colours. When using x,y colour coordinates as a measure of hue and saturation of a colour, interpreting the result requires placing the measured colour into the coordinate system and comparing it to the color point of the illuminant. (Vaarasalo 1999, 168-170)

CIELAB colour space results from the CIEXYZ system in the following manner:

$$L^* = 116(Y/Y_n)^{\frac{1}{3}} - 16 \tag{1}$$

$$a^* = 500\left[(X/X_n)^{\frac{1}{3}} - (Y/Y_n)^{\frac{1}{3}}\right] \tag{2}$$

$$b^* = 200\left[(Y/Y_n)^{\frac{1}{3}} - (Z/Z_n)^{\frac{1}{3}}\right] \tag{3}$$

where X_n, Y_n, and Z_n are the tristimulus values of the perfectly reflecting diffuser for the selected illuminant and observer. L* is a measure of perceived lightness, a* is a measure of hue in the red-green axis and b* is measure of hue in yellow-blue axis. (Vaarasalo 1999, 172)

CIEL*a*b* is a three-dimensional colour system (figure 5) adjusted to correlate with human interpretation of colours. Human visual system (HVS) is more sensitive to lightness variations (L* channel) than colour variations, and more sensitive to red-green (a* channel) variations than to blue-yellow (b* channel) variations.

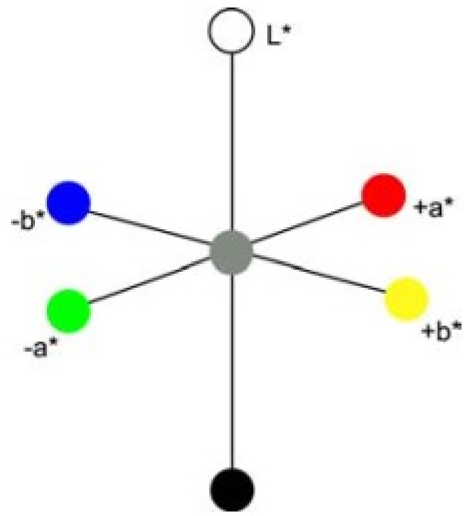

FIGURE 5. CIEL*a*b* colour representation through three channels: Lightness in channel L*, red-green in channel a* and blue-yellow in channel b*. (Christoffersson, 2004)

L* axis for luminance goes from 0 (black) to 100 (white). The a* -axis range from -100 (green) to 100 (red) and the b* axis range from about -100 (blue) to 100 (yellow). This system is unit independent and physically exact and therefore can be used in scanners, monitors and printers. According to Barten's contrast sensitivity function, the weighted relationship between L*a*b* is 8:2:1. Meaning change in b* channel needs to be 8 times larger than in L* channel to be equally disturbing to HVS. (Christoffersson, 2004)

3.2 Definition of mottling

The term mottle is used today across multiple disciplines, and it is generally used to describe a type of optical inhomogeneity. According to ISO/IEC 24790:2017(en) standard, mottle is measure of the appearance of unintended, aperiodic macroscopic fluctuations of lightness.

Paper is composite material with a non-uniform mass distribution, also known as formation, and thickness variation. This non-uniformity can give rise to unwanted print artefacts known as print mottle. Print mottle can be defined as perceived inhomogeneities in a print due to spatial variations in the amount of reflected light from a homogenous light source (Fahlcrantz, 2005).

This non-uniformity also affects the visual quality of layered products for which the perceived whiteness and shade can vary laterally due to properties such as thickness variation of the top layer or non-uniform fluorescent whitening agent (FWA) distribution. For products with a white-top on less bleached layers, this detrimental lateral variation of the product appearance is known as white top mottle. (Coppel 2012)

3.3 White top mottling

White top mottle is a type of paper mottle, i.e. variations in light absorbance over the unprinted surface that are seen in diffuse or directed light but not in specular angle (Fahlcrantz, 2005). In other words, it is variations in perceived whiteness. Depending on the scale of variation, it can be called e.g. graininess (small) or cloudiness (large) of the paper. (Coppel 2012) Most obvious difference between print mottle and white top mottle is the reflectance factor. Print mottle reflectance factor is between 10 to 50% while white top mottle reflectance factor is usually in 85 to 95% range. Since CIEL*a*b* metric is proportional to the cubic root of luminance, the perceived lightness differences are generally insignificant for white top mottle between samples. (Fahlcrantz, 2005) Other important factors include amplitude and coarseness of the variation as well as texture and to some extent the chromatic variations.

4 THEORETICAL BACKGROUND - DETECTION

4.1 Human visual system

The Human Visual System (HVS) is one of many evolutionary solutions to detect movements and objects in the surrounding environment. HVS is sensitive to electromagnetic radiation between wavelengths of 420 and 720nm. This "visual light" is most intense part of sun's electromagnetic spectrum (EMS) on earth and thus it is most likely that radiation from this part of the EMS is available in many scenarios for surface living mammals. Other evolutionary solutions to track surroundings include, for example, sonar systems used by bats and dolphins. (Fahlcrantz, 2005)

To better understand HVS, we need to first understand what is required to map surroundings. First, light reflected from all types of objects in the environment need to be registered by some kind of detector. Direction of the arriving light can be taken into account by a matrix of these detectors. For best performance, all light from a specific direction hit only a specific detector. Light from all other directions is deflected away. This can be achieved by allowing only tiny amount of light through a very small hole or more light through larger apparatus in combination with a type of lens system to sustain the directional information. Next the detection information needs to be collected and conveyed to a processing unit. For this we need a link between the detectors and the processing unit. This describes the main corner stones of HVS: detection, transmission and processing. (Fahlcrantz, 2005)

Approximately three out of four sensor cells in human body is located in the eyes making vision the most prevalent sense for experiencing the world. Therefore, any imaging model that concerns human experience should be based upon HVS. (Christoffersson, 2004)

4.1.1 The eye

According to fundamental nature of quantum physics, electromagnetic radiation is statistical in nature and described as a stream photons. To create a stable image, HVS must perform a smoothing operation, either by integrating over certain detection area or over time (or both). Secondly, most objects are not self-luminous, and perception of such reflecting objects is completely dependent upon surrounding illumination. For the object to register to us as same under different illumination conditions is therefore not dependent upon absolute reflected light by specific object but relative to the amount of light arriving from surroundings. This implies that HVS is more sensitive to relative luminance levels compared to absolute differences.

The eye is a sphere with a diameter of about 25 mm (Figure 6).

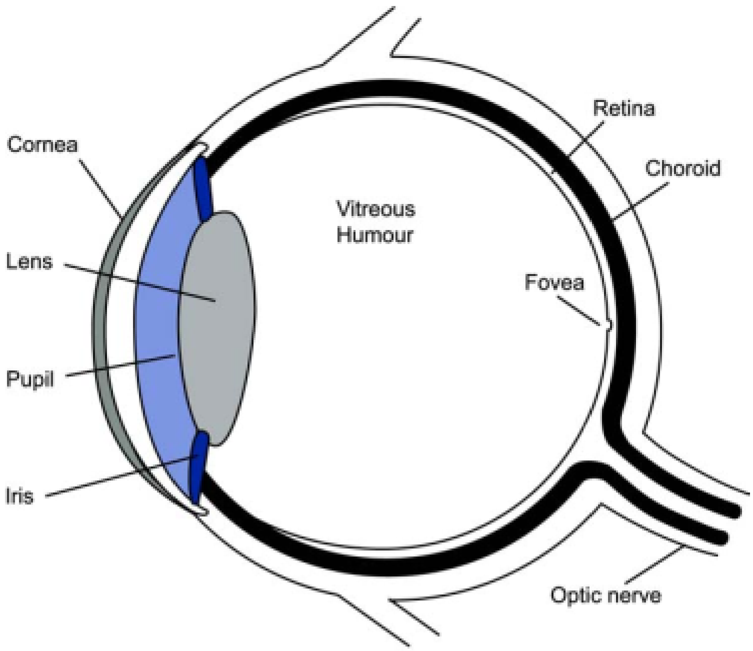

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FIGURE 6. Schematic view of the structure of human eye. (Christoffersson, 2004)

When light first enters the eye, it passes through the cornea: an outer layer on the front of the eye that is nonvascular and transparent. The cornea, and not the lens, is responsible for most of the bending of the incoming light. Behind the aqueous liquid, the light passes through the pupil, an opening of variable size in the middle of opaque iris (external eye color), into the eye and defines the illumination level on the retina. The overall level of illumination determines the size of the pupil, which varies between three and seven millimeters.

The lens divides the eye into two chambers. The transparent and elastic lens has a variable index of refraction by changing its shape, which makes it possible to focus on objects both nearby and in the distance (accommodation). After passing through the lens, light (photon) has gained its final direction and travels through the central chamber of the eye filled with vitreous humour before it hits a corresponding photoreceptor in the retina. Vitreous humour consists essentially of water with viscosity like that of gelatine.

The retina is a thin layer of cells located in the back of the eye. Photosensitive cells, photoreceptors are located at retina ‘under’ the thin layer of nerve cells facing away from incoming light. Dark brown pigment epithelium prevents internal reflections by absorbing photons not caught by photoreceptors.

4.1.2 Detection and transmission

Due to many imperfections of the eye, such as spherical aberrations, light scattering, and imperfect focus etc. The light from certain direction of space does not arrive at a singular point at retina but has a spatial distribution that can be described with a point spread function. This is a good thing to keep in mind when studying the retinal architecture. (Fahlcrantz, 2005)

The retina is responsible for detecting the radiation stimuli, transforming it to optical information and transmitting the information to the brain. Retina is layered and consists of four different categories of neurons (ganglion cells, amacrine cells, horizontal cells, and bipolar cells) and light-sensitive photoreceptors (figure 7). The axons of ganglion cells coalesce into the optical nerve fibre that transfers information from retina to cortex.

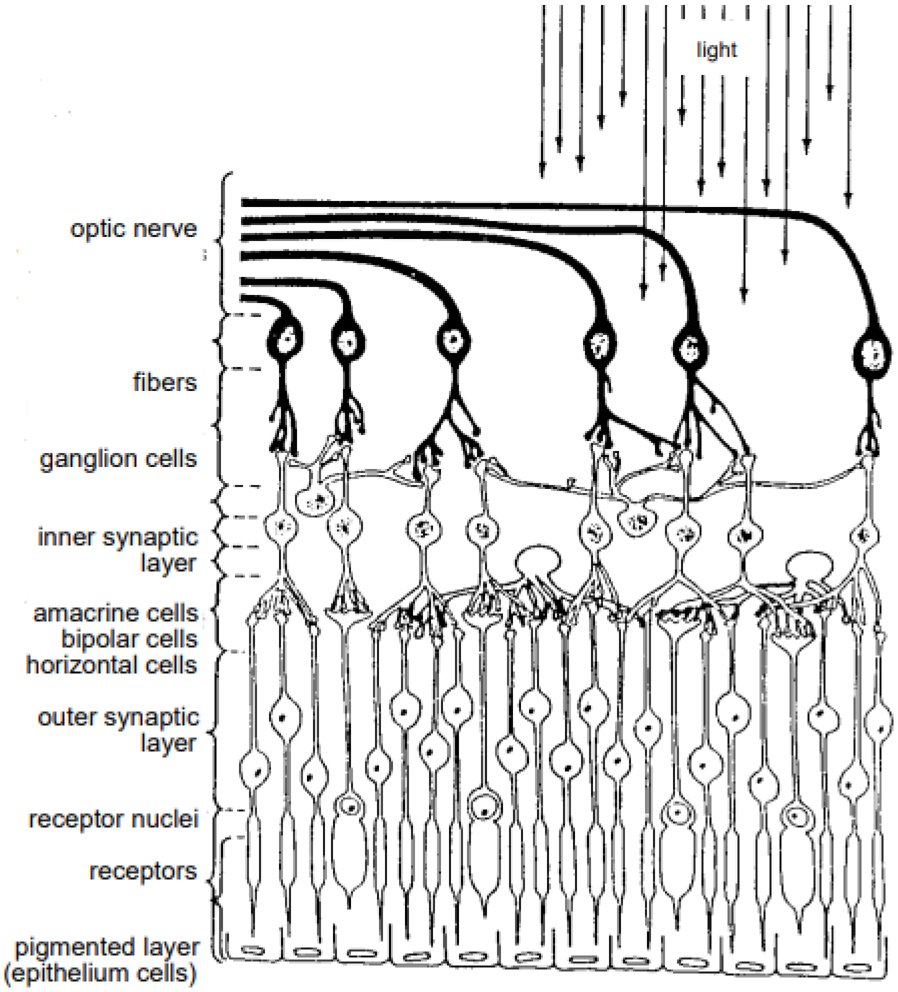

FIGURE 7. Structure of human retina. (Girod 2000, 4)

Detection is handled by the photoreceptors that come in two fundamentally different forms, rods, and cones. The receptors are named after their shapes. There are, depending on sources, between 5 to 9 million cones and 75 to 150 million rods. Rods are found everywhere on the retina with highest density at parafovea, region surrounding the fovea which in turn is characterized by an exclusive population of very densely packed cones. The fovea is responsible for our focally highly resolved vision.

The ratio of rods to cones (roughly 15 to 1) might give a false impression that the number of neurons connected to rods is a magnitude greater than neurons responsive to cones. A bipolar cell is usually connected to several rods while cones may have several bipolar cells connected to them. Bipolar cells work as relay neurons connecting photoreceptors and ganglion cells. In many cases, where bipolars are connected to rods, bipolars are not directly connected to ganglion cells but the signals are collected by amacrine cells which are in turn connected to ganglion cells. Spatial excitations are transferred horizontally between neighbouring bipolars and receptors by horizontal cells. The amacrine cells are responsible for same interaction between bipolars and ganglion cells. This architecture implies that some signals may be supressed by others and that information conveyed by the bipolar cells that collect information over large spatial area cannot contain information that is as high resolution as information from the foveal region.

The rods do not register light and operate at low light intensities. They are responsible for scotopic, or dim light, vision. They are dominantly located at the retinal periphery while cones are only located near and within the foveal area which is responsible for our sharpest vision. Cones activate under photopic (bright) conditions and therefore visual acuity in scotopic viewing conditions is very poor compared to photopic conditions.

The optic nerve carries the information to two main areas known as the Lateral Geniculate Nucleus (LGN) and the Superior Colliculus (figure 8). The optic nerve consists of more than 1 million nerve fibers, which is considerably lower compared to the approximately 130 million photoreceptors at the retina. This provides a very compelling explanation for why peripheral input is so heavily spatially low pass filtered and compressed by the cell structure of retina. There simply is not enough bandwidth available to convey all the visual information. (Fahlcrantz, 2005).

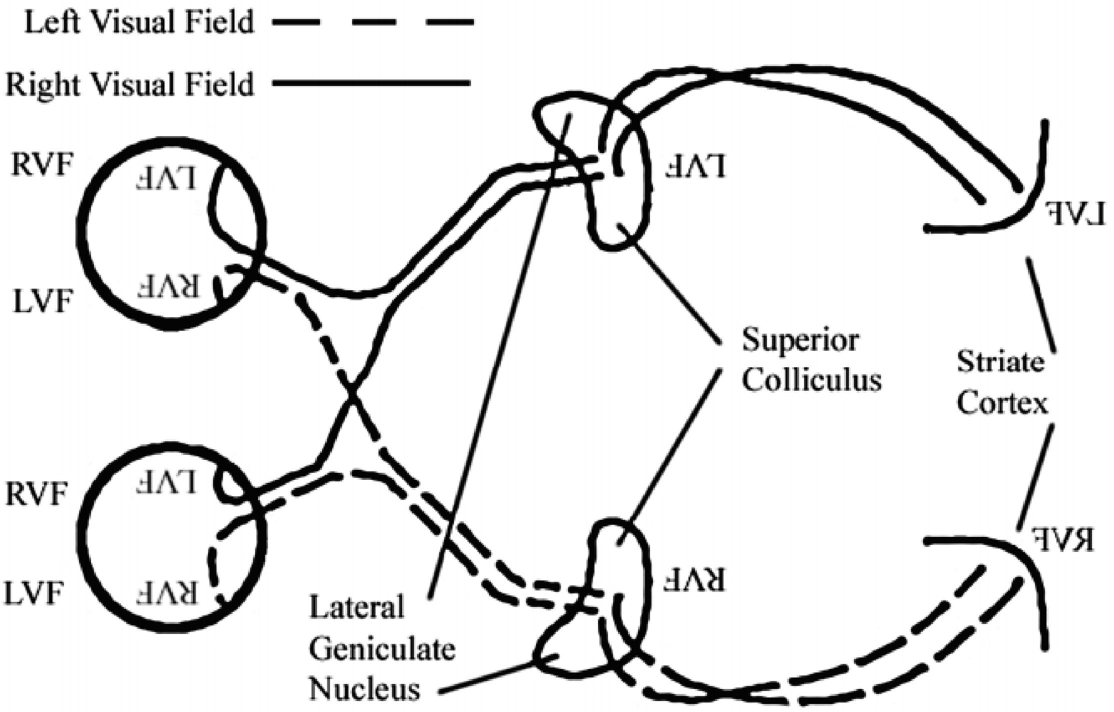

FIGURE 8. Pathways of visual information. (Fahlcrantz, 2005)

The LGN can be considered a relay station between the retina and the striate cortex. The fibers from corresponding halves of retina from both eyes first break up into three layers and are then interwoven into a six layered arrangement. Since the separation is not based on spatial regions, it is thought to reflect a functional division. Interneurons in the LGN perform functions such as spatial filtering of visual information similar to horizontal and amacrine cells.

Topographically, left visual field is projected to right side and right visual field is projected to left side of the striate cortex where final processing takes place. How this processing is achieved has many theories. Models based on empirical data and psychophysical evidence, describing how frequency and structure analysis may be achieved at cortex cell cluster level, suggest that we are less sensitive to random mottle compared to systematic mottle. It is theorised that visual perception of reality is a recursive process where visual stimuli are matched with previous stored experiences that are projected backwards. What we then end-up with is a loop, constant trial-and-error simulation to cope with reality. Assuming that memory is fairly constant over a short timeframe, its effect on perception should be heavily influenced by available visual stimuli and viewing conditions. For example, it can be hard to correctly identify an object under scotopic conditions or it can be hard to recall a specific memory under heavy photopic stimuli without closing eyes.

So, what has this to do with mottle evaluation? Well, it suggests that the evaluation should be made under neutral and very stable conditions so that influence of previous recent experiences during evaluation are minimized. As summary, the HVS is by design discriminating between relative levels of light and it is sensitive to variations within limited spatial frequencies and not to those far outside this range. Later processing makes human more likely to spot systematic rather than random noise as this is more useful in nature. These processes also interact with areas responsible for memories and reasoning which necessarily make quality evaluations subject to previous experiences. (Fahlcrantz, 2005.)

4.2 Colour perception

For HVS colour perception is a key element in helping distinguishing objects and their boundaries. Not only does terrestrial illumination vary extensively, depending upon whether object is under direct light or in shade, but the local intensities of illumination may also vary dramatically on different parts of the same object. This can make it very difficult to discriminate between boundaries of the object and boundaries of the shadows. The spectral distribution however is more constant compared to intensity of the radiation and may therefore help to classify objects and their boundaries.

Cells ultimately responsible for discriminating between different colours are the three types of cone photoreceptors. The classification is based on the wavelength sensitivity of the photopigment in their outer segment. These types are commonly called L-cones, M-cones, and S-cones, referring to long (peak sensitivity at 560 nm)-, middle (peak sensitivity at 530 nm)-, and short-wavelength (peak sensitivity at 440 nm) sensitivity (figure 9).

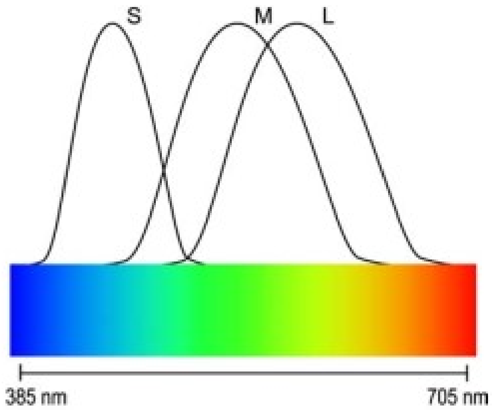

FIGURE 9. Photoreceptor sensitivities by wavelength. (Christoffersson, 2004)

The fovea is completely inhabited by cones, especially L and M cones, which are sparsely populated outside of this area. S cones are relatively uniformly spread across the retina with the highest population being just outside fovea. There is a relatively small number of S-cones, and about twice as many L-cones as M-cones, with the relative populations of 1:20:40 (1:5:10 (Fahlcrantz, 2005)). There are several reasons for this asymmetry. Main reason for s-cone structural sampling difference compared to M and L cones is that the chromatic aberrations of the lens make it impossible to detect high frequency spatial variations of short wavelength light (Fahlcrantz, 2005).

First modern colour theories of human perception were published in the 18th century. The trichromatic theory (Young-Helmholtz 1867) of detecting red, green and blue was later complemented by an opponent colour process theory (Hering 1878) that suggested receptors that detect colours in pairs: red-green, blue-yellow and black-white. These two theories were merged by (Hurvich & Jameson, 1957) into dual process theory in which the trichromatic receptors provide input for the Hering's opponent process. Such colour selective cells exist among bipolar- and ganglion cells that show chromatically opponent responses. (Fahlcrantz, 2005)

For colour mottle perception, using the opponent colour coding, the three-dimensional representation human colour vision (e.g. CIEL*a*b colour space) seems appealing. If early processes of HVS use these processes to code wavelength information, then it is reasonable to assume that HVS sensitivity for spatial chromatic variations are also related to these three dimensions. The attenuation of low spatial frequency luminance patters that is produced by centre-surround antagonism does not occur for colour due to effective centre-surround synergism. Ganglion cell receptive field is presented in figure 10. (Fahlcrantz, 2005)

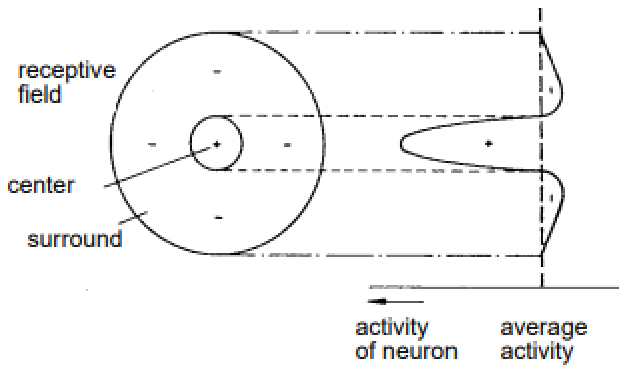

FIGURE 10. Receptive field of a ganglion cell. (Girod 2000, 6)

In other words, HVS emphasises local spatial similitude over contrast in the chromatic sense and implies lower sensitivity for medium to high frequency chromatic variations compared to sensitivity for spatial luminance contrast of similar frequency variations. This is supported by the differences in perception between scotopic and photopic conditions and how lightness variations are more disturbing to us compared to colour variations. In addition, the proportion and number of S-cone receptors and lack of 'yellow' receptors suggest lower sensitivity for yellow-blue variations compared to red-green variations. Moreover, since s-cones are far more spread out than M and L cones, sensitivity to blue-yellow variations in higher frequency spatial variations is considerably lower than to red-green variations.

In other words, HVS has evolved to attenuate low spatial frequency lightness variations and our achromatic perception gives us a middle to high frequency representation of the world emphasizing fine details. Our chromatic perception covers low to medium spatial frequencies and provides information about extensive areas. (Fahlcrantz, 2005)

4.3 Human visual acuity

HVS's ability to resolve details is known as visual acuity. The normal human eye can resolve line patterns of alternating black and white lines as small as one minute of an arc (1/60 degree or π/(60*180) = 0.000291 radians). This incidentally is the definition of 20-20 vision. For most people, any higher frequency will appear pure gray as will low contrast patterns at maximum spatial frequency. (Norman 2013) Minimum distance between cones at fovea limits the spatial resolution (2-2.3 μm or 25-29 arcseconds (Girod, 2000)). The human visual system's contrast sensitivity function (CSF) provides a characterization of its frequency response. It can be thought of as a bandpass filter, and there are several different tests to determine its characteristics. One of them involves a measurement of visibility thresholds of sine-wave gratings. (figure 11)

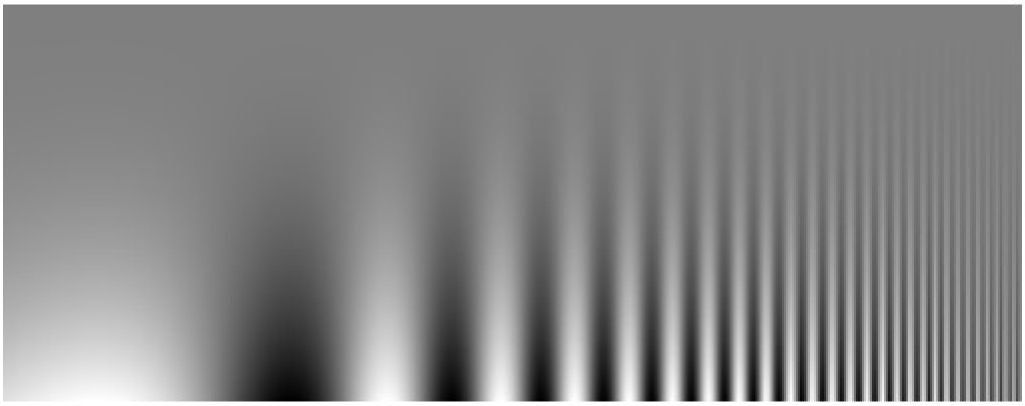

FIGURE 11. Example of a sinusoidal pattern with different frequencies. (Christoffersson, 2004)

For each frequency, a set of stimuli consisting of sine-waves of varying amplitudes are presented to an observer and detection threshold is determined for each frequency. This results into a curve (figure 12) that is called the contrast sensitivity function. (Christoffersson, 2004)

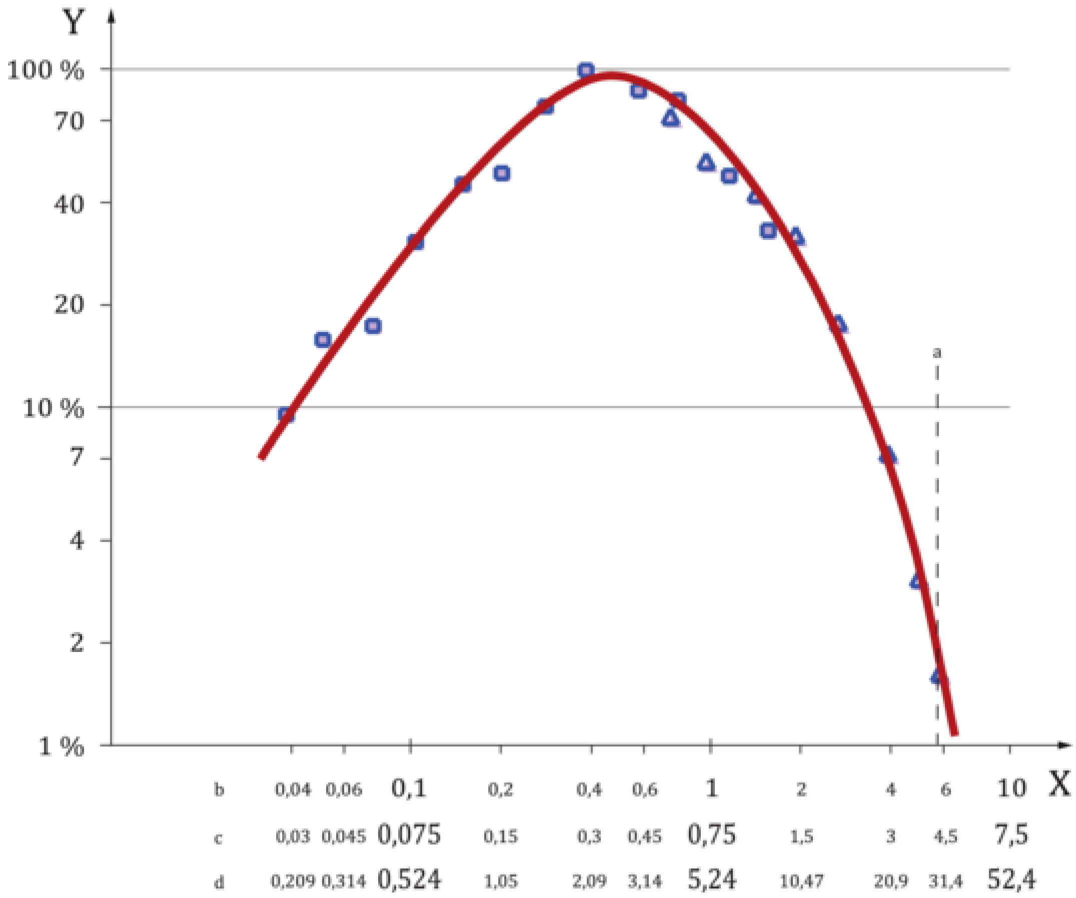

FIGURE 12. Human contrast sensitivity function CSF. Y is relative contrast sensitivity, X is spatial frequency, a is 6/6 visual limit, b is cycles/mm at 300 mm, c is cycles/mm at 400 mm and d is cycles/degree. (Technical Committee ISO/TC 130, 2020)

Lightness contrast sensitivity has a peak sensitivity around 3 cycles per degree of visual field with a band pass tendency. The chromatic contrast sensitivity function is weaker and has a peak sensitivity of ≤ 1 cycle per degree of visual field with a very weak band pass or a low pass tendency. Relative sensitivities between lightness and opponent colours are presented in figure 13.

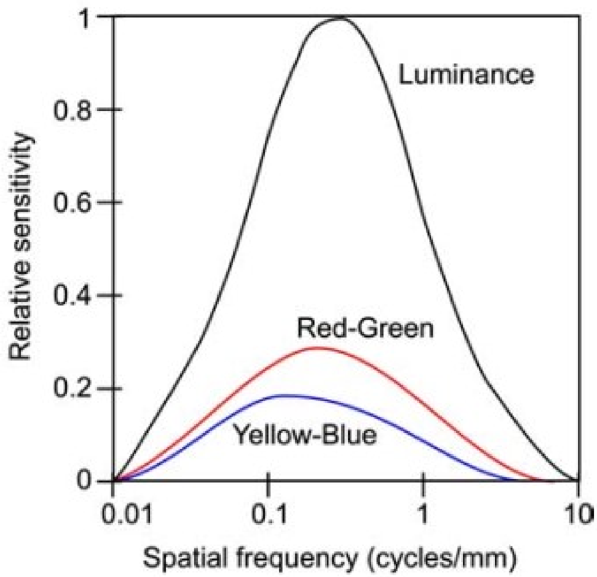

FIGURE 13. Relative contrast sensitivity for L* - channel, a* -channel and b* channel. (Christoffersson, 2004)

Contrast sensitivity of the eye indicates how perception of stimulus varies according to its frequency. While human eye is most sensitive to wavelengths of 1-8 mm, it can detect details in the range of 0.25 – 16 mm and therefore they should be included into the mottle calculations. (Christoffersson, 2004) Since spatial frequency is presented in units of cycles per degree of visual angle, visibility of details at certain frequency is a function of viewing distance. Therefore, it is important to specify a minimum viewing distance where distortion is maximally detectable. (Thrasyvoulos et al. 2005)

However, some details can be hidden under high CSF value objects and can only be seen further away like the number under the diagonal lines in figure 14 below. This may be relevant for white top mottling since the top layer with high reflectance factor may hide lightness variation under it when viewed from short distance away while mottling may become visible when viewed farther away.

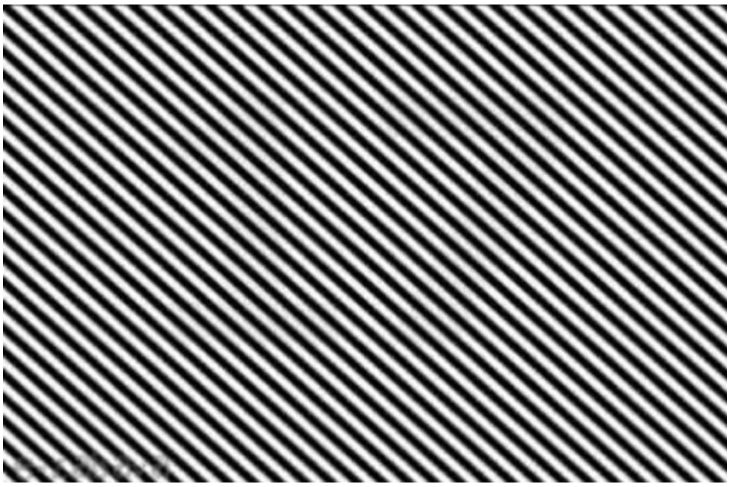

FIGURE 14. Lower CSF value number (17) hidden under high CSF value diagonal lines. (Imatest LLC)

5 PSYCHOPHYSICS

The notion of sensory threshold is central to the field of psychophysics. The idea that a sensory event must exceed a critical level to be consciously perceived was first introduced in the early 19th century by philosopher Herbart. It is important here to distinguish between two types of thresholds: absolute threshold and difference threshold. The absolute threshold is the minimum stimulus energy required to produce a detectable sensation, and it is closely related to the absolute magnitude of the stimulus. The difference threshold, on the other hand, is the magnitude of change in the stimulus that can produce a just noticeable difference (jnd) in the sensation. This threshold therefore deals with magnitude of variation of stimuli. Since white top mottle is defined mainly as spatial lightness variation in reflectance, the difference threshold is of concern when analysing mottle. Sensations can vary in other respects besides intensity, such as duration, quality, and extension. In the case of mottle, duration should not be an issue as long as samples are viewed under temporarily homogenous illumination. Quality variation here does not refer to overall excellence but rather to types of mottle i.e. systematic or random disturbances, although it may be relevant. Extension may be of interest when evaluating the size of the sample, in which the stimuli are observed, influences mottle magnitude assessment. (Fahlcrantz, 2005)

Regarding difference thresholds in human sensory stimuli, Weber discovered that just noticeable difference was larger for heavier weights than lighter ones, and the difference seemed to grow in a linear fashion. This has since been found to apply surprisingly well for whole range of sensory stimuli. The relationship can be described as follows:

$$c = \frac{\Delta\Phi}{\Phi}, \tag{4}$$

where the “Weber’s Fraction” c differs for different types of sensory stimuli, Φ. Weber’s fraction does not hold especially when stimulus levels are very low, and c grows rapidly. A modification is suggested to better match empirical data:

$$c = \frac{\Delta\Phi}{\Phi + \alpha}, \tag{5}$$

where constant α compensates for the deviation at low stimulus levels. A plausible neurophysiological reason (not related to any finding) for this compensation might be a correlation to background noise level of the nervous system. However, theory is not infallible, and disagreements at higher level stimulus have lead to suggestions of more complex relationships for many types of sensory stimuli. Fechner took Weber's work and founded what is today known as psychophysics. Fechner integrated Weber's law (1) over a series of physical values, and result is today known as Fechner's law:

$$\Psi = k \log(\Phi), \tag{6}$$

meaning that the mental experience of the intensity, Ψ, is proportional to the logarithm of the physical level, Φ. However, Fechner's conclusions are based on Weber's Law and are therefore only valid to the extent of Weber's law. Experiments suggest that Fechner's Law is only applicable as an approximation of reality and should be applied with caution. Both Weber's and Fechner's Laws are, however, good starting points in search for a model that agrees with empirical results. (Fahlcrantz, 2005)

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:

$$L^* = \beta Y^{\frac{1}{3}} - \gamma, \tag{7}$$

where β and ϒ are constants. The lightness equation is similar to Weber's and Fechner's laws, as the relationship between physical and the perceived level in both case is a concave non-linear function. Additionally, the functions do not hold for low physical values.

6 MOTTLING ANALYSIS

6.1 Frequency analysis

In mathematics, Fourier analysis is the study of the way general functions may be represented by sums of simpler trigonometric functions. Fourier analysis sprouted from study of Fourier series named after French physicist Jean Baptiste Fourier, who published his work "The analytical theory of heat" in 1822. This work argued that a periodic waveform of any complexity could be analysed by a linear sum of harmonically related sine and cosine waves. The method has also been extended to non-periodic functions and has been utilized in many fields of modern science. To use Fourier analysis, data must be equally spaced and different approaches must be utilized for analysing unequally spaced data.

An image can be transformed from spatial domain into frequency domain by using Fourier analysis. The number of frequencies corresponds to number of pixels in the spatial domain and each point in the frequency domain represents a particular frequency in the spatial domain. Aim of frequency analysis is to visualize the contribution of each sine and cosine component to whole signal. The complex numbered output image produced by Fourier transform can be displayed in two ways: with magnitude and phase parts or with real and imaginary parts. Magnitude part tells how great the contribution of a frequency is to the whole signal and phase part tells the location of that contribution. In mottling measurements, the magnitude is of more interest than the phase part since the amount of variation in different frequencies is of more interest than their location. Amplitude also seems to be more important in describing about the textural characteristics of the mottle (Fahlcrantz, 2005).

The amplitude component of a signal is commonly presented in a Power Spectrum. The power spectrum is often presented, due to symmetry, as two-sided where each peak occurs on both sides of the origin. Since image is two-dimensional signal, the frequency domain must also be in two dimensions. In two-dimensional case, the power spectrum is presented as an intensity image, where the amount of variation in particular frequency is revealed by the magnitude of the intensity at corresponding image point (figure 15). Orientation of variation can be found as the angle between horizontal axis of the spectrum and the component. Normally the frequency domain image is shifted so that the DC-component, the average intensity, or the mean reflectance divided by the number of pixels, is displayed in the centre of the image. The further away an image point is from the center, the higher its corresponding frequency. The minimum frequency is one cycle per image and located next to the DC-component.

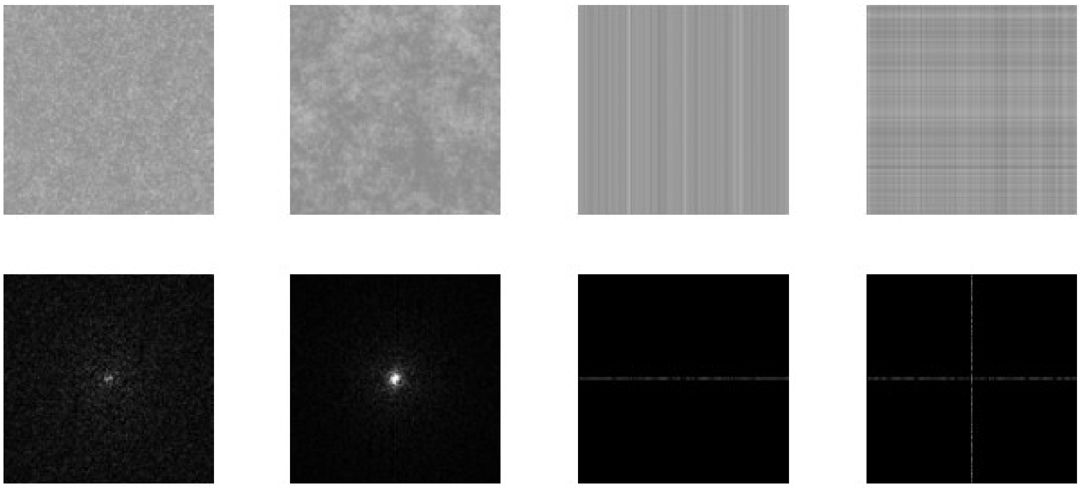

FIGURE 15. Examples of the Fourier transform. The top images show the sample in spatial domain and images below show the sample in the frequency domain. The pair of images illustrate (a) small-scale random mottle, (b) large-scale random mottle, (c) stripes and (d) wire mark texture. (Christoffersson, 2004)

6.2 Mottling characterization

HVS is attuned to detecting patterns and therefore detecting and characterizing mottle as either stochastic or systematic is important due to systematic mottle being more easily detected.

Fahlcrantz (2005) discusses in his work “On the Evaluation of Print Mottle” how theories presented could be divided into five heavily overlapping categories: 1) detection and characterization, 2) modelling, 3) texture perception, 4) segmentation, and 5) 3D texture. All these areas should be taken into consideration when aiming to minimize mottle or otherwise utilize such optical characteristics.

Discussing all these theories in relation to white-top mottle is out of scope for this thesis, so the following briefly covers some methods presented for characterization of mottle.

Systematic mottle can be characterized as three-dimensional texture on material with non-planar surface such as fibre structures. However, if paper structure is planar enough, texture can be treated as 2-dimensional. In paper, both the optical and mechanical properties are strongly influenced by the local densities and orientations of fibers i.e. formation. Marks in the paper web that are caused by process-related phenomena such as the wire, stripes, harmonics, and banding can happen due to imperfect movement of the paper web through the machine. These effects can be perceived as systematic mottle. (Fahlcrantz, 2005)

The textural character of an image is depended upon the spatial size of its texture primitives. Large primitives are found in coarse texture, small primitives in fine texture. To characterize texture, primitive grey level properties and their spatial relationship need to be typified. Texture can be thought of as a two layered structure where first layer concerns the local properties of grey level primitives and second layer their organization. The following briefly presents some methods developed for this purpose. (Fahlcrantz, 2005)

Co-occurrence approaches have long been used in the context of texture analysis. “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.” The strength of grey level co-occurrence approach is its ability to characterize the spatial interrelationship of the grey levels in a textural pattern. Downside to this method is the inability to capture the shape of the grey level primitives. (Fahlcrantz, 2005)

Auto-correlation function (ACF) can be used to describe the spatial size of the grey level primitives of paper and printing texture. In addition, if primitives in the image have regularity, i.e. systematic mottle, the ACF will rise and fall periodically. Both coarseness and periodic structures are features that are present in i.e. wave patterns of corrugated board which makes ACF an important tool. However, since ACF and power spectral density function are Fourier transforms of each other, means ACF is less frequently used than Fast Fourier Transform (FFT). (Fahlcrantz, 2005)

Texture analysis by use of digital transform method is based on the idea that digital image with N x N pixels can be divided into a set of square n x n sub-images that are not overlapping. The n^2 grey levels can be thought as an n^2 -dimensional vector. Most commonly these sub-image vectors are transformed with FFT, a standard discrete Fourier transform, into a new coordinate system. “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).” Fahlcrantz et al. used FFT to transform digital image of the print into frequency components. They found it particularly useful since perception of print is very dependent on frequency and it was fair to assume that mottle had a global characteristic. The use of FFT allows to carry out straightforward filtering operations to emulate the human visual system’s sensitivity. (Fahlcrantz, 2005)

Interval and orientation of systematic noise can be found by using frequency analysis. Systematic noise can be seen in the spectrum as a few peaks that are noticeable higher than average. A smooth spectrum with no exceptional peaks is indication of stochastic nature of the noise. These are demonstrated in figure 16. (Christoffersson, 2004)

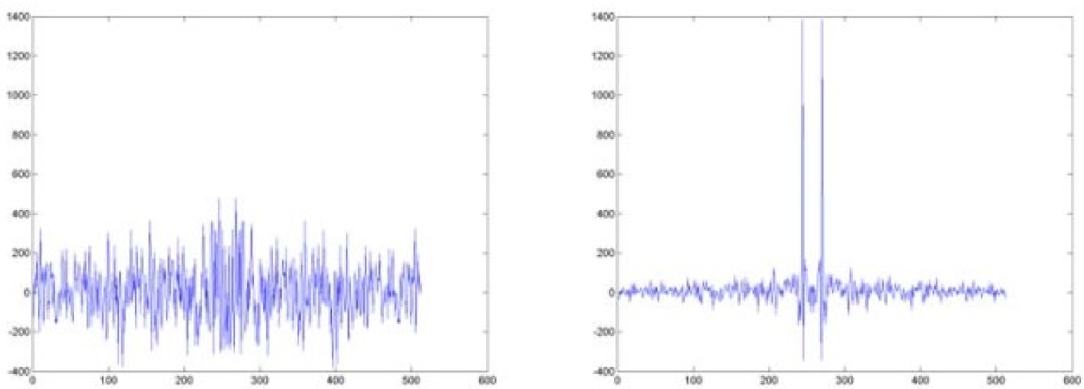

FIGURE 16. Example of 1-dimensional Power Spectrum in frequency domain. Left image is an example of stochastic noise and right of systematic noise. The DC-component has been set to zero in these images. (Christoffersson, 2004)

Christoffersson uses a Chi-Square Measure approach to find out whether or not the spectrum is smooth as well as the orientation of variation. The spectrum is then further divided into six wavelength bands and each band is divided into four orientations. A normalized Chi-Square measure is calculated for each area to find whether high order can be found in that wavelength. A cosine weight function, that declines with increasing distance from the center of analysed area, is used to avoid sharp cut-offs between regions. Mottle is given a weighted value based on the value of order and wavelength band based on HVS contrast sensitivity function. (Christoffersson, 2004)

Yongjian Xu, et al. (2016) evaluated print mottle images with model based on the theory of wavelet image denoising analyses that use the wavelet multi-scale fast algorithm. Wavelet transforming method for time-frequency was developed in the 1980s. It is widely used in digital image analysis fields due to the multi-resolution analysis function. Wavelet analysis can relate time domain with frequency domain and can therefore, according to authors, compensate for shortcomings of analysis methods done purely in frequency domain. When digital image of print mottle is decomposed using 2-D wavelet transformation, the result is a high frequency part and a low frequency part. High frequency part includes information about spatial orientations while low frequency parts give an approximation of the print mottle image. High frequency parts were removed as noise and the image, reconstructed with low frequency parts, was denoised and transferred to a smooth image of the print mottle. The coefficient of variance of the denoised image represents the index of print mottle. Model was tested on four different business papers and correlation between human evaluation system was calculated. Correlation was best on newsprint (> 0.76) and worst on art paper (< 0.68). (Xu et al. 2016)

Multidimensional scaling is a pairwise subjective testing method. It is used to collect information of similarity or dissimilarity between samples. Idea is to have a panel of judges to rate similarity of each pair in set of N samples. The average ratings for each similarity from all the judges are placed in an N x N proximity matrix. First aim is to find a best fit that minimizes differences between pairs in proximity matrix and the distances in the n < N dimensional space. Afterwards, an appropriate set of orthogonal axes along which the samples are though or known to vary, must be found from the final configuration. Multidimensional scaling methods are useful for evaluating samples that vary in multitude of dimensions. (Fahlcrantz 2005) Christoffersson (2004) used one-dimensional magnitude scaling to validate results for STFI mottling expert model.

6.3 Laboratory methods

Traditionally, mottling have been evaluated by comparing the quality of samples with standard papers. Reliability of such methods are subject to changing lighting and personnel as is obvious due to workings of HVS. ISO has proposed many standards for measuring image quality attributes for office equipment.

STFI mottling expert (attachment 1.) offers both greyscale and colour mottling measurements. Due to nature of white-top mottling and HVS ability to detect luminance contrast much more efficiently than colour contrast, the greyscale implementation should work well for mottling estimations. STFI also advertises their system for unprinted board evaluations.

STFI mottling expert model requires the sample to be scanned into digital form. Since the implementation may be used different scanners and settings, either a grayscale calibration or colour scanner calibration is needed. Calibration is done with help of Natural Colour System (NCS) verified surfaces that are scanned alongside of the sample. Since the NCS values are known, the scanner should be able to convert all the scanned grey-scale values into correct reflectance values.

Similar solutions are provided by techpap (attachment 2) and Conmark, Tapio PapEye mottling analysis.

7 CONCLUSIONS

The characterization and evaluation of mottle is a crucial factor in assessment of quality of papers and boards. Mottling, like all optical properties, is a psychophysical property, and therefore evaluation reliant on HVS should consider its limitations and the evaluation be done under stable and neutral conditions.

Much has been written about mechanisms and causes for print mottle and several models have been discussed and established by other researchers, such as the ISO print mottle model. While these models are not specifically designed for white top mottling measurements and analysis, frequency analysis and other methods in the field of image analysis should be sufficient and reasonable to apply in white top mottling measurements. This is demonstrated by the model created by Christoffersson (2004) for STFI mottling expert. This and other methods use office scanners to create a digital image of the sample for analysis. The basic concept is to grey scale the total reflected spectrum, analyse it based on the ability of HVS and type of mottling, and then give weighted coefficient of variation as result. This does give a result that is comparable between samples.

The following has a few ideas on how the measurements may be improved or modified for white top mottling measurements and analysis: First, instead of simply measuring the variation of total reflection, the interest in white top mottling is primarily in whether the reflection from the unbleached backing material is detectable and causing a mottling effect. The effect of the unbleached layer on the perception of the paper is similar to the effect of black back plate when determining opacity of a paper grade. Therefore, it may be beneficial to device a measurement method to estimate variation, and the location, of the opacity of the top layer to support scanner laboratory measurements.

Secondly, frequency analysis of the mottle often discarded the locational information of the variation. However, if several viewing distances are taken into account in perception of the mottle then the location of the mottle becomes more important. Spatial frequencies are units of cycles per degree of viewing distance and when an observer moves further away, fixed size feature takes fewer degrees of visual angle. Then effects as the one presented in figure 14 may appear and previously unseen patterns may become visible. Therefore, it may be necessary to take phase information into account in frequency analysis to both allow for both local opacity measurements and viewing distance in characterization of mottle.

In addition, optical measurements use standard light source spectra and viewing angles. Results for images taken with office scanners may not be comparable with traditional methods and may lack effects produced by FWAs and UV light.

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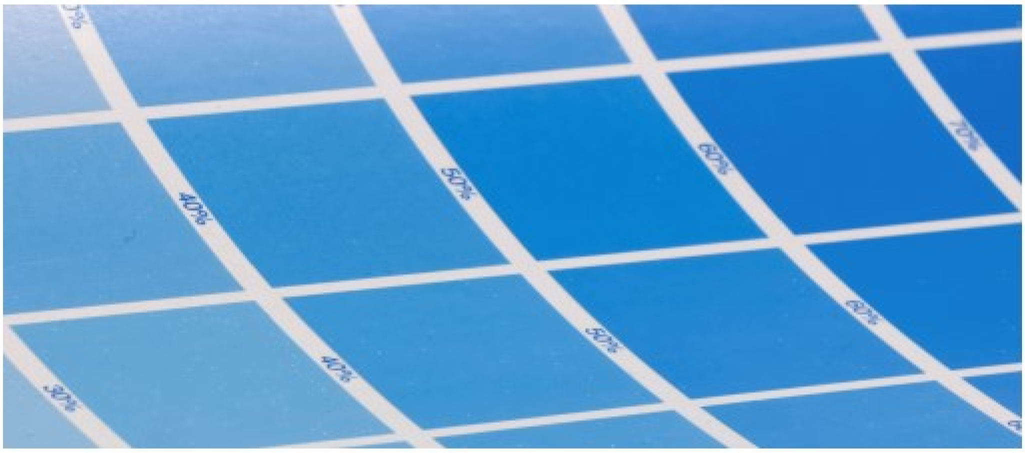
ATTACHMENTS

Attachment 1. STFI Mottling expert brochure. (RI.SE) 1 (2)



Mottling Expert software

Measure reflectance variations (mottle) as we perceive it

The software can be used for

- Measure if the mottle level is acceptable and stable over time
- Benchmark to competitors
- Monitor how new settings in the productions affect the mottle level
- Check if new products are better or not when it comes to mottle

Description

- Advanced image analysis technique is used to filter the scanned images to simulate the human vision system (eyes and brain). This makes the results very reliable and correlate well to panel tests where a group of people rank the samples
- To increase the reliability, the image from the scanner is calibrated to reflectance using the included reflectance calibration set

For more information and prices contact

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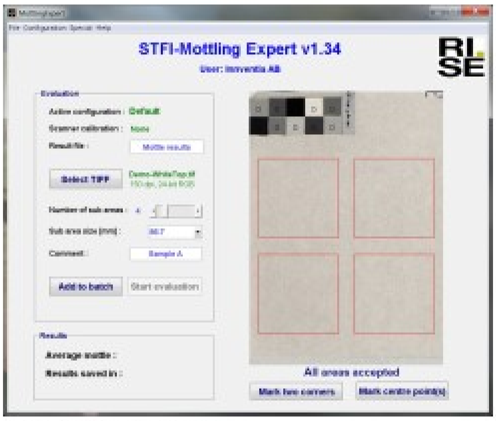


Mottling Expert software - user interface

Flatbed scanner used to acquire the images

Fields of application
Measure reflectance variations (mottle) on:

- Unprinted board (white top mottling)
- Mono-coloured full-tone prints
- Mono-coloured screened prints
- Uncovered area (UCA) - totally white spots in fulltone prints
- Coating thickness variations after using a burnout technique on the samples (making the wood fibres black and keeping the coating white)
- Optical formation can be calculated if the samples are thin enough for the scanner transparency unit
- Also other types of reflectance variations can be characterized, such as formation of nonwoven products and orientation of mottle on corrugated board

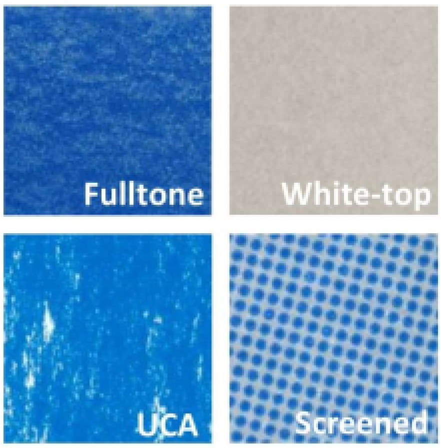
Calculated results

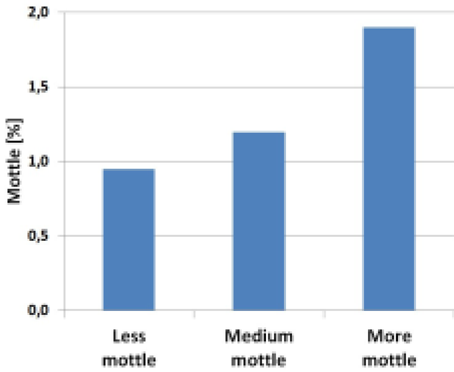
- The mottle value - Coefficiant of Variation in spatial wavelengths 1-8 mm
- Detailed mottle values divided in spatial octave bands, ex 0.25-0.5 mm, 0.5-1 mm, 1-2 mm, 2-4 mm, 4-8 mm, 8-16 mm reveiling the mottle in fine scale, medium scale and large scale
- Mottle values filtered as contrast sensitivity and possible to adapt to different viewing distances
- The orientation of the mottle. If the mottle is stripy this will be reveiled as mottle with high orientation.
- The results are saved in tab separated ASCII-files making it easy to import the results in spread-sheet software like Excel™

Other available versions and options

A reduced version of STFI-Mottling Expert, called STFI-Mottling Light. This light version is well suited for production control laboratories.

For users who measure white-top mottle and want to have comparable absolute levels of the mottle values if they use different scanner models (or even a camera system), we regulary make white-top reference sets used for scanner calibration possible to order.





Example of the calculated mottle values from three samples with different mottle

Required equipment

Standard PC, Win XP/Vista/7/10, a flatbed scanner, Mottling Expert software and a reflectance calibration set

Attachment 2. Techpap mottling brochure (Techpap)

techpap
innovation for paper

MOTTLING
Surface roughness measurement

LABORATORY SENSOR DESIGNED FOR MOTTLE AND SURFACE ROUGHNESS MEASUREMENT

> Designed for papermakers, baord makers, ink manufacturers, coating suppliers and printing operations

> Provides accurate and repeatable evaluations on :
- Quality of offset impressions, print mottling
- Precision of coating application
- Paper, board or other flat material roughness.

> Provides excellent correlation with human eye evaluation and sensitivity

> Practical, repeatable, and responsive

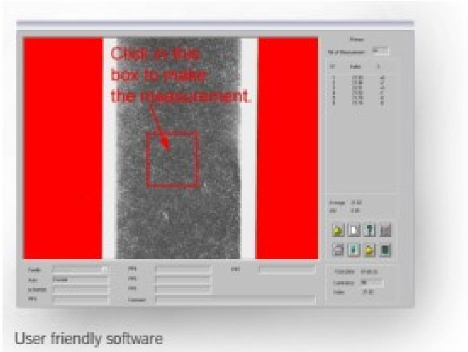
> Highly sensitive to mottle or smoothness changes

FRIENDLY SOFTWARE

> Measurement window
- 6 test reference windows
- Configurable results table

> Configuration window
- final mottling index is the result of the combination fo 5 individual class preset size categories

> Result output inludes:
- average print mottle or surface smoothness
- deviation between measurements
- tolerance threshold
- class distribution
- class distribution standard deviation



User friendly software

RELIABLE AND POWERFUL

> Composed of CCD Camera and 2 light sources

> Stable sample illumination during capture and measurement process

> Individual analysis < 1 second