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CHARACTERIZATION OF PAPER AS AN INFORMATION CARRIER

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ABSTRACT

Printing on a paper carrier falls into the generic class of 'visual communication processes'. This paper aims to provide a systematic overview, based on the literature, on current knowledge concerning the fundamental factors related to paper as an information carrier.

Published work on informational aspects of imaging can be found in diverse fields. Yet it seems that research specifically from the starting point of paper and printing is needed if future advances are to be made in our understanding of how paper properties contribute to visually perceived information.

INTRODUCTION

The performance of paper in printing is conventionally discussed in terms of runnability and printability /Fig. 1/. Runnability depicts the behaviour of the paper in relation to the requirements of the press, and printability the interrelations between the paper and the printing ink. A third collective performance characteristic, information capacity, depicts the potential of paper in relation to text and image data.

Printed products differ from other visual communication products such as photographs and television pictures in the sense that only a fraction – typically less than 20 per cent of the area of the information carrier, the paper – is covered by the information. This suggests that assessment of the performance of the visual communication system by human viewers derives not only from the performance of the technical process but also from the impression given by the properties of the carrier as such /Fig. 1/.

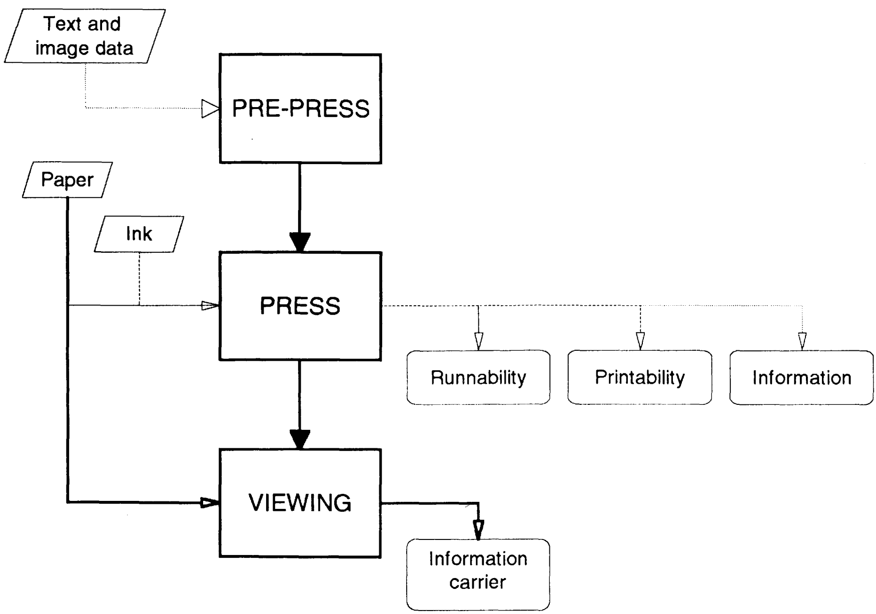


Fig. 1 Use of paper in printing.

The principles of information, in the sense mainly discussed in this paper, were developed as an outcome of communication research and the need to code messages efficiently for transmission. Applications to imaging problems in photography, radiogaphy and television soon followed; in photography (19,20,21,39,105,117,120) and radiography primarily to further materials development, in television to develop systems and promote international standardization. The new imaging processes, i.e. HDTV and computer driven display applications, which began to emerge in the 1980's are currently the driving forces behind research on informational aspects in imaging. The first studies in which the printing reproduction process was analysed as an information transfer channel (44,114) date back more than thirty years. The impetus to apply information theory to printing came from work on photography.

The technical approach to information is based on statistical concepts (103,104). The fact that images are mainly communicated for the purpose of human viewing has been increasingly recognized during the last ten years. Research efforts are increasingly being made to model visual perception in order to integrate it in simulation models of communication processes. These trends have led to the formulation of the term "visual communication system".

The aims of applying the statistical information approach to imaging problems fall roughly into three groups. First, information parameters can be determined for different types of imaging systems, i.e. analogue, digital, optical and visual systems or systems including various combinations of these (17,18,30,31). This facilitates comparisons of overall process performance and comparisons between different types of system and component. For instance, it is possible to compare the performance of printing and television imaging (14,54,72,101). Second, information-based metrics can be used to find optimal process parameters. Halftoning parameters for printing reproduction, for example, can be chosen using information criteria (71). Third, information is a component of quality, although visual quality assessment is influenced by a variety of other factors as well. Studies carried out on printing and paper have sought to formulate a quality metric which characterizes the process performance in an objective manner (29,68,90,91,99,100).

Our current understanding of the role of paper as an information carrier is largely confined to knowledge of its capacity to carry text and image data. How the overall impression of the informational performance of printed products is created in human viewers and what role the paper carrier plays in this, is not at all clear.

This article aims to to provide a systematic overview, based on the literature, of current knowledge concerning the fundamental factors related to paper as an information carrier.

The topic is organized in the following main sections:
- definitions of information,
- influence of information on quality, and
- influence of paper properties on information.

The first section defines different levels of information and also the statistical information concepts used. The visual factors which should be incorporated in expressions of statistical information so as to depict – at least as a first approximation – what is actually detected are overviewed. The presentation of the first section has a tutorial nature.

The second section explores the interrelations between information and image quality. Different types of information-related quality parameters are summarized on the basis of general imaging literature and on the paper and printing literature. The visual factors which complicate the prediction of quality using the information approach are briefly touched upon. In the discussion, quality is made subordinate to information and no effort is made to cover image or print quality comprehensively.

The third section reviews what is known about the limits set on information capacity by measurable paper properties.

The list of references reflects, on the one hand, the fact that a lot of work on information in imaging has been done in areas other than printing and paper. For this reason, the terms "image", "image signal" and "imaging" are used when not dealing specifically with prints made on paper by printing methods. On the other hand, the choice of references reflects the belief that, in order to further development of paper as an information carrier, research should combine measurement based approaches of study with evolving knowledge of what the human viewer actually perceives.

DEFINITIONS OF INFORMATION

To facilitate discussion of the topic defined in the title of the paper, information – an apparently elusive concept – has to be defined. Using the analogy offered by visual perception, we can find a hierarchy. Consistent with the steps in which image signals, such as reflection of ambient light from prints, are believed to be processed in the human visual system, information can be divided into three categories, as Table 1 suggests.

Table 1 Hierarchies of information.

TYPE OF INFORMATION	PURPOSE OF VIEWING	
	PERFORMANCE	NON-PERFORMANCE
Spatial frequency ↓	Statistically based instrumental or visual detection of tones and colours in an image (entropy, information capacity) Transfer of tones and colours in an imaging process and visual detection of tone and colour differences between two images (information transfer, channel capacity)	
Object ↓	Detection of objects based on contours, texture and shades	
Cognitive or artificial intelligence	Recognition of objects and understanding of images	Identification of objects and images relative to memorized impressions, preferences of impressions

The lowest level of information is represented by spatial frequency or pixel-based information. The term "low level" is consistent with definitions of "low level" or "early" and "high level" vision (12,58). Low level information facilitates extraction of higher level informational features from an image. This suggests that spatial frequency information and quality are interrelated. Instrumental characterization of prints, as it is done today, operates on the spatial level.

The image signal which the human visual system initially registers is a two-dimensional, spectrally and spatially varying image. On the second level of object information, images are processed to detect feature information (26).

Cognitive information or its machine vision equivalent, artificial intelligence, associate the detected image data with understanding and interpretation of images.

The extreme image-viewing situation, is either one in which the viewer should be or is encouraged to take action when detected or recognized objects or phenomena occur in the image or one in which pictures are viewed for pleasure. These are called "performance" and "non-performance" situations (33). Prints are primarily viewed in the non-performance mode, in which less strict criteria are set for information fidelity than in the performance mode. In order to increase the viewer's appreciation, the information in printed pictures is distorted, sometimes purposefully. In examining commercial printed matter, such as sales catalogues, high fidelity of printed pictures to the original objects is desirable because purchasing decisions are based on the pictures; the situation resembles performance type viewing.

Instrumental spatial information

Information based on spatial frequency has its origin in statistical communications theory, as developed by Shannon (103). The theory formulates expressions for two types of information, entropy and mutual information /Table 2/. The self information of an event is determined by its probability: the lower the probability of occurrence, the higher the self information. In a monochrome image or print, tone levels represent events.

Information capacity, in the sense used in this paper, is expressed by the maximum value for entropy: maximization takes place over every possible tone levels. Information capacity is maximized when all tone levels are equally likely. The probability is then constant and equals n^{-1}, which gives $\log_2 n$ for information capacity. Information capacity characterizes the performance limits of a process and its materials, such as the potential of paper in given printing conditions.

Mutual information places the output in relation to the input in the process. This takes place via a conditional transfer probability function. A printing process, for instance, gives rise to differences between an input, a test image or a real life or synthetic image, and the print, because of changes and impairments in tone, colour and detail rendering and introduced unevenness, called noise. In the expression for mutual information and its statistically averaged values /cf. Table 2/, distortions give rise to a decrease in the conditional probability, $p_{g/f}$. The formula for information transfer depicts how much tone and colour data from the original image have been unambiguously transferred to the print. Fig. 2 (14) illustrates the relationship between information capacity and information transfer.

Table 2 Definitions of statistical information.

Self Information: $-\log p_f$ **Information capacity H:** $H = \max_{p_f} \left\{ \sum_f p_f \log_2 p_f \right\}$ $H = \log_2 n$	f input signal p_f probability of signal level f n number of signal levels
Mutual Information: $-\log \frac{p_g}{p_{g/f}}$ **Information transfer I:** $\sum_g \sum_f p_f p_{g/f} \log_2 \frac{p_g}{p_{g/f}}$ **Channel capacity C:** $C = \max_{p_f} \sum_g \sum_f p_f p_{g/f} \log_2 \frac{p_g}{p_{g/f}}$	g output signal p_g probability of signal level g $p_{g/f}$ probability of level g in the output when input signal level is f

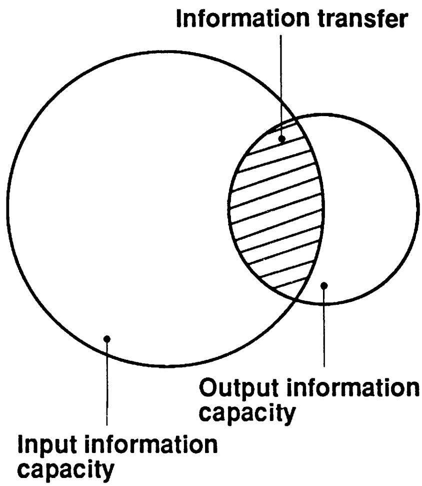


Fig. 2 Illustration of the concept of information capacity and information transfer by Venn diagram (14).

Using generalized assumptions about the statistics of the signal (image intensity or density) and noise, we can replace the definitions of Table 2 with expressions which are more practical for measurement purposes /Table 3/. The number of tone levels which can be statistically detected ("n" in Table 2) is limited primerily by the possible range of the image signal; in black and white printing, the 'dynamic range' is determined by the highest and lowest densities in an image. Secondly, the number of signal levels is limited by noise. An established convention is to calculate the number of instrumentally detectable tone levels using the ratio of the signal amplitude to the root mean square value of noise (SNR). The dynamic range achievable in images typically depends on the spatial frequency, defined as Fourier frequency; noise is also likely to be frequency dependent. Inserting these factors in the definition of information capacity gives the expression called 'micro scale information capacity' in Table 3.

Table 3 Spatial frequency dependent information expressed in terms of signal and noise.

Information capacity:	
"micro scale" (bit mm^{-2}) $H = u^2 \log_2[1 + SNR(u)]$ $SNR(u) = \frac{D_{max}(u) - D_{mn}(u)}{\sigma(u,D)}$ linear approximation: $SNR(u) = \frac{[D_{max}(0) - D_{mn}(0)]\,MTF}{\sigma(0)}$	u — spatial frequency s (u) — rms value of noise D_{max} (u) — maximum density D_{min} (u) — minimum density MTF — modulation transfer function (14)
"macro scale" (halftones), black&white (bit mm^{-2}) $H = u_h^2 \log_2\left[1 + \sum_{D_{min}}^{D_{max}} \frac{\Delta D(u_h)}{\sigma(D,u_h)}\right]$	u_h — halftone cycle frequency ΔD (u_h) — density difference in print between two successive halftone levels
"macro scale" (halftones), colour (bit) $H = \log_2\left[1 + \sum_{h^*}\sum_{c^*} \frac{L^*_{max}(c^*,h^*) - L^*_{mn}(c^*,h^*)}{\sigma(c^*,h^*)}\right]$	L* — luminance c* — chroma h* — hue (74,75)
Information transfer (maximized by digital processing) $H = \frac{1}{2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \log_2 \frac{\Phi F(u,v)}{\varepsilon^2_{FG}(u,v)}\,du\,dv$	Φ_F (u,v) — power spectral density of input image (radiance) $\Phi_F(u,v) = \overline{\lvert F(u,v)\rvert^2}$ F (u,v) — Fourier spectrum of input image ε^2_{FG} (u,v) — power spectral density of the mean square error $\varepsilon^2_{FG}(u,v)\ \overline{\lvert F(u,v) - G(u,v)\rvert^2}$ (31)

In printing, as in other types of imaging, the dynamic range decreases with an increase in frequency. This is a manifestation of spreading phenomena; sharpening would have an opposite effect. Under the assumption of system analytical linearity, spreading and its influence on the frequency-dependent dynamic range can be depicted by a system function, the modulation transfer function MTF. The inverse Fourier transform of MTF is the line spread function in the x dimension:

$$MTF = \int_{-\infty}^{\infty} l(x)\, e^{-2\pi iux}\, dx \qquad (1),$$

which is obtained from the point spread function h(x,y) by integration over the y dimension:

$$l(x) = \int_{-\infty}^{\infty} h(x,y)\, dy \qquad (2).$$

MTF is a measure of the relative amount of blurring. In imaging consisting of several steps, overall MTF is obtained by multiplying of the MTFs of the steps (MTF_k):

$$MTF = MTF_1 \; MTF_2 \cdots MTF_k \qquad (3).$$

Modulation transfer can be calculated from the amplitudes (density) of a sinusoidally varying test pattern consisting of a range of sinusoidal frequencies (u) as follows:

$$M = \frac{D_{max}(u) - D_{min}(u)}{D_{max}(u) + D_{min}(u)}$$

$$MTF = \frac{M_{output}}{M_{input}} \qquad (4),$$

where M is called modulation, and MTF is calculated as the ratio of modulation in the input test image to that in the output image, i.e. the print. Related concepts are contrast transfer and contrast transfer function, which are determined from a periodical line bar pattern /Fig. 3/ as a function of line bar frequency. MTF and CTF are mathematically related (102). Line bars are well suited to determining information capacity in printing (68,74,92,93).

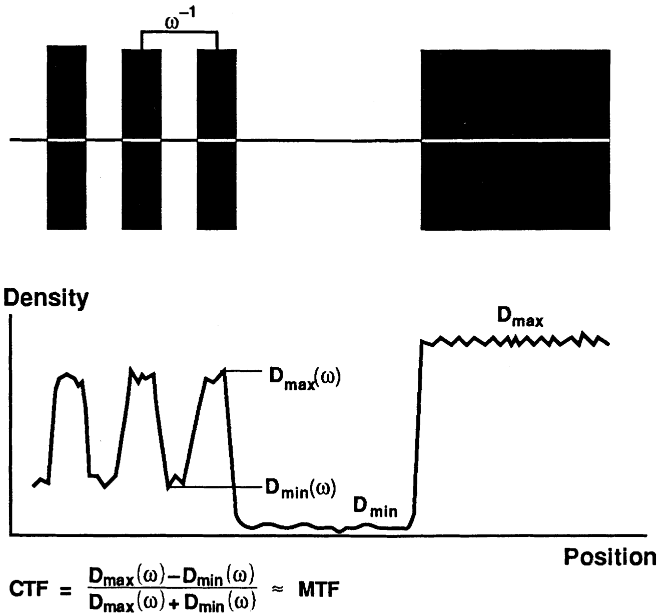


Fig. 3 The concept of CTF - approximation of MTF (78).

If the noise in a process is sufficiently independent of the signal level, the expression for SNR(u) used to calculate micro scale information capacity in Table 2 is simplified markedly and the noise term can be replaced by noise in solid area printing. Even if this were not the case, the simplification is often used. Micro-scale information capacity predicts information potential, assuming implicitly that the process functions in the continuous tone mode.

In printing, tones and colours are generated by the halftoning principle, which means that tones are generated by integration over a unit area. Macro scale information capacity depicts the number of these levels in logarithmic units, scaled relative to the size of the hafltone matrix. It is well known that noise in halftone printing is highly dependent on the halftone percentage (66); middle tones tend to be the most uneven due to variations associated with the interface between the dots and the paper. The simplication referred to above in the context of micro scale noise is not justified.

The meaning of colour information capacity /Table 3/ is analogous to black-and-white information capacity. Information capacity of colour printing is a quantized measure to the whole range of detectable colours, or colour gamut (34).

Because information transfer is more closely dependent on process distortions than is information capacity, expressions in terms of signal and noise would require modelling of the distortions (70). The formulation of information transfer in Table 3 (31) is associated with imaging when digital processing ("pre-press" in Fig. 1) is optimized to give maximum information transfer, and noise is additive and white. Under these constraints the formula is applicable.

From the standpoint of the characterization of paper as an information carrier, computations of information transfer come secondary to quantification of the performance of paper in terms of information capacity.

Visual spatial information

Statistical information concepts are concerned with detection of differences in the signal level amidst noise. The question of the relationships between statistical and visual information parameters thus becomes one of how humans see these differences, i.e. what the visually just-noticeable differences (jnd's) in tone levels are.

The factors which are understood to influence the visibility of differences fall into three categories (15), as given in Table 4. The first category is concerned with the nonlinearity of visual response as a function of the image signal luminance level. Different nonlinear functions have been suggested for this nonlinearity, such as the widely used logarithmic, i.e. densitometric function and the cube root relationship used to quantify the luminance of chromatic colours (35,106,115). The logarithmic conversion involves the assumption that the eye adapts either to the level of ambient light or, in the case of prints, to the level of reflection from the paper. In the cube root relationship, adaptation to ambient light is assumed. Recent, more sophisticated formulations deal with visual adaptation in a spatially dependent manner (15,77).

The hypothesis can be presented that adaptation of the eye influences the impression obtained of the optical properties of the paper in the nonprinted areas of printed matter. In the case of colour vision, adaptation takes place not only in terms of lightness but also in terms of the chromatic coordinates (36,45,59). This topic is the subject of considerable current interest in image processing.

Table 4 Types of factors with contributions to visibility of tone level differences in images.

FACTORS IN VISUAL MODELS OF JND'S	DESCRIPTION
Amplitude nonlinearity	Relation between image intensity and spectral content, and visual light and colour response
Spatial frequency and colour-dependent contrast sensitivity	Dependence of visual response on spatial frequency and colour
Masking effect of noise	Influence of noise on contrast sensitivity
Detection mechanism:	
– Spatial frequency selectivity of vision	Sensitivity of visual detection to information in given frequency bands
– Probability of detection	Statistics relating detection to contrast

A similar type of phenomenon can be to spreading phenomena in technical imaging systems distinguished in the human eye. This phenomenon is called the visual contrast sensitivity function or its inverse, the visual contrast threshold function. Numerical formulae for contrast vision are given in the literature (cf.15,23,37,98). Fig. 4 illustrates visual contrast sensitivity (no noise) in relation to printing performance.

Visual contrast sensitivity is highly adaptive and varies as a function of light adaptation, image size, noise and colour, for instance. Noise acts by increasing the magnitude of contrast required at the visibility threshold (3).

In the human visual system a physical difference in an image is transformed into a visually detected difference via detection mechanisms. The common understanding is that the human visual system detects signals in a spatially selective manner (81,82,107), followed by probabilistic decision making. The essence of spatial selectivity is that a structure may, for instance become visible even if its different spatial frequency components do not. The main application of the concept of spatial selectivity is in analyses of object-based information. It has been used to predict visibility halftone dot structures in printing (62,94).

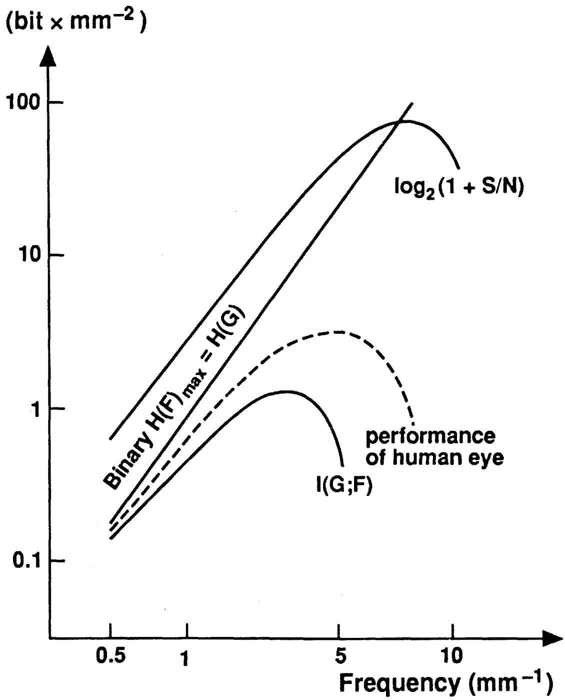


Fig. 4 Performance of the human eye and an example of printing performance in terms of information capacity and information transfer (69).

It is evident, that generally speaking, equality between instrumentally determined statistical information parameters and visually detected information cannot be expected, because too many visual factors are involved in detection. Visually detected and instrumentally detected differences may, however, be correlated. The fewer the number of variables which cause differences, the more likely this is. To account for visual characteristics, efforts have been made to incorporate the most important of the factors in the expressions in Table 3, the aim being to develop models for visual quality (60,43). Quality aspects are discussed in the next section.

INFLUENCE OF INFORMATION ON QUALITY

Principles

Statistical information theory was developed for communication purposes, the key issue then being how to achieve reliable transfer of signals in communication channels in the presence of noise when the signal is received and decoded by a device. In such applications noise and other impairments act by reducing reliability; they have no other effects.

When the explicit purpose is to assess the performance of an imaging process with respect to quality without any reference to the use of the imaging process as a visual communication channel, spatial frequency type information provides a representative description. Information capacity depicts overall process performance which, for instance, allows comparisons on a general level of different processes or different grades of paper. Fig. 5 gives an example of maximal information capacity for different types of imaging. Maximal values are typically obtained at the frequency at which two tone levels are distinguished.

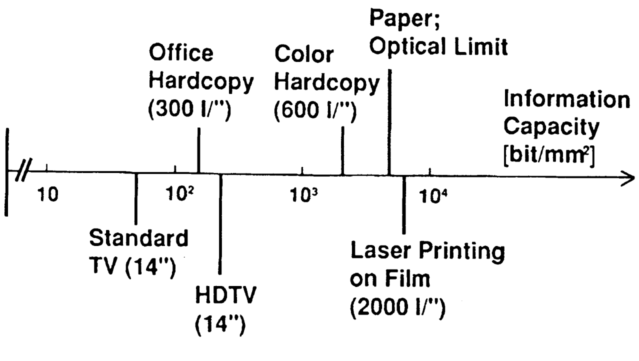


Fig. 5 Information capacity of different types of imaging (72).

The ratio of information transfer for a specified test image to input entropy, is called information transfer efficiency. It describes the role of distortions in a process in greater detail. The parameters have applications in the development of digital processing algorithms and in selecting process parameters (56,57,67,71,95,96). In printing applications, typical areas of application include halftoning and choice of halftoning parameters.

All early studies of the application of information theory to imaging were from a technically orientated viewpoint. In the 1970's, the realization gradually emerged that the human viewing situation is in fact a step in the communication chain, just as the technical steps are /Fig. 6/. This awareness has led to a shift in emphasis towards visually based approaches. People look at pictures for a purpose, albeit the viewing situation may be of the non-performance type. This means that quality is subordinate to purpose; quality facilitates purpose. Our current understanding of the interrelations between quality and the purpose in viewing printed pictures is nonexistent. Nonethless, the types of factors which influence visual quality assessment as well as the detection of differences /Fig. 6/ can be named, or at least some of them can. They include general visual perception characteristics, the test situation and the type of image.

In human viewing, noise, other impairments and the signal background, i.e. the paper, are not likely to influence the assessment only in as far as they influence the signal-to-noise ratio; rather, they influence quality as such. That this is so is suggested by studies in which visual test results have been analysed by multidimensional scaling techniques (48,49,63,76,85,86). No general theories exist to account for these influences on quality, but such theories would certainly be useful.

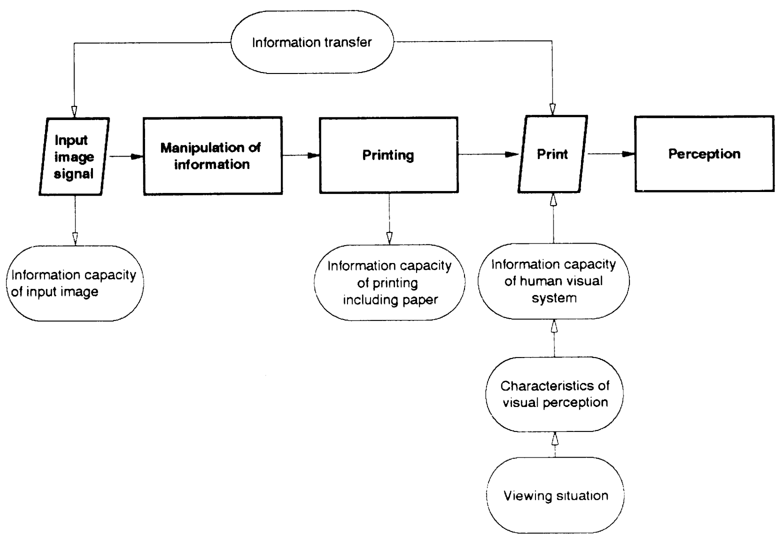


Fig. 6 Human viewing as a step in the communication process of printing.

The situations used to test the visual quality of images fall roughly into three groups: difference testing, preference testing and disturbance testing. The methodological complexity increases correspondingly. The thinking behind difference testing is closest to the argumentation in favour of information-based quality parameters. If we assume that any perceived difference is meaningful, visual information data from difference testing can be used to develop printing and paper. Yet, preference and disturbance tests provide more valuable data than difference testing because they specially address the question of the significance of perceived differences. Studies in which information criteria are modified to incorporate data on preference or disturbance testing appear to be lacking.

Difference and preference testing is usually carried out by pair comparison methods (6,49). At least as far as prints on paper are concerned, the concept of disturbance and the conditions needed to test it are more closely associated with the real-life situations of reading and looking at printed matter; viewers rarely compare two versions of the same print. Any assessment, perhaps unconscious, of whether quality, or some aspect of it, is acceptable is made without a reference. It seems to be important to develop a methodology for the disturbance testing of quality factors in printed matter.

Psychophysical research on jnd's uses simple test images such as sinusoidal patterns. Such images are also suited to a quality assessment of differences, but they are not useful for preference or disturbance testing. This intuitively obvious fact adds support to the hypothesis that image quality is dependent on the purpose of viewing.

The use of complex real-life or synthetic images, however, immediately raises the question of how to choose the images. From the standpoint of the paper, it might be assumed that it does not matter what the test image is like, because the paper has to function equally well irrespective of the type of image or image content. Yet, depending on the image, the weight given to different quality factors such as details, tones, colours, noise, impairments or the paper background varies. The reason may lie in variations in the visibility of noise and impairments (depending on statistical properties of the image) or variations in expectations with respect to tones, colours and details (depending on the image content). Not only should the test images represent the average image, but the paper should also perform well in extreme cases.

Information-based quality parameters

In addition to information capacity as such, its components – the dynamic and coiour range, the modulation transfer function and noise, and their modifications – have been used as quality parameters. The following discusses a classification of the different types of quality parameters. An overview is also given of such print quality factors, which are associated with information-based characterization of imaging.

In printing, dynamic range at zero spatial frequency, i.e.; solid density, is a foremost quality parameter. As concerns colour, to be a visually relevant quality metric, the colour range should be expressed in uniform colour space (4,5,35).

In essence, MTF-based metrics are related to detail reproduction capability and sharpness of imaging. A variety of quality metrics based on measured MTF but modified with visual MTF or its inverse the contrast sensitivity function VT(u), have been suggested, as summarized in Table 5. To convert the modulation transfer curve into a single number, it is integrated over the frequency. The range of frequencies extends over either the whole frequency scale or the most visually meaningful part of it. The hypotheses behind the metrics, differ as is indicated by the fact that visual sensitivity has been incorporated in the models in a variety of ways. Multiplication of system MTF by visual MTF, or the equivalent, division of system MTF by threshold function, is consistent with the interpretation that human viewing is a process step in a communication chain /cf. Fig. 5/.

Most MTF modifications suffer from the fact that the influence of noise is neglected. The Square Root Integral /cf. Table 5/ is an exception. It is also well known that in images, including prints, the impression of sharpness (32) is highly dependent on solid density.

In printing, spreading phenomena are manifested, alongside loss of sharpness and detail, as enlargement of halftone dots, called dot gain. When the dots spread beyond the spaces between them, the condition of filling-in is reached. Dot gain leads to higher integrated densities of halftone areas than are predicted by the halftone percentage. The most commonly used method of quantifying the magnitude of spreading is based on macrodensitometric measurement of halftone area density. Measured densities are either presented as tone rendering curves or converted to dot gain percentages with models such as the classical Murray-Davies and Yule-Nielsen models (7, 118). More recent characterization methods utilize micro-scale image analytical techniques whereby the sharpness of halftone dots or printed lines can be determined as parameters of the edge gradient. The data can be converted to modulation transfer curves using the relationships between the MTF, point spread function and line spread function /cf. Expressions (1) and (2)/.

Table 5 Use of MTF-based metrics as performance parameters of imaging systems.

PARAMETER	
Modulation transfer function area MTFA $\mathrm{MTFA} = \int_0^{u_{max}} [MT(u) - VT(u)]\,du$ $MT(u_{max}) = VT(u_{max})$	(11) MT(u) modulation transfer function of process VT(u) visual threshold contrast sensitivity
Integrated contrast sensitivity (ICS) $\mathrm{ICS} = \int_0^{\infty} \frac{MT(u)}{VT(u)}\,du$	(53)
System quality factor (SQF) $\mathrm{SQF} = \frac{\int_B MT(u)\,d(\ln u)}{\int_B d(\ln u)}$	(22,24) B spatial frequency band at which visual contrast sensitivity has a peak
Square root integral (SQRI), J $J = \frac{1}{\ln 2} \int_0^{u_{max}} \sqrt{\frac{MTn(u)}{VT(u)}}\,d(\ln u)$ $VT_n(u) = [VT(u)^2 + kM_n(u)^2]^{1/2}$	(2,3) $VT_n(u)$ threshold modulation contrast in the presence of noise k parameter $M_n(u)$ modulation contrast of noise

The fact that representation of pictorial information in the Fourier domain is widely accepted suggests that, in so far as the difference approach to quality is taken, quantification of noise as the root mean square (σ) value of the signal and the noise spectrum, i.e. the power spectrum, is well justified. Characterization of noise by means of the ratio of noise to the mean value of the signal, i.e. the variation coefficient, is in fact the inverse of the SNR and thus consistent with the arguments of statistical information theory.

Modification of the signal-to-noise ratio with visual parameters is problematic and few papers on this subject have been published (28,43). If both signal and noise were multiplicatively weighted with the visual contrast sensitivity function, the visual SNR would be the same as the statistical SNR. Multiplicative visual weighting would require different weighting functions for the signal and the noise or modification of the SNR with a "optical noise term" as illustrated below:

$$\text{SNR} \xrightarrow{\text{visual modification}} \frac{\Phi_F(u)\ \text{MTF}\ M_1^2(u)}{W(u)\ M_2^2(u) + n} \qquad (5),$$

where $\Phi_F(u)$ and $W(u)$ are signal and noise power spectra, $M_1(u)$ and $M_2(u)$ are visual weighting functions and n is noise generated in the eye. How the weighting functions should differ is not known at present.

In printing, a great deal of research has been done on questions on print noise; noise is a key quality factor. Prints may be uneven with respect to density, gloss and colour. Table 6 gives a summary of different types of unevenness in prints on the macro scale (solid area noise, solid area colour noise and halftone area noise) and on the micro scale (halftone dot noise and spatial frequency dependent noise).

Measurements of print noise have so far focused on variations in diffuse reflection. Interest in variations in directional reflection, i.e. gloss noise, is of fairly recent origin. The realization that prints are likely to be uneven also in terms of visual colour, too, is only just emerging.

In macro scale noise measurements on halftone areas, the noise effect of the halftone structure is removed either by choosing a measuring aperture which is at least as large as the halftone matrix, in other words by optical filtering, or by digital filtering. On the micro scale, the structural halftone noise is meaningful. Image analysis systems based on an electronic camera have facilitated computations of noise in individual halftone dots and have led to a proliferation of measuring algorithms.

Table 6 Characterization of unevenness in prints.

TEST IMAGE	TYPE OF NOISE
Solid area	Mottle, gloss mottle – unevenness (47,50,84) – frequency spectrum of noise (8,42,112) – cf. Table 7 Noise in solid colour areas – variation in luminance, hue and saturation (79)
Halftone area	Halftone mottle – removal of the halftone structure by low pass filtering (89) – noise caused by halftone structure (96)
Halftone dots	Regularity, raggedness – randomness in radial properties (9,10,25,109) Edge noise – imaging particles on non-printing area (13)
Frequency-modulated sine wave and line patterns	Frequency-dependent noise – frequency spectrum of noise (92)

None of the types of noise discussed above, i.e. solid and halftone area noise and halftone dot noise, relates noise to the spatial structure of the input image. Noise in solid and halftone areas may be presented as a function of spatial frequency, but the spatial frequency refers to the size of the measuring aperture and not the input image modulation. The difference is illustrated in Fig. 7. Noise as a function of spatial frequency in the sense defined in statistical information theory can be determined with the same kinds of test pattern used in determining of the modulation or contrast transfer functions. Print formation is frequency dependent, as proved by the fact that halftone dot edges tend to be noisy.

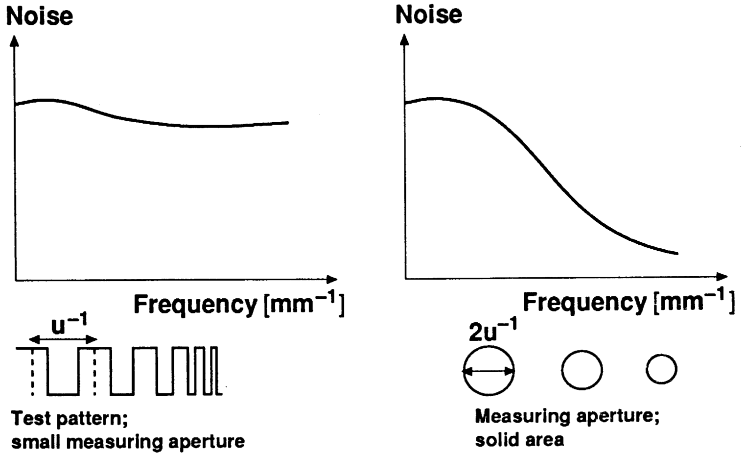


Fig. 7 A schematic illustration of noise measured as a function of the spatial frequency of the input image (line bar pattern) and the spatial frequency of the measuring aperture (solid area) (77).

A variety of formulae have been used to compute useful figures for solid area print noise from relative reflection data, as shown in Table 7. Archieving better correspondence with visual assessment has been the motivation for these formulae. The types of parameter can be divided into rms noise-based parameters, neighbourhood-related parameters, including power spectra, and area classification and textural parameters. Understandably, characterization of noise over the years has been constrained by the measuring and computing capacity available. Recent published work has been concerned with characterizing the textural properties of noise. From the standpoint of visual quality testing, whether of differences, preferences or disturbance, textural characterization provides data likely to be related to preference and disturbance assessments.

Table 7 Characterization of noise in a solid area.

TYPE OF PARAMETER	SYMBOLS REFERENCES	
Variance-based parameters		
– σ value of density		
$\sigma_D = \left\{\int_0^{\infty} [D-\bar{D}]^2 p_D(D)\right\}^{1/2}$	$p_D(D)$	probability distribution of density
	$\bar{D}$	mean density of solid area
– variation coefficient of density		
$V = \sigma_D/\bar{D} = SNR^{-1}$	SNR	signal-to-noise ratio
– σ value of reflectance (diffuse or directional), V of reflectance		
– unevenness number		
$\sigma_R \log \bar{R}/\bar{R} = \sigma_D \bar{D}/\ln 10$	$\bar{R}$	mean reflectance
	(50)	
– σ value of colour (CIELab coordinates)		
$\sigma_E = \left[\sigma_L^2+\sigma_a^2+\sigma_b^2\right]^{1/2}$		
Neighbourhood-related parameters		
– power spectrum of noise P(u) (1-dim)	$\mathcal{F}$	Fourier transform
	r	spatial coordinate axis
$P(u) = d\sigma^2/du$	D_1, D_2	density levels of points located at a distance of r
– autocorrelation function of noise A(r)	$p(D_1,D_2,r)$	probability distribution for D_1 and D_2 as a function or r
$A(r) = \mathcal{F}[P(u)]$	(8)	
$A(r) = \int_0^{\infty}\int_0^{\infty} D_1 D_2 \, p(D_1,D_2,r) \, dD_1 \, dD_2$		

Neighbourhood-related parameters ...	
– contrast ratio R_{small}/R_{large}	ratio of reflectances measured with a "small" and a "large" aperture
– average density difference (ADD)	(47)
$A(r) = \int_0^{\infty}\int_0^{\infty} (D_1 - D_2)\, p(D_1, D_2, r)\, dD_1\, dD_2$	(40)
Classification of surface area	(9,10)
Textural characteristics	(61)
– geometric properties of unevenness	(41)
– co-occurrence matrix Md(i,j) and its properties, such as correlation coefficient normalized correlation coefficient	(80)
entropy	(110)

INFLUENCE OF PAPER PROPERTIES ON INFORMATION

The contribution made by paper to information in printed areas (information capacity and information transfer) arises through its influence on printed image properties. It is thus evident that analysis of the influence of paper properties on information capacity has points in common with the classic printability approach.

Printed images on paper are generated through

- interactions between the paper and ink in printing and drying which determine how the ink is distributed in the roughness and pore structure of the paper surface, and
- interactions between light and the print which are dependent on the distribution of ink in the paper structure and the optical properties of the paper and the ink.

Clearly, optical paper properties influence information more staightforwardly than structural properties, i.e. porosity, roughness and possibly surface energy effects. The influences of structural properties are subordinate to the mechanisms which govern the interactions at the transfer stage and during drying. In other words, fundamental limits on information capacity set by the optical paper properties can be presented, whereas the limits dictated by the structural properties are constrained by image formation during printing (79).

Optical paper properties

This section examines the limits imposed on information capacity by optical paper properties through the dynamic range, modulation transfer function and noise.

As a rule, print densities are measured in given geometrical conditions of illumination and detection (viewing). From the information standpoint, the dependence of the dynamic range on the viewing angle is a performance parameter. In cases in which surface reflection is nondiffuse, i.e. the surface has some level of gloss, the dynamic range varies with the viewing angle. This is so even if the illumination is diffuse because nondiffuse surface reflection implies that the surface reflection is directionally selective. In display technology, the concept of the angular field of view is defined as the range of viewing angles over which the dynamic range is above a given level. It is used as a figure of merit.

Fig. 8 illustrates schematically how the dynamic range may vary in different viewing angles when print gloss is higher than paper gloss. Away from the specular angle, the dynamic range is typically higher when surface reflection is directionally selective rather than diffuse. In the directionally selective case, the dynamic range decreases around the specular angle and may even become negative. This suggests that, from an information standpoint, there is reason to balance the advantages of print gloss against the disadvantages of angular instability of information capacity. Yet, viewing paper more broadly as an information carrier, the human preference of gloss may outweigh the information aspect.

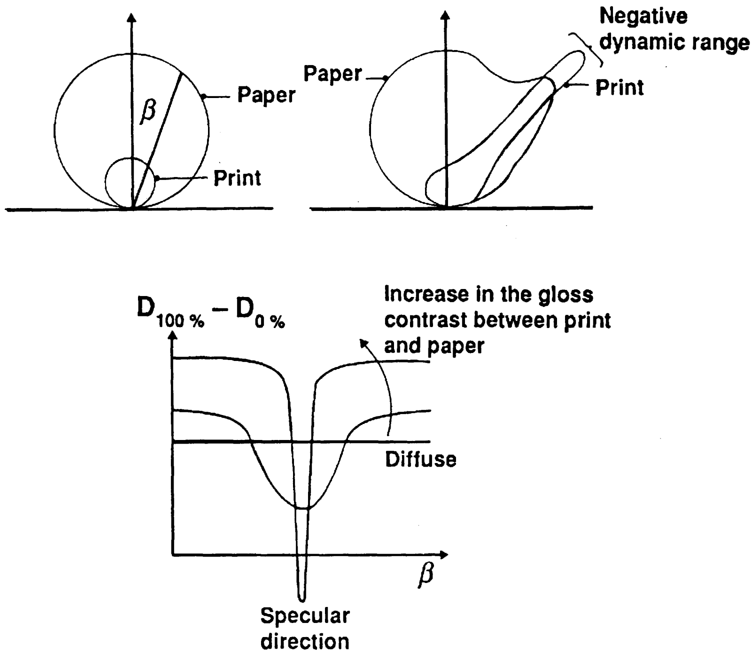


Fig. 8 Angular variation of dynamic range (77).

Colour measurements are also made in one specified condition of illumination and viewing. Because reflection from colour prints never consists of surface reflection alone but contains a sizeable spectrally selective diffuse component, the angular variation of the colour gamut is somewhat less drastic than the variation of density may be.

It follows from the definition of dynamic range that minimum density is controlled by reflection from the paper, expressed in density units. In colour printing, with the currently established CIELab colour representation /Fig. 9/, the equivalent of minimum density is the highest luminance which can be obtained at given levels of hue and chroma /cf. Table 3/.

Figs. 10...12 illustrates how colorimetric paper properties have been found to influence maximum luminance in the hues – cyan, magenta and yellow – of the process colours. The reason for this lies in the additivity of colour formation in halftone prints from the colour of the paper and the colour of the printed dots.

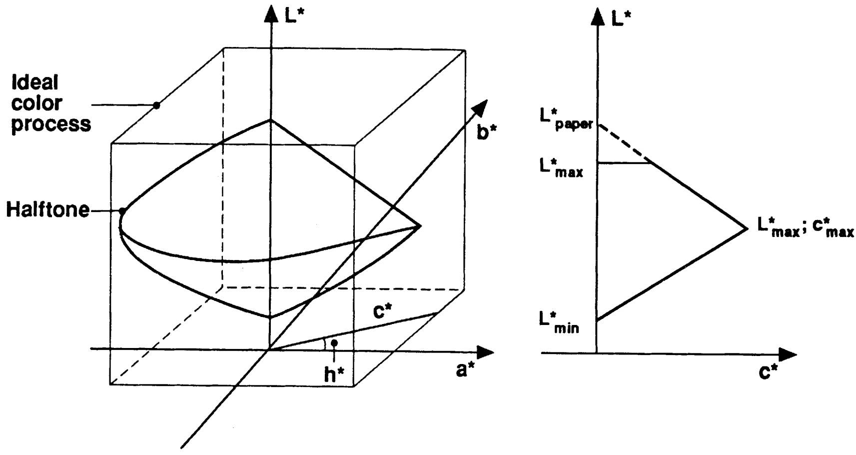


Fig. 9 Colour gamut in an ideal process and a halftone process (74).

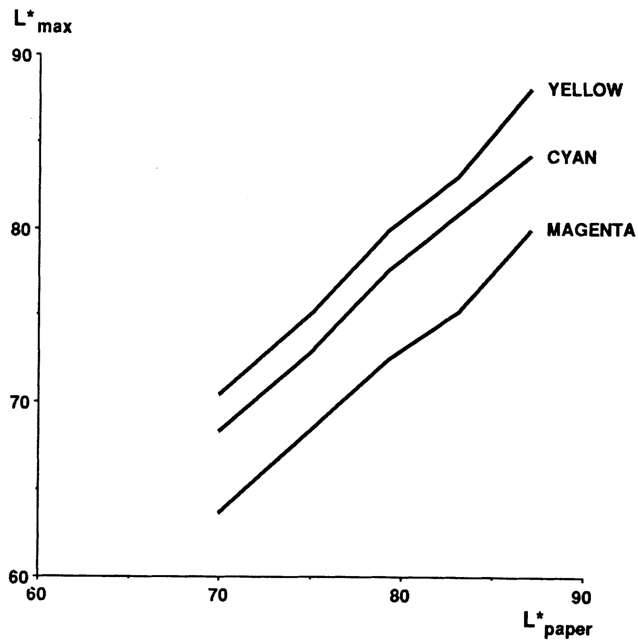


Fig. 10 Influence of the luminance of paper on maximum achievable luminance in cyan, magenta and yellow hues (75).

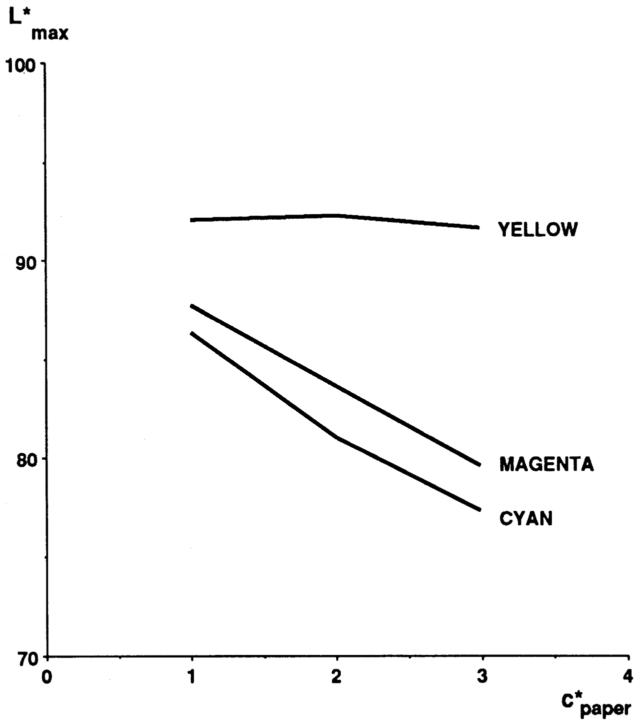


Fig. 11 Influence of the chroma of paper on maximum achievable luminance in cyan, magenta and yellow hues (75).

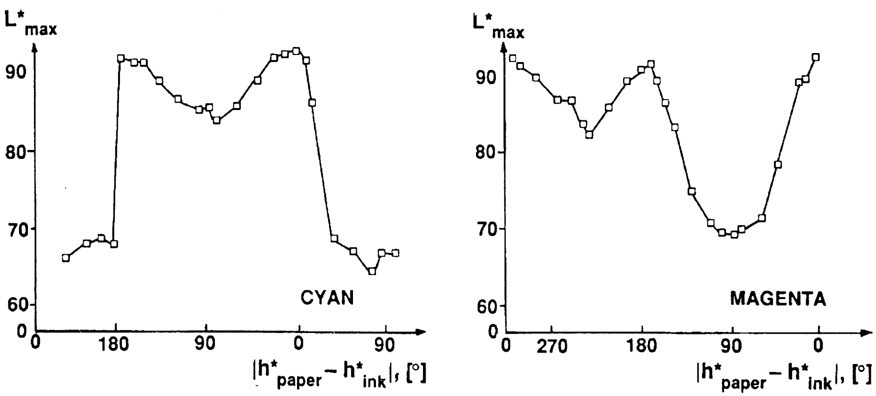


Fig. 12 Influence of the hue difference between the paper and ink on maximum achievable luminance in cyan, magenta and yellow hues (75).

It is also possible to determine the limit placed on maximum density by optical paper properties, although this is hypothetical. The magnitude of the light emitted from an optically ideal black ink layer is the magnitude of the light surface reflected from the print surface. Assuming that no interactions arise between the paper structure and the ink layer – which is equivalent to assuming that the ink layer is infinitely thin – the distribution of surface reflection from the print is the same as the distribution of surface reflection from the paper (78). In other words, maximum density in different viewing angles can be calculated from the surface reflection indicatrix of the paper.

Similarly, minimum luminance in colour printing is limited by surface reflection. Because surface reflection has roughly the colour of incident light, the influence is approximately similar at all hue angles.

Two paper and ink related mechanisms are responsible for spreading phenomena in prints: spreading of ink on the paper (51,64) and sideways spreading of light in the paper. Spreading of light takes plase as well in measuring the print with an optical device or in viewing the print (119) /Fig. 13/. Early research in the 1950's on spreading of light in the paper focused on its influence on halftone tone reproduction (118,119, 88). Other aspects of interest include sharpness (116) and information capacity (78). The light spreading phenomenon is systems analytically linear in intensity, whereas ink spreading is linear in density. It appears that ink spreading and light spreading contribute to roughly the same extent to total spreading in typical printing conditions (65). Yet, for engineering purposes, spreading can be depicted by a systems function calculated in density units.

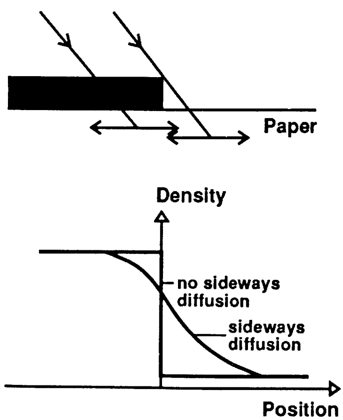


Fig. 13 Spreading of light paper (78).

Experimental data suggest that spatial variations in light spreading may be considerable in uncoated papers (72,78). This means that light spreading is also a source of noise. Unevenness of paper properties when measured as a variation in internal and surface reflection in principle constitute other optical sources of noise. Spatial variations in internal reflection seem to be negligible compared with the influence of other sources of noise in prints. Spatial variation in specular reflection is likely to be relatively greater (73) in other than matt surface papers.

Structural properties of the paper surface

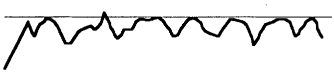
Realistic models of print formation are a prerequisite for predictions of the influence of structural paper properties on maximum density. Usable models would relate printing phenomena with the ensuing distribution of ink in the porous and roughness structure in the z-direction of the paper and with variation in the distributions in the x,y-directions. No such models are available however. Present models of ink and paper interactions in printing are macro scale models which do not predict spatial effects (1,16,52,113).

Ultimately two extreme cases of ink and paper interaction can be distinguished /Table 8/: all the ink is absorbed into the porous structure, or the ink completely fills the roughness volume. Very low quality newspaper printing may approximate the penetration limited case. Printing on double coated paper, on the other hand, resembles the roughness limited case.

As is well known, penetration into the paper causes a loss in the light absorption efficiency of the ink due to light scattering from the paper. Variation in local amount of and penetration of ink constitute sources of noise. The influence on information capacity of noise originating from variation in paper formation has been analysed (42). The fact that the influence was found to be small was attributed to the low frequency of the variation which has its origin in formation; information capacity is related to the square of spatial frequency.

If the ink fills the roughness volume, producing a smooth and thus perfectly glossy print layer, print density is limited by the variation in the coverage of the paper. The only source of structure-related noise arises from variation in the ink layer thickness. Noise is smallest in the specular angle. This suggests that not only dynamic range but also noise should be measured in different geometrical conditions of illumination and detection.

Table 8 Extreme cases of interaction between the ink and paper.

INTERACTION OF INK AND PAPER	INFLUENCE ON INFORMATION CAPACITY
Penetration of all ink into the pore structure of paper  Paper surface Ink	Maximum density and colour gamut are reduced due to light scattering and porosity of paper (27,83) Uneven absorption of ink contributes to noise via variation in internal reflection (42) Variation in the specular angle is controlled by the surface reflection variation in the paper
Filling of the roughness volume of paper  Paper surface Ink	Maximum density and colour range are reduced due to uneven coverage of the paper surface (55,87,108) Maximum density away from the specular angle is increased due to surface gloss (73) Variation in ink film thickness is a source of noise (108)

CONCLUSIONS

This paper had the aim to present a systematic overview of paper as an information carrier, on the basis of the available literature. As concerns the fundamental concepts of information, the discussion had a tutorial nature. The feasibility of using an information theory framework to characterize the information potential of paper was analysed and the limits imposed by paper properties discussed.

The conceptual framework provides a well-weathered set of criteria for quantifying information capacity with overall comparisons in mind. Yet it seems that if they are to be fully applicable to paper, the general criteria should be further developed and modified to take into account the particular characteristics and viewing situations of printed media.

Our understanding of the interrelations between structural paper properties and information capacity appears to be hampered by a lack of fundamental research on ink and paper interactions in printing. After all, ink distributions in the paper structure are obtained as a result of these interactions, and light in measurement and viewing interacts with these distributions. From the standpoint of information, knowledge of micrometre scale interactions is particularly important.

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Transcription of Discussion

CHARACTERISATION OF PAPER AS AN INFORMATION CARRIER

P Oittinen (Review Paper)

ERRATA:
Table 3 (p319) Information transfer (maximized by digital processing):
$\Phi F(u,v)$ should read $\Phi_F(u,v)$

Table 5 (p329) Square root integral (SQRI), J:
$\frac{MTn(u)}{VT(u)}$ should read $\frac{MT(u)}{VT_n(u)}$

Table 7(p333) Neighbourhood-related parameters:
$A(r) = \mathcal{F}[P(u)]$ should read $A(r) = \mathcal{F}^{-1}[P(u)]$

Dr R Grant, Consultant, UK

I have no familiarity with this field, both conceptual and the terminology. I failed to appreciate the first two thirds of the speakers' paper, just in case there is anyone else in the room in the same boat I feel it is both interesting and important this area, could you just briefly and simply summarise the first two thirds of your paper?

P Oittinen

The point I was trying to make is that in my understanding it is not sufficient that we look at printing only as a process where the ink meets the paper. We should look at it from the standpoint of the data, where the texts and images meets the paper and to do this we need concepts and parameters which differ from those with which we are familiar and the information theory provides a framework and concepts which we can apply to this problem.

Prof N Wiseman, UMIST, UK

Although I don't claim to be an expert on the subject the important message which you gave is that if we don't strive to improve our paper quality we may find ourselves overtaken by other media. The same message was given in the September 1993 issue of Pulp and Paper International. I have one particular point that I would like to ask you about. You did not mention specially the question of dirt in paper. It is well known among the manufacturers of newsprint which supply the Far Eastern market that, for newsprint on which Chinese characters or Japanese kanji are to be printed, the dirt specification must be tighter than that when Western characters are to be printed. Presumably this is connected with the level of redundancy in the Chinese characters, a topic covered by the Shannon theory. Can your level of understanding of the topic at present help such manufacturers to precisely specify dirt levels which are needed for different types of printing, particularly in the very important market in the Far East which looks like being a very big growth area in our business over the next 10 years.

P Oittinen

My understanding is that Dr Ebeling will be talking about this topic in his prepared contribution, We have been looking at the influences of dirt in Western type text not in kunji but I can well believe that the redundancy in text is far less in kunji and makes it more critical. But that really is an area of application, of what I have been trying to say.

Prof B Lyne, Royal Institute of Technology, Sweden

I wonder if an illustration might be useful here of the application of this theory to printing on paper. Near the end of your presentation you were comparing optical spreading of half tone dots which is a function of the scattering properties of paper with edge raggedness of halftone dots and the density fall-off the edge of dots. I was thinking a good illustration of that would be a newspaper. In newsprint there is a long scattering path for light and thus a lot of optical broadening. Therefore, there must be some limit to how sharp the dots can be before they are no longer perceived as being sharper because of optical broadening. Is there a point where the modulation transfer function is equally influenced by optical broadening and edge raggedness, or in other words, is there a limit to how fine the raggedness can be in half tone dots and still be perceived in newsprint.

P Oittinen
Yes there certainly is a limit. Optical spreading and mechanical spreading of ink contribute towards the sharpness equally, roughly speaking, depending on the type of printing.

B Lyne
Could you say therefore that there is no point in printing a sharper dot on newsprint or going to a finer raster pattern as it would not be seen as being a sharper image because of optical broadening.

P Oittinen
Yes exactly.

Dr P Mangin, PAPRICAN, Canada
There are two developments now in the printing industry, one is related to moving from three colour primaries for colour separation to six or maybe more and of course in this case, I believe you mentioned it, the paper, optical properties will have a very important impact. I do believe you have two graphs in the paper showing

exactly that point. The second point is related to random screening or stochastic screening. Basically, instead of regular lines per inch you have random frequency modulated screening. In your presentation you haven't touched on the structural properties of the paper, the surface. Do you have any feeling on how this type of screening will affect the paper surface property requirement?

P Oittinen

Random frequency modulated screening is likely to produce smaller dots which makes the surface profile of the paper more critical but I don't have any practical experience about the requirements.

P Mangin

That's all new technology. I think Agfa Gaevert are the people that are actually starting in this field. I think they have just started printing on very smooth paper because the dot rendering being now random, printing is of high quality. We might then be getting pretty close to the limits you stated in your paper.

P Oittinen

It's a very well known fact that if the screen is random, then of course the noise which comes with printing is also random and that's far more disturbing to the human eye than a regular screen structure so that if we used stochastic screens then they would really have to be fine meaning that of course the surface structure of the paper would also have to be very fine.