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# PAPER AND PRINT NOISE AS LIMITING FACTORS OF INFORMATION CAPACITY

Hannu J. Saarelma and Pirkko T. Oittinen
Helsinki University of Technology

## ABSTRACT

Print noise and its effect on information capacity and visual image quality are analyzed. Noise in prints originates from the signal (immaterial image information), the printing process and the materials. The frequency bands and orders of magnitude of the noise associated with the different sources are discussed with emphasis on general principles and limits in offset printing.

## INTRODUCTION

Density, gloss and colour variations, i.e. print unevenness, visible halftone dots and faults such as specks decrease print quality. The different variations are generally considered to be distinct print properties. Yet they all represent undesired variations in prints, i.e. noise. Noise connected to tone, gloss, colour and details determine the information capacity of printing. Information capacity is an integrated measure which is influenced by several factors. These are associated with the ability of the printing process to form an image on the image carrier, the paper. The behaviour of paper in printing can be predicted in terms of runnability, printability and information capacity. Printability and runnability have been studied extensively and discussed over the years, whereas information capacity has received less attention.

Of the factors which determine information capacity, print noise and its formation are not well understood. Noise originates from several sources: the image signal, the printing process and the materials. Signal noise is immaterial, originating from signal generation such as electronic or photographic detection, transmission and digitalization. Process noise originates from printing process variations such as variations in inking and dampening. Material noise is believed to be due mostly to local variations in paper properties, although the contributions of printing plates and blankets in offset printing are largely unstudied. As concerns offset printing ink, it appears to be a relatively homogenous material on the critical size scales of noise.

The level of noise in prints typically varies as a function of spatial frequency, defined as the inverse of wavelength. Noise at different frequency bands is perceived differently. Zero and very low-frequency noise is seen as tone and colour variations. If modest, these are not necessarily detected visually without comparing a print to the original picture or scene reproduced by it. High-frequency noise is seen as print unevenness. It is understood to be most critical from the standpoint of visual print quality. The highest frequency noise is not distinguished with the naked eye. It does, however, markedly affect lower-frequency image formation as the example of the relationship between surface roughness and print gloss illustrates.

The purpose of this paper is to analyze print noise sources from the standpoints of information capacity and visibility. An overview of research problems of the use of paper as information carrier is presented in ref. (4). The approach is general and partly qualitative, as there is a lack of data on some of the sources. This is especially true of noise originating from paper. Transformation of paper fluctuations into quantitative print noise would require an image formation model. Paper-based sources of noise are briefly discussed, with focus on paper roughness. Previous work by the authors has dealt with the effects of optical paper properties on information capacity (5,6). The significance of paper formation from the standpoint of print unevenness and information capacity has recently been analyzed extensively (2). Due to the low frequencies, the effect was found to be minor. As for noise originating from the signal and the offset printing process, quantitative limits can be presented.

Image noise shows up as density, gloss and colour variation which does not originate from the object. Noise is usually expressed in terms of the-signal-to-noise ratio S/N, which is calculated as the ratio of the signal amplitude (S, density range, colour gamut or gloss) to the r.m.s. (N) value of noise. In the computating the S/N-ratio, the assumption is made that noise is gaussian and additive. In information theoretical computations and in digitizing analogue signals, S/N is interpreted as the number of correct signal levels. If the noise is gaussian, this is true with a probability of 68 percent. The probability level is generally accepted and used in transformations of continuous or analogue information to discrete, i.e. digital information (1). Information capacity (C[bits/area])

$$C = u^2 \log_2 [1 + S(u) / N(u)] \qquad (1),$$

expresses the ability of an image to carry information. In Expression /1/ u is spatial frequency. C reaches its maximum value at the frequency where S/N is equal to one. This level is considered to be the ultimate information-carrying capacity of an analogue image.

Expression /1/ contains three basic factors: signal amplitude, modulation transfer and noise. Signal amplitude as a function of spatial frequency, S(u), is approximately equal to solid density times the modulation transfer function (MTF) of the print. MTF gives expression to image transfer in a process as a function of spatial frequency. It can be used for instance to characterize reproduction from original to print, or imaging from printing plate to print. Signal amplitude at zero frequency, i.e. density of a solid print, has been an object of much interest and its formation as a function of material and process variables is quite well understood. Data on colour gamuts are also available.

The modulation transfer function in prints is controlled by two phenomena, the physical spread of ink on the paper surface in printing and the optical spread of light in the paper when the print is visualized by light for viewing. These phenomenona also determine "halftone dot gain", which is known in practical printing. Physical spread is mainly controlled by the printing conditions and ink properties. It is also known to be affected by the surface properties of the paper. Optical spreading in unprinted papers can be measured. Results suggest that local variation in optical spreading in papers is a source of noise in prints /6/. Optical spread in prints is, however, also likely to be affected by ink penetration into the paper.

The third component in Expression /1/ is noise. Noise in printing has been mainly studied by means of visual assessments without quantification of the results. Previous results are thus difficult to apply to analyses of information capacity.

## PRINCIPLES

In a printed picture, the information content is composed of details ranging typically from 0.1 to 10 mm. Information is carried by the halftone dot structure consisting of pixels, normally 10 to 20 μm in width, and halftone dot cycle, normally 100 to 200 μm in width. Paper fibres, coating particles and coating particle shape cause noise-like variations in paper structure which contributes to tone and colour variations in print. The size scale of fibres ranges from 20 μm to 1 mm, coating particles from 1μm to 10 μm and particle shape from under 1μm to 10 μm.

Print fluctuations may occur on the macro, i.e. low frequency, micro, i.e. high frequency, and invisible scales /Fig. 1/. The effect of noise on prints is twofold. Firstly it controls information capacity. By reason of the multiplicative effect of frequency, the effect tends to increase with a rise in the frequency. Secondly it affects the visual quality of the printed image through visibility.

Noise can be random or deterministic. In prints, both types occur. Random noise is generated in any analogue image formation process where several variables contribute to the result. Printing is typically such a process. Also paper, the image carrier, is characterized by statistic light absorption, reflection properties and structural properties. Deterministic noise in printing originates mostly from the discrete nature of the pre-press reproduction.

Pictures for printing are at present processed by means of computers, which means that the image signal is discrete in terms of both spatial and amplitude coordinates. This is manifested in prints as finite pixel size and a limited number of tone levels for each ink. These factors generate pixel noise and quantization noise respectively. However, the most prominent deterministic noise source is halftone noise originating from the halftone dot structure. As is well known, halftone noise is usually visible. Its disturbing effect on visual image quality is not known.

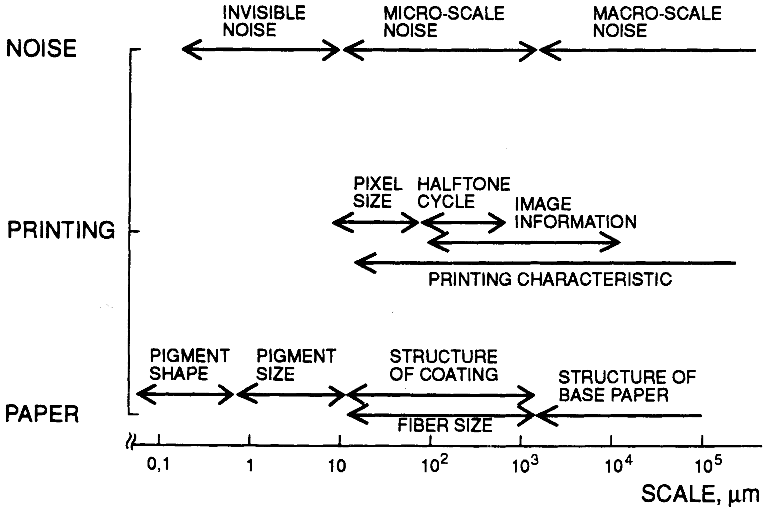


*Fig. 1* Noise scale and contriburing micro scale factors.

Macro-scale noise at very low frequencies (< 0.1 $mm^{-1}$) appears in prints as low-frequency tone and colour variations. These are not necessarily detected as errors without comparing a print with its desired reproduction i.e., scene, original or proof. This is so because even distorted tone and colour rendering may look correct, although the visual impression is different from that desired. High noise level is first seen as hue errors of known colours such as human skin, blue sky, green grass or some generally known trade-mark colour. On lower noise levels- noise disturbs tone and colour rendering. The reason for low-frequency noise usually lies in variation of inking in the press. Inking varies not only spatially but also temporally. Noise caused by inking is typical process noise. A low -level noise may also be associated with the signal, in which case it is due to errors in image processing.

Macro-scale noise in the frequency band of 0.1 – 10 $mm^{-1}$ coincides with the frequency band of image information. Its visibility depends on the frequency structure of the printed image. In images containing much high image frequency information this noise is much less visible than in images containing mainly low frequencies. Some of the halftone structure noise and quantization noise are in this band. Random noise in this band is generated by adjacency effects in different imaging steps of the reproduction process and the formation of paper.

*Table 1.* Noise sources in prints.

| NOISE | CHARACTER | TYPE/ORIGIN |
|---|---|---|
| Shot noise | random | signal/camera |
| Amplifier noise | random | signal/camera, transmission |
| Johnsson noise | random | signal/camera |
| Sampling noise | deterministic | signal/digitalization |
| Quantization noise | deterministic | signal/digitalization |
| Halftoning noise | deterministic | signal/digitalization |
| Inking noise | random | process/printing |
| Dampening noise | random | process/printing |
| Impression noise | random | process printing |
| Formation noise | random | material/paper |
| Absorption noise | random | material/paper |
| Spreading noise | random | material/paper |
| Fibre structure noise | random | material/paper |
| Coating particle size noise | random | material/paper |
| Coating particle shape noise | random | material/paper |
| Smoothness noise | random | material/paper |
| Roughness noise | random | material/paper |

Micro-scale noise (frequency band 10 – 100 $mm^{-1}$) is seen as high-frequency variations in prints. The main sources of micro-scale noise are deterministic pixel and halftone structure noise and random paper structure noise. The visual influence of micro-scale noise has not been quantified, but it is a generally accepted fact that visual print quality is largely controlled by micro-scale noise. Typically, this type of noise can be intuitively recognized as not belonging to the image. The deteriorating influence it has on quality can be tested without comparing the print with a reference image, i.e. an original or proof.

Invisible noise originates from interactions between light and material. Light itself is random; in constant illumination during a fixed period of time a random, Poisson-distributed number of quanta is reflected from a constant print. This is called shot noise. Its effect will increase at low illumination levels, but at normal print viewing levels its effect can be omitted. Invisible noise from prints is generated partly by random interaction of light quanta with inhomogenous paper structure before reflecting back to form the optical image. The other mechanism is uneven distribution of ink on the paper surface and uneven penetration of the ink into the paper. Both of these are mainly related to the properties of paper.

Print formation in the invisible frequency band sets limits to density, gloss, colour and details. Due to this, invisible noise affects the signal amplitude and modulation function of printing, and thus indirectly the information capacity (Expression /1/). Invisible noise occurs at a frequency band beyond the range of interest in computations of information capacity. Table 1 lists the variables which contribute to noise in prints and Fig. 2 gives a compilation of the factors and influences on noise.

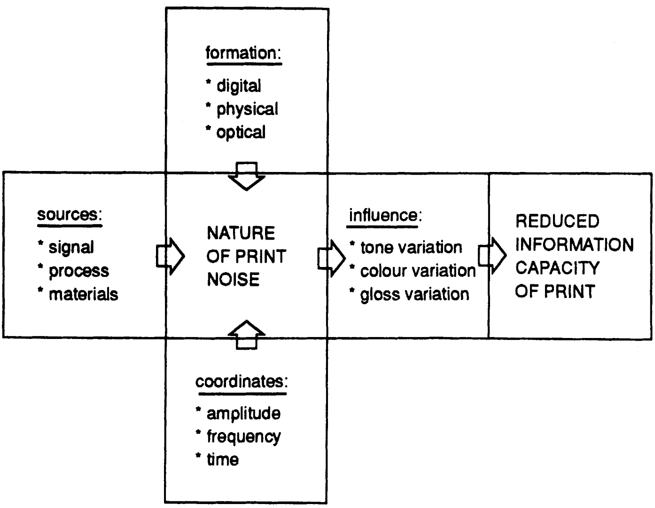


*Fig. 2* Components and influences of print noise.

## RESULTS

### Low-frequency noise

The signal-to-noise ratio S/N is usually expressed on the logarithmic scale as decibels [dB]:

$$SN_{db} = 20 \lg [S/N] \qquad (2).$$

If it can be assumed that S/N >>1, $SN_{db}$ is linearly related to information capacity at a given level of frequency. $SN_{db}$ is commonly used as a quality specification figure, for instance in electronic cameras. It can also be used to specify the overall quality level in printing. If noise is assumed to be gaussian and additive, the noise components of an imaging system can be summed as:

$$\Sigma N(u_i) = \left[N_1(u_i)^2 + N_2(u_i)^2 + \ldots + N_n(u_i)^2\right]^{1/2} \qquad (3),$$

where the $N_k(u_i)$ terms can for instance depict noise generated by different steps or different sources of an imaging process. Summation in Expression /3/ is for frequency $u_i$. The nature of noise as a function frequency evidently changes from one step to another, which is why simultaneous summation over process steps and frequency should be avoided.

In printed pictures, apart from spatial variation, i.e. variation within one image, temporal variation, i.e. variation from one copy and one run to another, can be distinguished. Table 2 lists typical noise levels for offset newspaper printing. The data are computed as averages from several presses and several runs performed during the last few years. High-frequency temporal noise in Table 2 refers to temporal variations during one run and low frequency to temporal variations between runs and presses.

The noise levels measured from newspaper printing correspond to those typical of a home video system, whereas high-quality video systems give far better S/N-ratios. According to our measurements, temporal noise in high-quality printing such as sheet-fed offset printing is not necessarily lower than in newspaper printing. The explanation for this lies in less sophisticated control of the presses. In case of manually operated presses, the low-frequency noise values do not necessarily correlate with visual print quality, because printers enhance the result by means of ink feed; one man's enhancement is another man's noise.

*Table 2.* Typical noise levels in newspaper printing. Temporal noise and spatial noise are cumulative.

| | BLACK INK | | COLOURED INKS | |
|---|---|---|---|---|
| | S/N | dB | S/N | dB |
| low-frequency spatial noise | 90 | 40 | 45 | 30 |
| +high-frequency temporal noise | 85 | 38 | 30 | 30 |
| +low-frequency temporal noise | 25 | 28 | 10 | 20 |

Low-frequency spatial noise of high-quality printing gives S/N values of 45 – 50 dB. The ultimate ability of the human visual system, expressed as noise, reaches a level of 50 dB. Consequently, the quality of printing in terms of low-frequency spatial noise is sufficient in the best conditions.

## High-frequency noise

Figure 3 shows S/N values as a function of spatial frequency for analogue components of offset printing, for the most critical signal noise sources, and the performance of the human visual system. The noise components are shown separately; summation can be done using Expression /3/. The curve depicting the S/N in offset printing is calculated from noise values of ref. (10) and from contrast behaviour as a function of frequency reported in ref. (8,9).

The curve for the visual system in Fig. 3 indicates whether the noise is visible or not. If summed noise has a lower dB value than the visible curve, noise will be visible in ideal viewing conditions. The visibility of print structure depends on both viewing conditions and general image quality. High-quality pictures are more sensitive to visual effects because of higher contrast and lower noise level; noise is less likely to mask low-frequency contrasts (3).

It is evident from Fig. 3 that noise carried by quantized signal is low except in the case of 6bit quantization per pixel. Because the effect is additive, even quantization by 8 bit/pixel reduces print quality. Noise originating from printing is visible even in high quality printing at the frequency range of maximum visual sensitivity. Most of the noise originating from halftoning is visible. In general, noise originating in the signal can be set low enough by choosing pre-press devices of sufficient quality and by adjustment of the parameters. Halftoning noise is an exception. The screen ruling is determined primarily by the paper used for printing, the screen ruling controls the frequency band of halftone structure noise. In conventional printing, coarse screens and poor print quality go hand in hand, although the structures are less visible. In computer printing, screen ruling is determined by pixel size rather than paper quality. This makes halftone noise more critical.

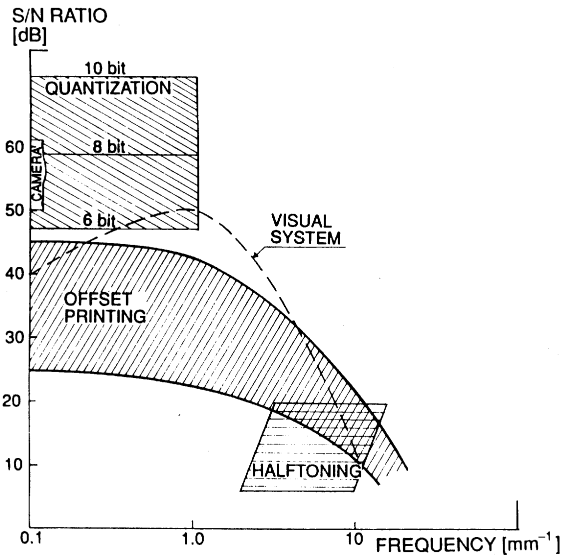


*Fig. 3* S/N-ratio as a function of frequency for some components in printing.

Visible noise at the frequency band of 0.1 to 10 $mm^{-1}$ is visually more disturbing than noise at lower or higher frequencies. This is so because noise in this band is seen as print unevenness. At lower frequencies, variations are understood as tone and colour variations, whereas, at higher frequencies, the human visual system low pass filters the variations. The visibility of noise as print unevenness can be predicted by its noise value, but the degree of disturbance cannot be predicted in a simple way. The visual system seems to interpret deterministic noise and random noise of the same decibel value differently.

## Noise formation

On the level of principles the paper and print related factors which constitute sources of noise can be identified. Determining the relative significance of the factors and their relationship with measurable paper properties poses a far more complex question. In order to establish how paper properties affect print noise, statistical, and spatial-frequency-dependent models of image formation in printing and viewing would be needed. Such models are not yet available.

The main sources of noise in physical and optical print formation can, however, be identified by means of the known phenomena in print formation. In printing and drying these include contact, spreading, penetration, splitting and modification of printed roughness after nip by ink binder penetration and roughening of the paper. In optical print formation surface reflection, internal reflection and optical spread can be distinguished. Fig. 4 sums up the phenomena and their character using terminology from systems modelling.

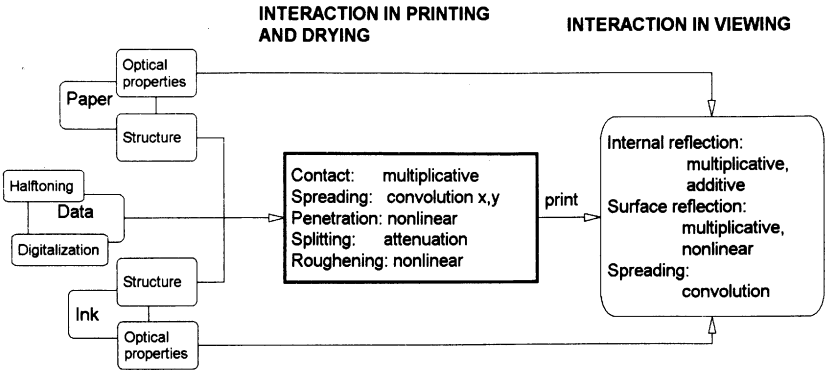


*Fig. 4* Phenomena in print formation which are also potential sources of noise.

The following discussion is limited to effects of print noise on the surface roughness profile of the paper. The question addressed is how paper roughness contributes to print noise and what the frequency band of the noise would be.

In mechanical printing methods, contact between the paper and ink, i.e. paper smoothness, is a prerequisite for any image on the paper. From the standpoint of paper roughness- two cases can be distinguished: smoothness-controlled printing and roughness controlled printing /Fig. 5/.

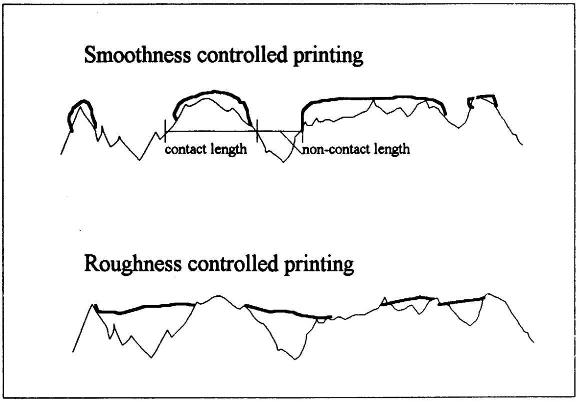


*Fig. 5* Effect of paper roughness on print noise.

Measurements of surface profiles suggest that in printing papers most of the contact and non-contact area (measured at the mean depth of the profiles) (cf. Fig. 4) is characterized by a linear dimension on the order of 25 to 50 μm or less, as exemplified in Fig. 6. This means that noise in density, gloss or colour originating from individual contacting and non-contacting areas is likely to be mostly invisible.

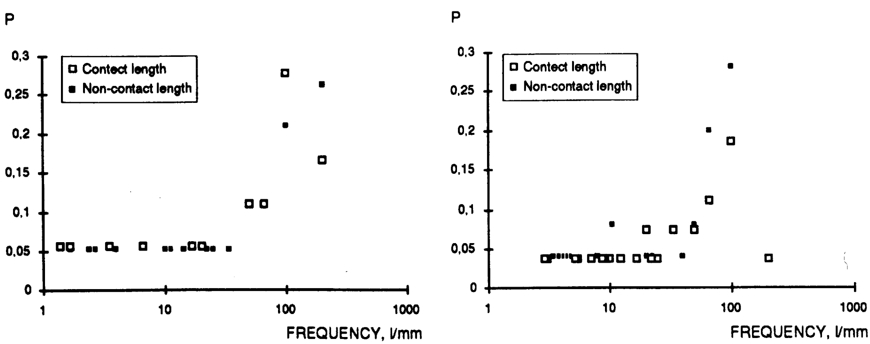


*Fig. 6* Probability distributions (p) of contact and non-contact frequency at the mean depth of the surface profile. Double-coated woodfree paper (left) and LWC paper (right).

The frequency spectra of surface profiles appear to be fairly flat /Fig. 7/ over a range of medium to high frequencies. This means that statistical roughness parameters vary on the same scale. The variations are potential sources of visible density, gloss and colour noise in both of the cases depicted in Fig. 5.

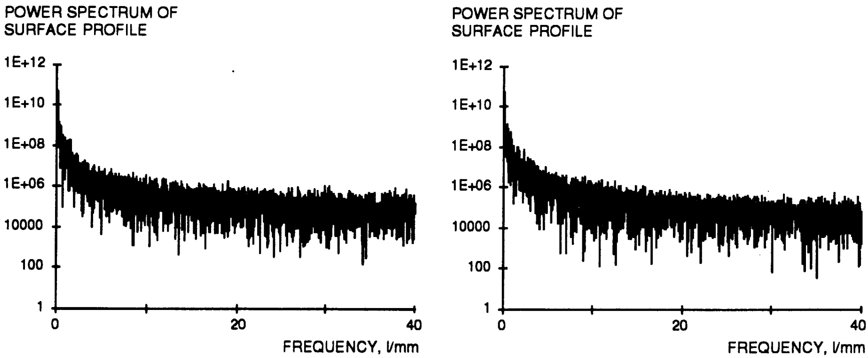


*Fig. 7* Example of frequency spectrum of surface profile of paper. Double coated offset paper (left) and respective print (right).

By way of example, comparisons of profile measurement data from coated offset printing papers indicate that roughness of prints, in terms of the r.m.s value of the surface profile, is only marginally smaller than roughness of the respective papers (7), whereas the slope of the profiles in prints is gentler. Apparently the ink has accumulated on the contact area during printing. This suggests that in offset printing conditions the unevenness of the ink film due to paper roughness, which is distinct from paper smoothness, is an insignificant source of noise.

An upper limit to the effect of incomplete contact on density and gloss noise is obtained by assuming that contacting areas in print are characterized by given density and gloss levels and non-contacting areas have zero density and gloss. Upper limits to $SN_{db}$ values can be calculated from simplified expressions:

density:

$$SN_{db} = 20 \lg \frac{D}{\sqrt{A (D_{max} - D)^2 + (1 - A) D^2}}$$

gloss:

$$SN_{db} = 20 \lg \sqrt{A/(1-A)} \qquad (4),$$

where A denotes relative area of contact, D mean density of the area and $D_{max}$ density of the contacting areas. D, $D_{max}$ and A are related through additivity of reflections:

$$D = -\lg\left[1 - A + A\,10^{-D_{max}}\right] \qquad (5).$$

At full contact, the expressions predict infinite signal-to-noise ratio. At finite levels of contact, the surface is noisier in terms of gloss than in terms of density. At 50 per cent of contact, the $SN_{db}$ value of density is 6,5 and that of gloss zero. Contact thus turns out to be a very critical noise factor.

## CONCLUSIONS

The above discussion is based on the realization that different kinds of noise in prints can be quantified by means of the spatial-frequency-dependent signal-to-noise ratio S/N, which also determines printing performance as information capacity. The sources of noise were divided into the classes of signal-related, printing-process-related and material-related sources. Signal related noise is mostly deterministic due to the fact that it is associated with quantization, digitalization and halftoning of image signals. The other sources generate random noise. In the class of material-related noise sources, the effect of paper roughness was discussed.

The analysis seems to indicate that the different sources of noise can be identified with confidence and their typical frequency bands, low, high or invisible, located. The printing process is primarily a source of noise at low frequencies. Halftoning in monochrome printing exerts an effect at high frequencies. The frequency band overlaps the band at which the surface roughness of paper is a potential source of noise. Both of these sources also contribute to invisible noise which effects the level of density, gloss and colour. Quantitative understanding of random types of noise is deficient. Little is also known about interaction between random and deterministic noise with respect to visual image quality.

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# Transcription of Discussion

## PAPER AND PRINT NOISE AS LIMITING FACTORS OF INFORMATION CAPACITY

P Oittinen, H Saarelma

**ERRATA:** Table 2 (p359): Typical noise levels in newspaper printing. Temporal noise and spatial noise are cumulative.

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|---|---|---|---|---|
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| low-frequency spatial noise | 90 | 40 | 45 | 33 |
| +high-frequency temporal noise | 85 | 38 | 30 | 30 |
| +low-frequency temporal noise | 25 | 28 | 10 | 20 |

**Prof B Lyne, Royal Institute of Technology, Sweden**

In table 1 of the last paper you gave, you list all of the sources of noise associated with the paper as being random. Perhaps if you look only at the 1-dimensional Fourrier analysis of noise you might deduce that it was basically random, but if you take a 2-dimensional Fourrier transform of a gravure print or a solid offset print you find that there is a great deal of orientation in the noise and that paper does have a great deal of structure which cannot be characterised as random. Given that the human visual system is very much attuned to pattern recognition doesn't the fact that you have orientation and structure that's not random in paper have a significant effect on perceived print uniformity?

**P Oittinen**

I am sure you are absolutely right. Those values refer to an 1-dimensional frequency structure. I have no understanding of the relative influence of the orientation but I am sure it's there.

**P de Clerck, Avebe (Far East) Pte Limited, Singapore**

This is not a question, more of an observation. The figures in the table 2 describing the decibel levels in normal printing are transposed in that in the book the black and coloured levels are the opposite of those shown in the slide. Which is correct?

**(EDITOR'S NOTE: THE CORRECTED TABLE CAN BE FOUND UNDER ERRATA AT THE BEGINNING OF THE DISCUSSION ON THIS PAPER).**