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THE QUALITY OF MASS COMMUNICATED IMAGES
with special reference to digital image processing in the graphic arts industry

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PREFACE

In the scope of the Innovation Management task we tried to explore the impact of new computer based technologies on some traditional industries and crafts--printing being one of them.

In this field we could use the results of intensive research done in Finland on assessing digital image processing which is illustrated in this paper coauthored by Professor Oittinen. In order to compare picture quality delivered by different technologies Professor Oittinen uses a specific methodology and defines the components of the picture quality and its role in an overall quality assessment. He also discusses new approaches to these questions brought about by digital processing in imaging technologies.

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Deputy Area Chairman
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Pirkko Oittinen and Hannu Saarelma *

ABSTRACT

All visual communication technologies are composed of detection, processing and multiple copying processes. Image quality in a copy is influenced by these three processes, and in addition the principle of processing (optical, analog or digital) also plays a role.

In order to characterize the relevant components of quality, a systematic analysis was carried out. Imaging technologies were compared with respect to their quality components. On the basis of the quality analysis, the possibilities of quality improvement arising from the innovation of digital image processing are discussed with particular emphasis on the graphic arts industry.

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INTRODUCTION

Visually communicated information /22,39,41/ can be in the form of either text (coded images) or pictures (images). This paper is concerned with the communication of real world pictorial images. These present one of the most challenging problems to the communication technologies /4/. Mass communication of real world pictorial images in all commercial technologies such as television broadcasting, video and graphic arts production is composed of three cascaded processes /Fig. 1/, i.e. detection, processing and multiple copying.

Image detection refers to the capture of an object scene on a two-dimensional surface. In the processing stage the image thus obtained is manipulated and edited in preparation for copying. The meaning of the term copying in this context has been extended to cover transmission, formation of a visible image and multiplication.

The final image, as well as the original scene, is an optical image signal. However, image manipulation in the detection, processing and copying processes need not necessarily be optical but can be analog or digital /Fig. 2/. In essence, all imaging technologies are composed of different combinations of the basic processes and production principles /Fig. 3/.

The graphic arts industry represents the oldest technology with the capability of mass-scale production and distribution of images (text and pictures). Until very recently, copying of the images has been exclusively on a material carrier, paper. Furthermore, the image detection and processing stages have for the most part also utilized image transfer by the route of material carriers /30/. The material intensiveness and the fact that graphic arts products are characterized by advanced data structures have resulted in long intervals between image detection and copying /Fig. 4/. By contrast, the copy rates achieved with conventional printing methods are considerable when compared with alternative technologies. These are not, of course, competetive with the copy rates obtained in television broadcasting, which are virtually instantaneous. It must be pointed out, however, that the pictorial information in a graphic arts process is in an edited form, which is not the case in television broadcasting.

At present, a gradual transfer to digital production techniques, i.e. computerized processing, is taking place in established imaging technologies. Digital techniques provide in particular a new freedom with regard to image processing /28/, interfacing processing with image detection and also editing of text and images /19/. The cost effectiveness of digital techniques is improving with time, as are also the advantages on the time scale. The disadvantages arising from the fact that a digital signal is discrete with respect to tone, colour and position are not likely to outweigh the advantages.

It is apparent that, with the growth of digital processing in visual communication technologies, the information collection and dissemination aspects will increase in significance at the expense of copying. This implies that the features common to all technologies will also increace.

In addition to the application of digital processing in established technologies, the possibilities of storing and processing images digitally has functioned as a catalyst for new innovations. This development will no doubt continue. Mention may be made of videotex- or teletex-type services. In the field of mass production of hard copy images, a whole new class of production methods, the so called non-impact printing methods, has emerged. Examples of these methods include electrophotographic laser printing /34,36/ and ink jet printing /7/.

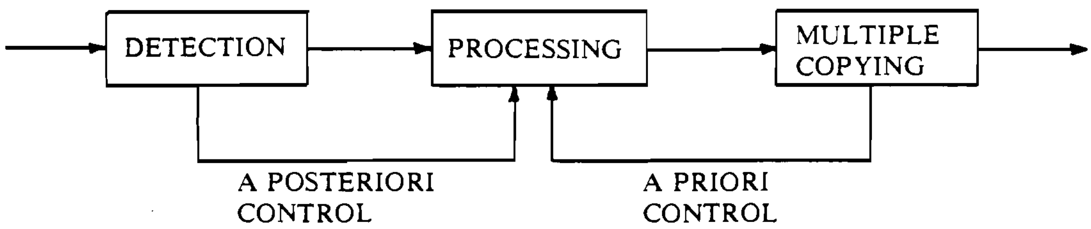


Fig. 1 A system diagram of imaging technologies.

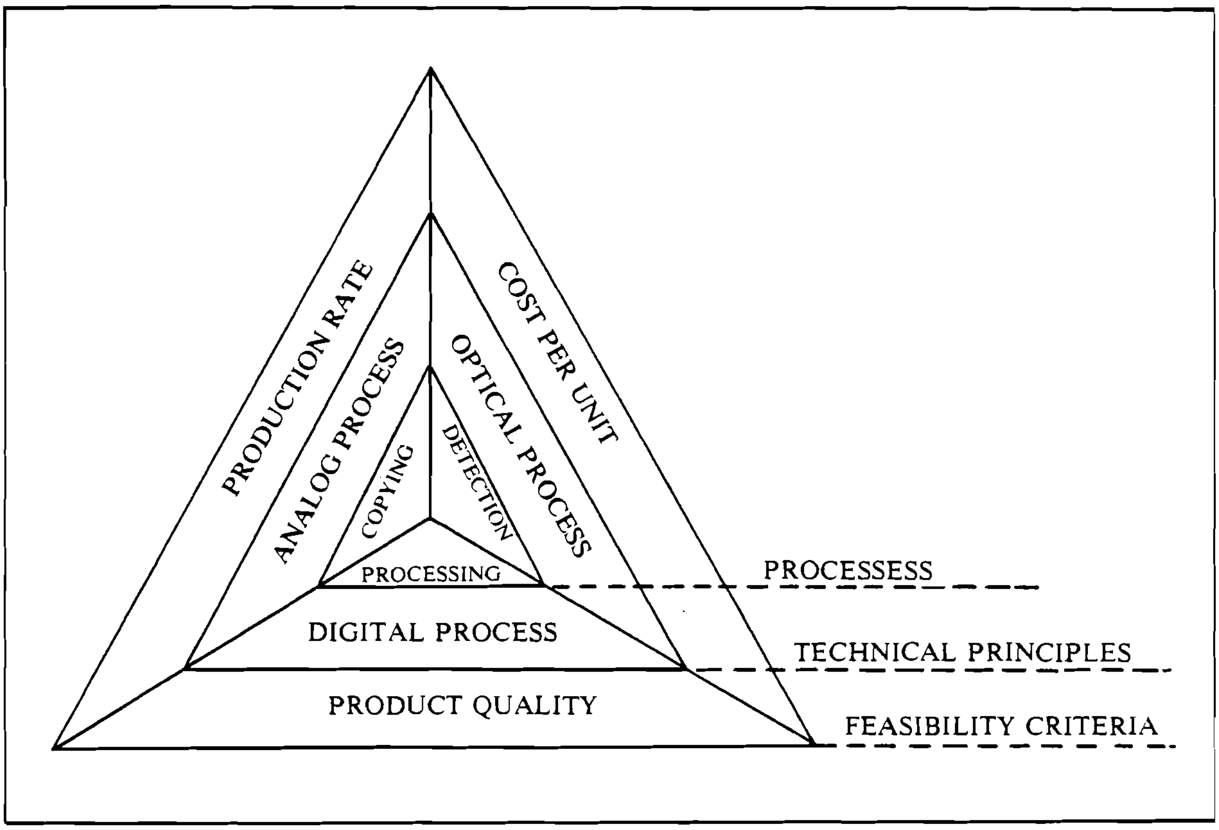


Fig. 2 Definition of the problem.

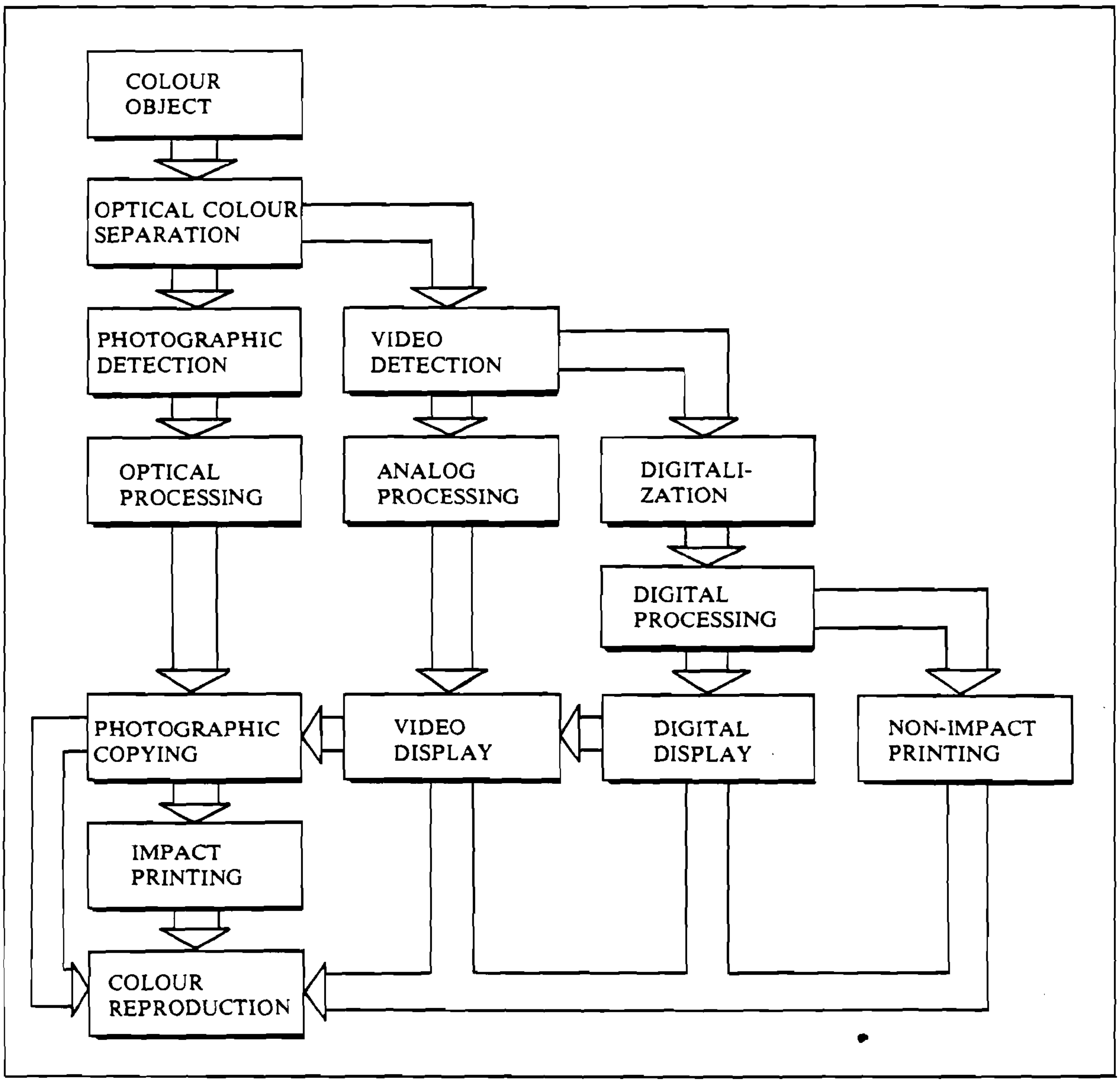
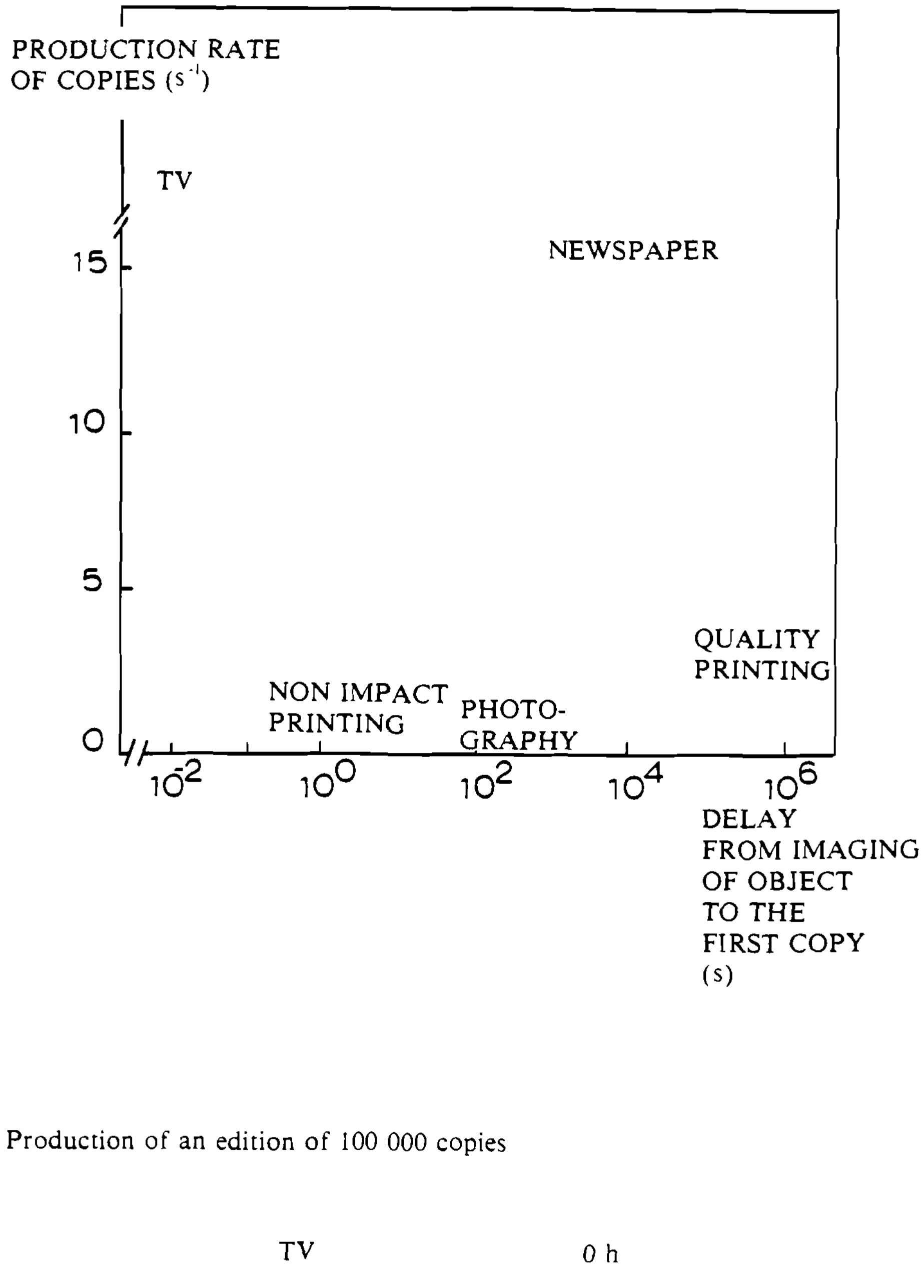


Fig. 3 Alternatives of the production of multiple copies in imaging technologies.



Production of an edition of 100 000 copies

TV	0 h
newspapers printing	2 h
quality printing	10 h
electrophotography	100 h
photography	1000 h

Fig. 4 Production rates.

Assessment of the value of a new innovation, such as digital image processing, requires that the current level of technology can be sufficiently quantified. A condition for this is availability of accepted feasibility criteria. In this paper discussion is directed to quality aspects of feasibility, thus excluding a more detailed discussion of other production factors such as rates and costs as well as user aspects and social influences. It is maintained that the production quality of images as a concept is the least understood of the feasibility factors and requires further analysis. Results of such an analysis are presented in this paper and applied to image communication technologies. The purpose is to provide a basis for evaluation of the possible impacts of technological innovations. In particular, the role of digital image processing in the graphic arts industry is discussed from the viewpoint of quality.

IMAGE QUALITY

It follows from the cascaded build-up of imaging technologies from detection, processing and copying operations that image quality is influenced by all these processes. Image quality in a copy is limited by the poorest of the processes.

Detection is often limited by the quantity of light which is available during exposure. More precisely, image quality in detection, when expressed in terms of the resolving power, is frequently limited by the number of quanta of light falling on a unit area of light-sensitive material during exposure /Fig. 5/. At high levels of exposure, the wavelength of light is the limiting factor. Theoretically, the smallest image unit which can be detected is of the order of the wavelength of the incident light /15/. In practice, an image unit with a diameter of about ten times the wavelength can be detected when the exposure is optimum. The deterioration of resolution from the theoretical is due to light scattering within the process.

In a general sense, image quality is determined by some combination of the properties of the process or of the image. Quality analysis as understood here is concerned with determining the relevant properties, i.e. quality components, and indicating how these should be combined into quality criteria.

Image quality has been widely discussed in the literature /17,43/, but generally from only one aspect at a time. How overall quality is built up from the individual quality components has received little consideration previously. One obvious reasons for this is the difficulty of controlling the different image quality components independently in an imaging process. Digital image processing considerably improves the possibilities of quality adjustments and thus makes relevant the quality analysis carried out in the following.

To the viewer, a real-life image is, to some extent at least, a replicate of the object scene. This has the implication that the same quantities which optically characterize object scenes are suitable for the characterization of images. More specifically, characterization is provided by the spatial, wavelength and angular distributions of the intensity of the emitted light:

$$I = I(x,y,\lambda,\varnothing) \qquad (1)$$

in which I is intensity, x and y two-dimensional spatial coordinates, λ the wavelength of emitted light and $\varnothing$ the angle of light emission.

Hard copy images such as prints, which are by nature passive, cause light emission only when being illuminated by light. Consequently tone and colour form subtractively in situations in which light falling on

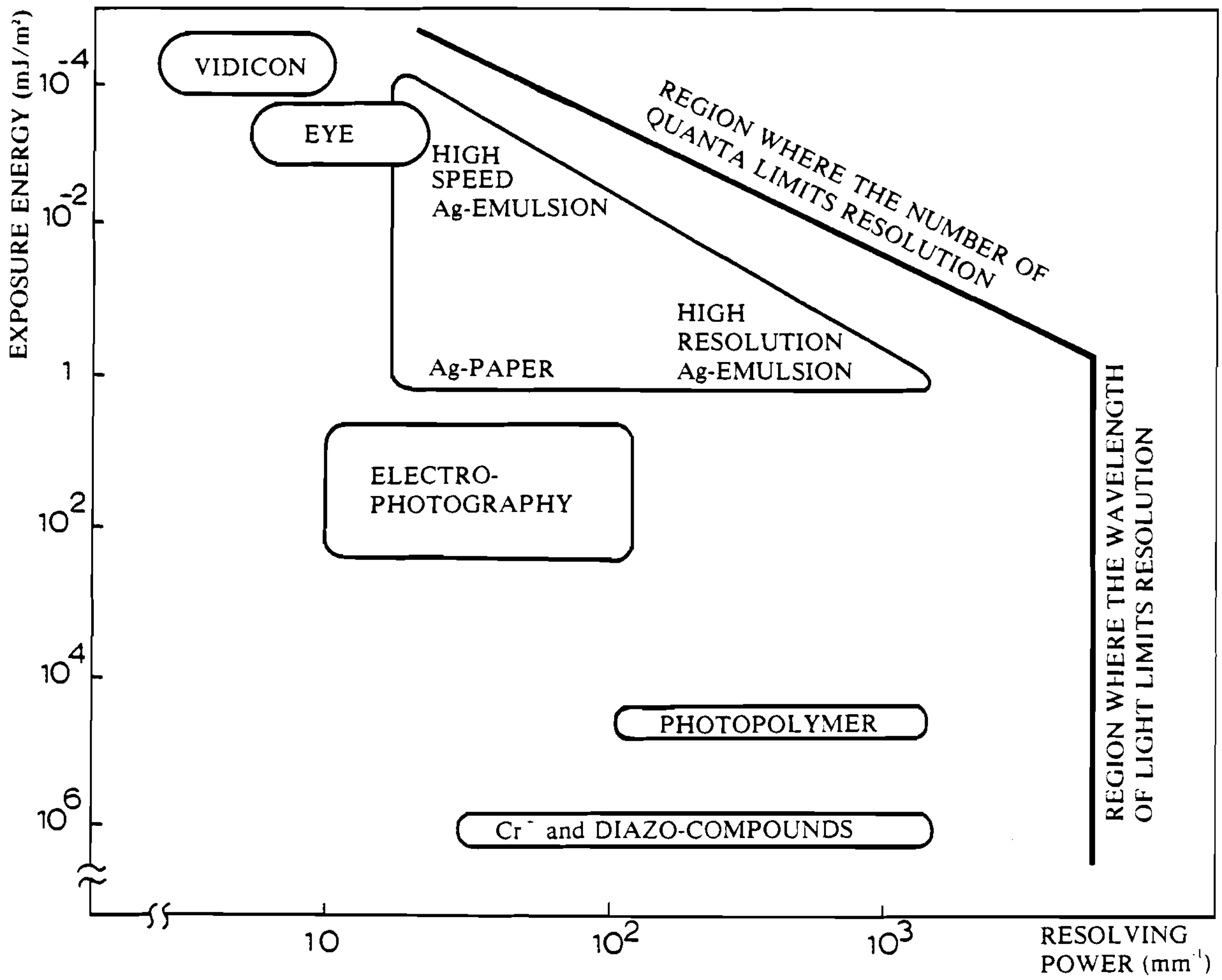


Fig. 5 The requirement of exposure energy and the corresponding resolving power for some detection techniques /6,11,18,26,32,37/.

an image is filtered by means of colourant layers on a substrate. In active images such as displays /5/ the image itself produces visible radiation; this occurs as a result of electro-optical conversion processes. Colour formation on displays is thus additive, i.e. the colours are generated by mixing three coloured lights, red, green and blue, in different ratios.

Because emission is generally linearly related to excitation, either optical or analog, images are commonly characterized by relative emitted intensities. Additional consideration of the logarithmic response of the human visual system /8,12,14/ leads to the concept of optical density:

$$D = \log(I_o/I) \qquad (2)$$

in which D is density, I_o excitation and I is emitted intensity of light.

In an effort to pinpoint the image properties of which quality is composed, images can be examined either as independent products or as representatives of some object scene. In the former case, images produced by a given technology can be analysed as a group. It follows from this that the relevant image properties are synonymous with the performance ranges of the technology as an image formation process /Fig. 6/, called spaces. The optical characterization of images as expressed in Formula (1) makes it evident that the spaces concern the reproduced

— colour space (wavelength selectivity),
— tone space (intensity selectivity) and
— frequency space (detail reproduction resolution).

The performance spaces of different communication technologies are illustrated in Figs. 7 and 8. Colour /13, 16/ can be defined and measured as three independent parameters of emission corresponding to the three different kinds of colour sensitive cells in the human eye. In the CIE-system as used in Fig. 7, two colour coordinates define the average wavelength and purity (proportion of white light) of colour while the third coordinate defines the total light emission, which is related to the optical density. In additive colour formation (display), the locations of the three lights in the coordinate system define the triangle of colour which will be rendered /Fig. 7/. This implies that by choosing the light sources appropriately, a wide colour space can easily be rendered.

In subtractive colour formation three types of colourants are used. Each colourant should absorb one third of the wavelength range of the visible spectrum but none of the remaining two thirds. Practical colourants such as printing inks do not accurately meet these demands, which is why the colour space of printing remains narrow; narrower than that of colour television. The same restriction applies to non-impact copying /2,10/. Colourants used in photography are at present better in this respect as can be seen from Fig. 7. A difference in tone and colour formation between photography and most types of printing should be noted. In photography, tone and colour are produced by a variation in the concentration of colourants at a picture element, whereas in printing a picture element is either covered or not covered by a colourant /cf. Table 1/, and the image is formed more or less as an integrated version of several picture elements. This is called a halftone structure.

As far as the tone and density ranges are concerned, the copying techniques can be divided into three categories on the basis of the combination of the type of tone and colour formation and of the illumination conditions. In the first category the optical image is generated by means of additive colour formation and internal light sources, such as is the case with a CRT display. In this case the density range is controlled by the illumination in the vicinity of the display, because the darkest point of the image is determined by the surface reflection from the screen. Exact values for the density range cannot be given, but in normal

	IMAGE PROPERTY	COMPONENTS
property of image formation	GAMUT	color space
		tone space
		frequency space
property of image transfer	FIDELITY	color rendering
		tone rendering
		detail rendering
property of image system noise	INFORMATION	statistical information
		semantic information

Fig. 6 The components of image quality.

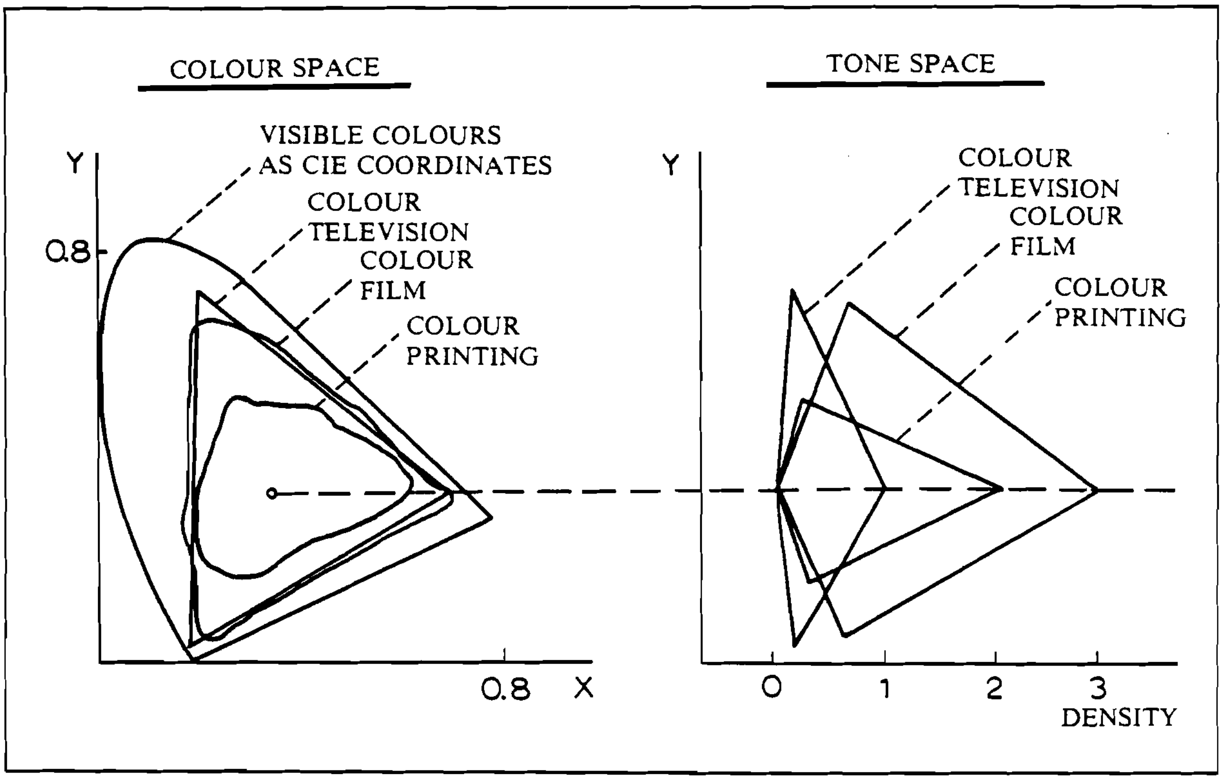


Fig. 7 Colour and tone space for different copying techniques /3,42,43/.

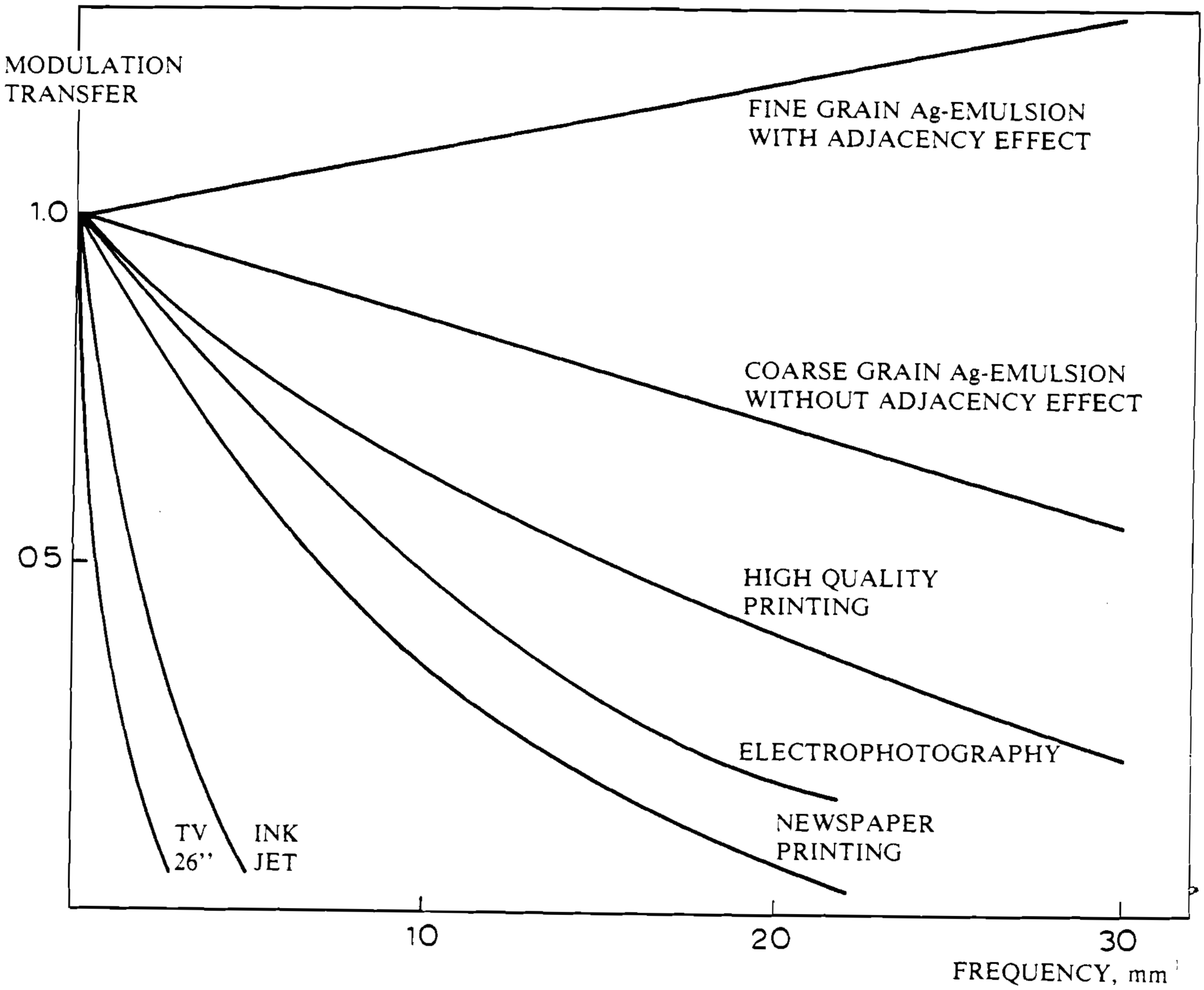


Fig. 8 Detail rendering for different copying techniques /3,15,20,24,29/.

Table 1 Estimated performance of visual communication processes /3,23,24,32,40/.

TECHNOLOGY	COPYING PROCESS	TONE RANGE D	FREQUENCY RANGE mm^{-1}	INFORMATION CAPACITY bit $\times$ mm^{-2}
PHOTOGRAPHY	successive exposure on light sensitive layers; development	0 - 3	0 - 10^2	3×10^5
ELECTRO-PHOTOGRAPHY	successive generation of a charge pattern; development and transter of colouring material according to the pattern	0 - 1	0 - 10	150
NEWSPAPER PRINTING, OFFSET	continual ink application to and transfer from a master on which the the image is in the form of of surface chemical variations	0 - 1	0 - 8	100
QUALITY PRINTING OFFSET	as above	0 - 2	0 - 15	500
QUALITY PRINTING GRAVURE	continual ink application to and transfer form a master on which the image is in the form of depth variations	0 - 2	0 - 15	500
INK JET PRINTING	continuous image formation by spatial deflection of ink drops by electrical means	0 - 1	0 - 2	50
TELEVISION SCREEN	continuous image formation by means of electro-optical conversion of a sweeping beam	0 - 1	0 - 1	10

viewing conditions it covers about one density unit, being more in dark and less in light viewing conditions.

The second category is represented by subtractive colour formation combined with an internal light source. The slide-projector system falls into this category. The density range is determined by the light absorption of the slide film, and can be as high as 3...4 density units.

The third alternative consists of subtractive image formation combined with external illumination, as in the case of printed pictures. The density range is limited by the surface reflection of the darkest point of the print. With matt surfaces, values higer than 1,4 are not usually obtained, while glossy surfaces may produce values somewhat above two density units. Consequently, colour photographs are superior in both colour and tone space. Printing on the other hand, gives a better tone range but a more limited colour range than displays.

The ability of processes to reproduce small details is expressed in terms of the modulation transfer function /Fig. 8/ /21/. The MTF expresses contrast rendering as a function of frequency. Normally, a frequency value of zero is normalized to a contrast value of one. A contrast value of zero indicates that no reproduction of details occurs.

The best reproduction of details is obtained with photographic film materials /Fig. 8/. In these, the rendering of details is limited partly by the granular structure of the light sensitive silver halogenide emulsions and partly by light diffusion in the layer during exposure. When the image is formed on photographic paper the rendering of details is considerably poorer, due to light diffusion in the paper when the image is illuminated for viewing.

In the case of printing, the halftone dot structure also influences the modulation transfer. As for non-impact printing, the limiting factor at present is the size of the picture elements in the output. The problem is not so much one of generation of sufficiently small picture elements but rather of controlling their size when they impact on paper. Furthermore, with diminishing size of the picture element the magnitude of the data flow increases, easily giving rise to data flow problems.

Detail rendering in video display images is limited by the number of lines in the screen.

From the point of view of visual image quality, a standard video screen and newspaper printing can reproduce a rather similar range of details when measured in relation to the visual angle of the human eye in typical viewing conditions. High quality printing has the capability of reproducing as many details as the human eye can discern, while high resolution photographic materials reproduce far more details than can be detected by the naked eye. Performance data of tone and frequency are listed in Table 1.

When an image is related to its object scene, wide performance ranges of the process do not necessarily guarantee that the image is a faithful reproduction. Thus fidelity is conceptually a separate image property. Fidelity of colour, tone and detail are independent fidelity components /Fig. 6/. In a process with given performance spaces, fidelity is controlled by intensity or density distortions and noise. Fidelity in an average sense is further dependent on the statistics of optical density in the object scene. The performance spaces as such naturally also influence fidelity; a tone, colour or detail which lies beyond the performance spaces simply cannot be reproduced accurately. Traditionally, the major emphasis in quality evaluations has been on fidelity.

Parameters of the tone, colour and detail rendering curves relating to the input and output are typical fidelity measures. Because the spaces in a copy are narrower than those in the original scenes, optimization of subjective quality by controlled distortion of fidelity has been explored repeatedly. Tone rendering in one-colour reproduction has in particular been the object of interest /1,17,43/. Intentional modification of frequency rendering has also been discussed.

It should, however, be noted that all measures of fidelity are likely to be insensitive image properties in technologies in which the performance ranges are limited and thus not well suited to quality evaluation purposes. Instead, it may be meaningful to examine how intensity or density relations, i.e. information, is transferred from the object scene to the image. In communication theory, the interpretation given to information is that of statistical information /9/. If image rendering is perfect, the transfer of statistical information is limited only by noise. Finite performance ranges and distortions further reduce the degree of information transfer. On the other hand, mapping of the object scene tone, colour and frequency ranges lineary in the image preserves the information in the absence of noise /9,35/. Rough estimates of information capacity are presented in Table 1. The estimates were assessed by means of the formula /23/

$$I = \frac{1}{MNA} \log_2 \int \frac{dD}{\delta_D} \tag{3}$$

Table I illustrates that the information capacity in which I is the information capacity, A the area of a picture element, MN the size of a tone matrix and δ_D the root mean square variation of density. Value for photography supersedes those of the other imaging technologies by two orders of magnitude. High quality printing comes next in performance.

Besides statistical information, object scenes contain what might be called semantic or intelligent information such as forms. Transfer of these to the image is another image property, although its quantification in the present situation has not been solved.

The problem which is addressed next is how the image properties should be combined to give meaningful quality criteria. A starting point for the discussion is the fact that images are reproduced for a purpose. The suitability of an image for a purpose determines its quality /14/. The uses of images can be considered to fall into one or several of the following categories:

- general viewing,
- comparison with a known object scene or
- decision-making.

The performance aspect in viewing, i.e. whether the viewer is expected to take action on or after seeing the image, increases in significance from the first to the third category. Comparisons with the classification of image properties presented in Fig. 6 makes it obvious that the two approaches are compatible.

A purely general viewing situation is one in which image perception is based solely on the image. Consequently the performance spaces determine image quality. It should be added that no viewing situation is likely to fall totally into this category. Some comparison with a known or imagined object scene may always be inevitable and thus fidelity has some significance. In a decision-making situation, on the other hand, all the viewer requires is information concerning the object scene on which to base his decision. Fidelity in the absolute sense is insignificant.

The way in which humans view images is not known in such detail that the principles presented above could be transformed into mathematically formulated quality criteria. However, it is feasible to strive towards such criteria because they are a necessity for full utilization of the potential which digital processing in imaging technologies offers with respect to quality control and improvement.

IMAGE PROCESSING

From the point of view of quality, the purpose of image processing is to correct for those distortions of tone, colour and detail which occur in the detection and copying processes and to modify the rendering characteristics of an image in a desired way. In digital processing terminology, correction of the detection process is called a posteriori restoration, of the copying process a priori restoration and image modification is called enhancement /27/. The aim of restoration operations is improvement of image fidelity, while improved utilization of the performance ranges of the copying process, viewer preferences or better information transfer serve as criteria for enhancement.

In addition to these quality improvement operations, the format and shape of images can be modified at the stage of image processing by means of enlargement, reduction, cropping and merging operations.

In the following, image processing for quality improvement by optical, analog and digital processing is briefly reviewed.

Optical processing is effected primarily by means of photographic technology /15/. For the adjustment of tone and colour, the exposure, material and development variables are varied in the process. All control operations are constrained by the characteristic curves of the process. An established technique for the enhancement of detail rendering is so-called unsharp masking. Typical of optical processing is that at best only one quality improvement operation can be performed within one exposure-development cycle. For example two cycles are required for unsharp masking. A consequence of this is that optical processing lacks flexibility. Further, the controllability of the adjusment operations is deficient.

In analog processing, the optical image signal is transformed into an electric video signal in which the current or voltage varies as a continuous function of tone and colour in the image. The signal is processed by means of electronic hardware. Video processing of images is thus as such very fast, but not flexible as far as frequency corrections are concerned. This is so because no memory is associated with a video signal; only one point in an image can be processed at a time. Frequency corrections can be carried out using a two-aperture system in the image input or by providing signal delaying with appropriate hardware. In all conditions, the spatial adjusment properties remain poor.

Digital processing /27,31/ is performed as arithmetic operations using computers. The operations which can be performed are usually divided into the groups of mapping, algebraic, geometric and filter operations. Mapping operations are used for the adjustment of colour rendering, algebraic operations for generation of combinations from separate images by means of addition, subtraction, multiplication and division, geometric operations for correction of coordinate distortions and filter operations for controlling of detail rendering and edge sharpness. Low-pass filtering attenuates details (causes blurring) and thus suppresses noise, while high-pass filtering enhances edges.

As well as data on process distortions, statistics of image density values can also be utilized in digital image processing. This allows images to be fitted into the copying processes on an individual basis with a view to the achievement of maximum possible quality /25,38/. Optical or analog methods do not permit such processing. Interactive image processing is also worthy of note, with associated possibilites of image enhancement and extraction of relevant information according to subjective preferences.

In principle, digital picture processing suffers from no constraints. In practical conditions, limitations are set on the one hand by the discrete spatial and tone spaces of a digital image and on the other by the long computation times of complex operations such as filtering. A compilation of the versatility of image processing by optical, analog and digital methods is presented in Table 2 by way of a summary.

CONCLUSIONS

The data presented show clearly that a distinct inverse relationship exists between image quality and production rate of mass-communicated images. In short, a requirement of high quality and rapid response between detection and mass distribution cannot be met.

Conventional printing methods are lacking in tone and colour spaces. This is a result of the subtractive image formation and the properties of the colourants used in the inks. New non-impact technology is gradually becoming competetive with conventional printing methods as far as image quality is concerned. Low production rates are still, however, a major impediment. In the case of video images, quality suffers mainly from poor resolution.

Application of digital processing in imaging technologies makes it possible to approach quality in a new and more composite way. Quality need no longer be regarded only as image fidelity, as has previously been the case. This is significant because fidelity is not the most important quality component in all viewing situations. Other quality components which can be taken into account with the facilities of digital processing include optimum utilization of the performance ranges of the imaging process and maximization of the transfer of relevant information from the object scene to a copy.

Table 2 Versatility of the different processing principles with respect to processing operations

	MAPPING	ALGEBRAIC	GEOMETRIC	FILTER
OPTICAL	constrained by characteristic curves of photographic processes	spatially invariant additions of image densities possible	spatially invariant operations possible	some low-pass filtering always occurs; can be amplified; high-pass filtering possible under the constraints of the characteristic curves and the number of processing cycles
ANALOG	no constraints	spatially invariant operations possible provided several processing devices can be synchronized in real time	spatially invariant operations possible	restricted possibility using small filter matrices
DIGITAL	no constraints	spatially variant algebraic operations possible without constraints	spatially variant operations possible without constraints	spatially variant operations possible without constraints

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