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Thermal Analysis of Ink-Substrate Interactions and Drying in Ink Jet Printing

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Väri/paperi-vuorovaikutusten terminen analyysi ja inkjet-tulosteen kuivuminen.

ABSTRACT

This paper presents documented data on thermal (TG and DSC) analysis of ink jet inks and on the relationship between the thermal results and the results of drying tests with ink jet prints. The purpose of the thermal analysis was to determine whether the evaporation of ink solvents from ink differs from the evaporation from mixtures of ink and substrate components such as chemical, thermomechanical and deinked pulp, kaolin, talc, PCC, gypsum, starch, SB, acrylate and PVAc, and whether there is any connection between evaporation of solvents and the smearing tendency of ink jet prints. Thermal analysis was carried out to determine whether solvent/media and dye/media interactions can be detected by these methods.

The evaporation energy from a mixture and the retention of solvent in a substrate showed a distinct trend: a large evaporation energy corresponds to a large retention capacity. Proportions of solvents in commercial inks vary greatly, but the evaporation energy ratios were found to be comparatively stable. The second solvent and the proportion of solvents in ink had a great effect on the retention of the first solvent.

The energies of evaporation were highest in mixtures of ink and cationic starch and lowest in mixtures of ink and PCC. A proportion of the first solvent was retained. Evaporation rates from mixtures are reduced most, most strongly for rapidly evaporating inks. The evaporation energy tends to be higher from ink/component mixtures than from pure inks. The evaporation energies at the first peak tend to be higher in pulp mixtures than in pigment mixtures. Obviously, the evaporation energy of a solvent depends mainly on the internal forces of the ink itself. Freezing energies and freezing points changed more in ink/substrate mixtures than in water/substrate mixtures compared plain water. A major change in freezing energy between ink and a ink/solvent mixture indicates interactions between the solvent and substrate component.

The drying time tests were carried out with four model inks and paper series with different pigmentation. Kaolin-based papers had the longest drying times and talc-based papers the shortest, both in offset and smudge smearing tests. The precipitating model ink and pigmented ink were found to have the longest drying times when tested by smearing. This was attributed to the dye or pigment remaining mainly on the surface of the paper.

TIIVISTELMÄ

Tässä artikkelissa on esitetty inkjet-värien termisten analyysien (TG ja DSC) tuloksia ja niiden yhteys inkjet-tulosteiden kuivumistestituloksiin. Termisten analyysien tarkoitus oli selvittää eroaako inkjet-värin haihtumiskäyttäytyminen tapahtuessaan puhtaasta musteesta tai muste/paperikomponentti-seoksesta ja onko löydettävissä yhteyttä liuottimien haihtumisen ja inkjet-tulosteen tahraamistaipumuksen välillä. Käytettyjä paperikomponentteja olivat kemiallinen, termomekaaninen ja siistattu massa, tärkkelys, SB, PVAc, akrylaatti, kaoliini, talkki, PCC ja kipsi. Termiset analyysit toteutettiin, jotta nähtäisiin voidaanko liuotin/paperikomponentti- ja väriaine/paperikomponentti-vuorovaikutukset todeta käytetyillä menetelmillä.

Haihtumisenergia seoksesta ja liuottimen retentio paperikomponenttiin osoittivat selkeästi: Suuri haihtumisenergia vastaa suurta retentiokapasiteettia. Liuottimien keskinäiset osuudet kaupallisissa väreissä vaihtelivat laajalti, mutta väreittäin liuottimien haihtumisenergioiden suhteet olivat miltei vakiolliset. Sopivalla apuliuottimen valinnalla ja määräosuudella voidaan lisätä tai vähentää värin retentiota.

Suurimmat haihtumisenergiat mitattiin värin ja kationisen tärkkelyksen seoksesta, kun taas pienimmät haihtumisenergiat mitattiin värin ja saostetun kalsiumkarbonaatin seoksesta. Osa ensimmäisenä haihtuvasta liuottimesta retentoitui. Seoksista mitatut haihtumisnopeudet hidastuivat, eniten hidastui nopeiten haihtuvien värien haihtumisnopeudet. Haihtumisenergiat olivat korke-

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ampia väri/komponentti-seoksista kuin puhtaasta väristä mitattuna. Ensimmäisenä haihtuvan liuottimen haihtumisenergiat olivat korkeampia massaseoksissa kuin pigmentti-seoksissa. Ilmeisesti liuottimen haihtumisenergia määräytyy pääasiassa värin sisäisistä voimista. Jäätymisenergiat ja -pisteet muuttuivat enemmän väri/paperikomponentti-seoksissa kuin vesi/paperikomponenttiseoksissa verrattaessa puhtaan veden arvoihin. Suuri muutos jäätymisenergiassa värin ja väri/paperikomponentti-seoksen välillä osoittaa vuorovaikutuksien olemassa oloa liuottimen ja paperikomponentin välillä.

Kuivumisaikatestauksissa käytettiin neljää malliväriä ja pigmentoinniltaan erilaisia papereita. Kaoliinipohjaisilla papereilla todettiin olevan pisimmät kuivumisajat ja talkkipohjaisilla papereilla lyhyimmät, sekä kosketus- että hankaustahraavuustesteissä. Saostuva malliväri ja pigmentoitu väri kuivuivat hitaimmin tahraamattomiksi, koska niiden väriaine tai pigmentti jää suurelta osin paperin pintaan.

INTRODUCTION

The low-cost, low-volume, office and home printing market is served by drop-on-demand ink jet technology, producing almost photographic-quality prints. In this ink jet segment, ink jet inks are water-based. They contain mainly water and a water-soluble solvent. They employ dyes instead of pigment and do not contain resins /2/. They smudge very easily because of their poor resistance to wetting.

The drying of ink can be separated into setting and drying stages. In the setting stage, ink forms a set-off resistant layer. In the drying stage, ink forms a rub-off resistant layer. Most of the solvents in ink jet ink must evaporate or penetrate into the capillary pores of the paper surface before the ink will meet any setting resistance. In the drying stage, when the rest of the solvent evaporates or penetrates and the dye precipitates and makes adsorption bonds to paper components, the final rubbing resistance is formed.

Research concerning ink-media interactions can be divided into the following phases: generation of interaction, detection of interaction and analysis of data. Printing produces interaction in "real-life" conditions. Printed samples are well-suited for further characterisation by optical and durability measurements. Because the conditions in commercial printing devices cannot be systematically varied, experiments based on printing and print characterisation are not ideal for identification of fundamental interactive modes. This study was started by conducting model component experiments to explain drying and drying interactions between specified ink and paper components. By mixing inks, or ink components and single paper or film components, the influence of the porous structure of the substrate can be largely eliminated. This supports identification of other than structure-related interaction modes. A drawback of the analytical approach is that verification of its practical relevance requires further experimentation to relate analytical data to behaviour in real printing conditions.

The purpose of the TG and DSC analyses in this study was to determine whether the evaporation of solvents of ink jet inks is different from mixtures of ink and substrate components than from inks as such. In other words it was studied whether the substrate components exert retentive or accelerating effects. Generally, retention slows down ink drying and results in a lower mechanical durability of the print /7/.

Thermographic analysis allows characterisation of substances as a function of temperature or time. This is usually done by using a so-called recording balance /13/. From weight loss curves of inks, the rough composition and proportions of components — including the amounts of solvents, binder and pigment — can be determined /4,5,6,9/. Thermal reactions with energy changes can be measured with DSC. The behaviour of a sample is determined by comparing it with a reference, an inert substance, which shows no thermal activity in the temperature range of interest. It is obvious that this allows changes in the temperature of the sample to be detected much more accurately than when only the absolute temperature of the sample is measured /10,13/.

Reactions that cause energy changes are phase changes during heating like melting, evaporation and sublimation, and reactions like oxidation, degradation and polymerisation for example /10,13,14/. Melting, evaporation and sublimation are energy-releasing (exothermic). Oxidation, degradation and polymerisation are energy-binding (endothermic). Oils and some of the binder are evaporated during heating. Double bonds, for example, in dyes can be oxidised during heating in the presence of air /11/. Condensation and polymerisation reactions occur in double bonds of binders. Thermal degradation of a binder and dye or a pigment may occur at high temperatures. A solid component may be sublimated during heating directly into gaseous form /8/.

EXPERIMENTS

Materials

The combinations of ink jet inks and substrate components covered by the tests are listed in Table 1. The ink samples include commercial and experimental inks. The commercial ink series consists of inks used in the most common ink jet printers. The substrate components are samples of widely used fibre and coating components. The samples were chosen to represent materials used in drop-on-demand ink jet printing in the best possible way.

Table 1. Inks and fibre or coating paper components in the study.

Ink jet inks	**Paper and coating components**		
Commercial inks	**Fibres**	**Pigments**	**Binders etc**
Series1 Series2 Series3 Series4	Pine sulphate TMP Deinked	PCC Kaolin Gypsum Talc	Acrylate PVAc Starch (cationic) Styrene butadiene
Model inks			
Pigmented black (P), Magenta (M), Food Black 2 (FB) and Projet Fast Black 2 (PFB)	Birch sulphate Pine sulphate Eucalyptus sulphate TMP	PCC Kaolin Talc	Starch (cationic)
Ink solvents			
Water 1.5-Pentanediol TEG (Triethylene glycol monobutyl ether) DEG (Diethylene glycol)	Pine sulphate Deinked TMP	PCC Kaolin Gypsum Talc	Acrylate PVAc Starch (cationic) Styrene butadiene

The model ink, Food Black 2, is a traditional diazo dye having –SO_3-groups as functional groups /1, p. 4251/. The structure of Projet Fast Black 2 differs from Food Black 2 mainly in the sense that part of the –SO_3-groups are replaced by *HOOC* groups to improve the wet resistance of the dye on the substrate in the printing process.

In the pigmented black, the colourant used is a modified carbon black pigment. It consists of carbon particles covalently bound to sulphonic acid groups to make the pigment self-dispersible. The particle size is around 100 *nm*. In the magenta ink, the dye is a diamine-based molecule.

Diethylenglycol and 1.5-pentanediol were of analytical quality (purity over 96 %) and triethylene glycol monobutyl ether of technical quality (purity about 75 %). The water was deionised.

The papers were pilot papers containing different pigments. The paper pulp consisted of 70 % eucalyptus and 30 % pine/spruce mixture. The proportion of pigment in the papers was 15 %. The pigments studied were TiO_2, PCC, kaolin, ground chalk and talc.

METHODS

Thermogravimetry

For thermogravimetric analysis equal amounts of ink and fibre or coating components (1–2 *mg*) are mixed manually in a crucible. The analysis is carried out immediately. Heating from 30 to 650°C is accomplished at a rate of 20°C per minute. Some evaporation of solvents may occur before heating begins. Fast heating, at a rate of 20°C/*min*, results in sharper thermogravimetric curves than if using slower heating. When using fast heating, the sample should be quite small, about 2 mg, to guarantee uniform heating across the sample. The starting temperature was the lowest possible with the equipment used. The measurements were carried out using nitrogen as balance (60 *ml*/*min*) and sample purge gas (30 *ml*/*min*). A Perkin Elmer 1020 TGA7 thermal analyser was used for the measurements.

Interactions in component mixtures occur as

- changes in total weight loss within a given temperature range,
- changes in weight loss rates
- and changes in the temperatures corresponding to the highest weight loss rates.

Figure 1 illustrates how these criteria are read from TG curves. The first two weight losses are due to solvents (the ink contains two solvents), and the third small weight loss is due to degradation of dye. In the measurements, two regions of evaporation could commonly be identified.

According to replicate measurements, the standard deviation of TG measurements is fairly small, about 1–2 % of the weight loss of solvents.

Isothermal analyses were carried out, keeping sample mixtures at a constant temperature long enough. The temperatures in the isothermal analyses were 30, 40, 50 and 60°C.

Differential Scanning Calorimetry

The DSC analyses were carried out with a Mettler TA 4000 thermal analysis system using a DSC 30 measuring unit. The DSC 30 unit is a heat-flux DSC measuring the differences in temperature between a reference and a sample cell. The amounts of sample were 2–4 *mg*. The measurements were carried out using synthetic air as purge gas (15 *ml*/*min*). The samples were cooled rapidly with liquid nitrogen. In the instrument, a sample and a reference substance are placed in small (40 μl) aluminium crucibles and positioned on a heat-flux plate. This plate generates a controlled heat flow from the furnace wall to the sample and reference. The initial temperature was 0°C. The settling time was 2 *min*. The heating rate was 20°C/*min* in all measurements. The final temperature was 500°C. Open crucibles were used, because the samples studied mainly contained solvents.

Generally, interactions are detected as changes in energy consumption and as changes in the temperatures corresponding to the energy consumption /13/. A typical DSC curve of ink jet ink in a paper component mixture is shown in Figure 2. A solid component may be sublimated during heating directly into gaseous form.

Functional groups in an ink jet dye, such as –*N*=*N* , *HOOC* and –SO_3 groups, are obviously degraded during heating. Degradation of functional groups occurs at higher temperatures (300–500°C) and can be observed as exothermic reactions /12/. The amount dye in ink, and its effect on the energy curve of DSC, is small. In Figure 2, the baseline is rising because the sample amount diminishes during heating (the ink mainly contains solvents). A non-linear baseline sometimes causes difficulties in accurately calculating the heat capacity of a sample. The standard deviation of DSC measurements is greater than in TG measurements, over 10 % of the evaporation energy of the solvent.

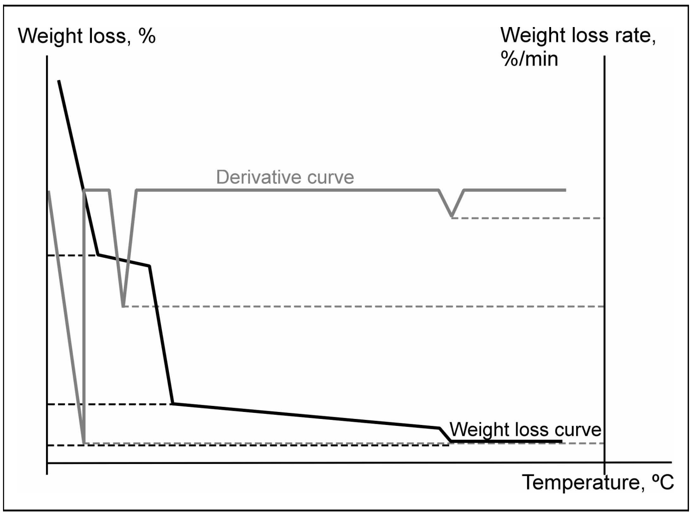

Fig. 1 Typical weight loss curve of an ink jet ink.

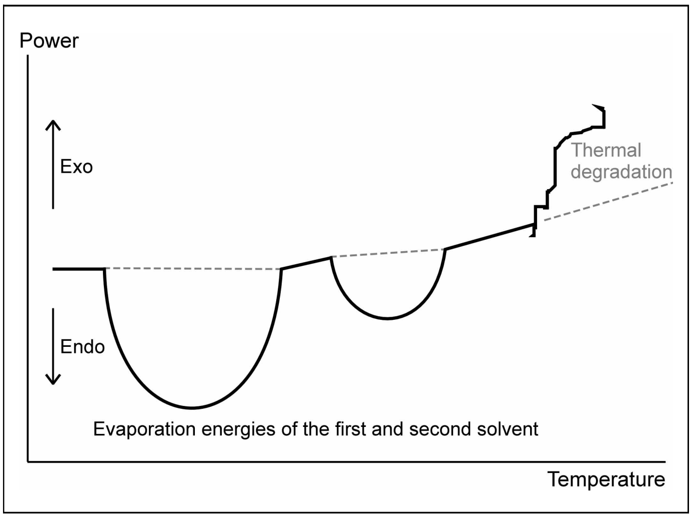

Fig. 2 Typical DSC curve of ink jet ink.

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The temperature programs in differential scanning calorimetry analysis were the increasing (20°C/*min*), isothermal and decreasing temperatures. Different temperature programs were used to determine all changes in energy. Isothermal analysis gave the best value of total energy change, and increasing and decreasing temperature analyses were carried out to separate various energy changes occurring in the same mixtures.

Drying Time Tests

The test procedures were based on the test methods Ink drytime -Offset and -Smudge /16/. The tests was carried out in a conditioned environment at 23°C and 50 % relative humidity. Printings were carried out with an Olivetti JP790 colour printer using self-filled black ink cartridges. The procedure was the following: A piece of foamed plastic was impregnated with ink. The total impregnated ink amount was about 42 *g*. The impregnated piece of foamed plastic was pushed into an ink cartridge (a part of the ink was decompressed due to compression). Before printing, some ink was added by injection.

Ink jet inks were model inks: Food Black 2 (FB), Projet Fast Black 2 (PFB), pigmented black (PB) and magenta (M) ink. The papers were a series with different filler contents (5 papers).

In set-off smearing, the roller (2.5 *kg*, length 110 *mm*, diameter 84 *mm*) passed over the test prints was made from a paper-covered metal plate.

The ink drytime corresponds to the first point at which the optical density average of the offset image was 0.01 or lower. The drytime range with the Olivetti printer was 3–51 *s*, using a test figure (compact black 240 *mm* length, 9 *mm* width).

In rub-off smearing, the plastic strip (230 *mm* × 36 *mm*) is held over the print and a metal weight is placed on top. The weight is placed at the top of the sheet with the sides of the square base parallel to the edges of the paper. It is then drawn down over the print (running parallel to the long edge of the paper) by smoothly pulling the plastic strip over the paper surface.

The test sheet was examined to determine at which point the ink dried and therefore stopped smudging (the optical density average of the offset image was 0.01 or lower). The measuring range with the Olivetti printer was 3–45 *s*, using the test figure shown in Figure 3.

RESULTS AND DISCUSSION

Inks

Making the simplified assumption that ink jet inks contain solvents and dye, ink-media interactions can be discussed in terms of interactive modes between solvent and media on the one hand, and dye and media on the other. In the case of solvents, interactions are likely to lead to changes in the evaporation behaviour. Thermal measurements have been made to find out whether interactive solvent retention can be observed. Dye-media interactions by definition mean some tendency of the dye to be attached on the substrate.

Data on commercial inks show that there are fairly extensive differences between the inks. In a m_1/m_2 vs. E_1/E_2 plot /Fig. 4/, inks from a different manufacturer fall within a characteristic area. Though the proportions of solvents vary greatly between the inks, the evaporation energy ratios of solvents are almost the same.

The model inks differ widely from the commercial inks, because they have only one solvent, water. Evaporation energies of the model inks correspond to the evaporation energies of the first solvent of commercial inks. Thermal data of the studied model inks are presented in Table 2. According to information provided by the manufacturer, pH values of all ink solutions were 9.0.

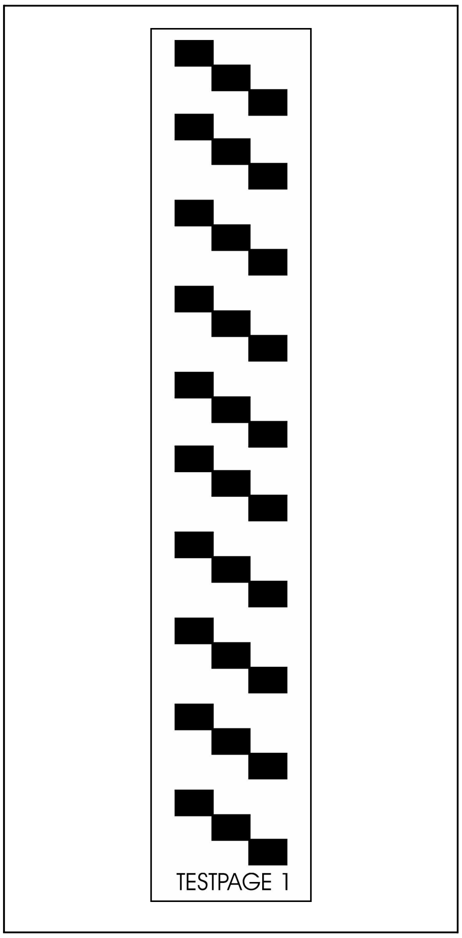

Fig. 3 Test figure used in Drying time -Smudge test.

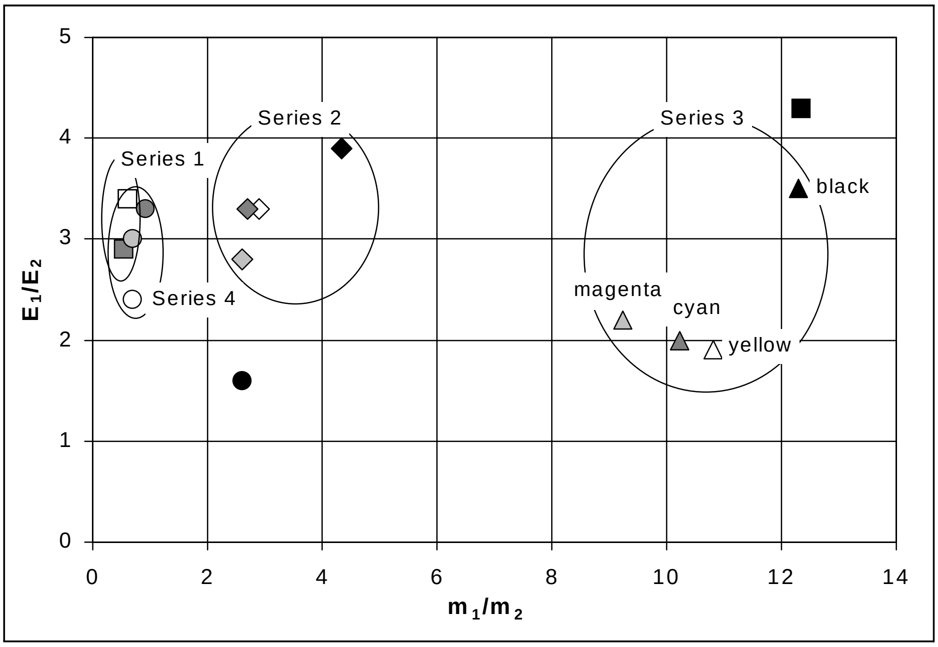

Fig. 4 Thermal analysis data of commercial inks.

Evaporation Rates

The evaporation from mixtures of ink and substrate components differs from the evaporation from the inks as such. This is shown by the examples of data for the experimental inks presented in Table 3. Table 3 lists the evaporation rates of solvents from some commercial inks and the respective rates from mixtures of ink and chemical pulp (pine sulphate), precipitated calcium carbonate (PCC) or starch.

The rate of evaporation is lower in mixtures. The first solvent (water) evaporates faster from precipitated calcium carbonate than from pulp and starch.

The evaporation rate from mixtures is mostly reduced; more so for rapidly evaporating inks. The studied model inks were the most rapidly evaporating ones. Figure 5 illustrates the change in evaporation rate in a mixture of pulp (TMP, pine sulphate pulp and deinked pulp) as a function of the evaporation rate of the first solvent of the studied commercial inks. Variations in evaporation surface areas during measurements caused errors in the measured evaporation rates.

Retention of Solvents

The percentage of solvent which evaporates at the first peak of the TG curves is lower in mixtures than in inks. This indicates water retention. A second peak also tends to emerge. Figure 6 shows average proportions of retained solvents of the commercial inks. The first solvent is water and the second a water-soluble organic solvent.

Moisture in the substrate may cause an error in the retention results. Pulps contained about 5 % water, pigments less than 1 % (except gypsum which contained 20 %) and binders 2–3 % (except starch which contained 12 %). Gypsum and starch had the greatest retention of the studied substrate components. Because of the great proportion of chemically bound water in gypsum, the calculated retention of solvents to gypsum may include a certain error.

The effect of the solvent system on retention was studied using mixtures of two model solvents and a paper component. In all mixtures, water was the first solvent. The second solvent was 1.5-pentanediol, DEG or TEG. The proportions of water of total solvent were 50, 67 and 75 %. The amounts of solvent and paper component were the same in the mixtures. In the thermogravimetric analysis, the first evaporated solvent is regarded as water and the retained proportion of water is assumed to evaporate with the second solvent at a higher temperature. The moisture in paper components is assumed to evaporate with water.

Table 2. Thermal data of studied model inks.

	Solvent, %	Dye or pigment, %	Temperature of the greatest evaporation rate, °C	Evaporation energy, J/g
Pigmented (PB)	91.1	8.9	124	1940
Magenta (M)	94.5	5.5	102	2010
Food Black 2 (FB)	97.4	2.6	88	1890
Projet Fast Black 2 (PFB)	97.4	2.6	85	1930

Table 3. Evaporation rates (% per minute) of the first solvent of studied ink jet inks and solvents in some paper components.

	Ink	Pine sulphate pulp	PCC	Starch
FB	62.0	31.2	60.3	36.7
PFB	54.6	33.8	48.8	35.3
1.5-pentanediol	63.5	36.8	45.2	44.9
DEG	52.1	30.2	40.7	35.5
TEG	48.0	39.8	34.6	33.7
Series 3, black	58.8	62.6	47.1	38.9
Series 3, cyan	49.4	32.7	38.1	40.1
Series 3, magent	49.9	18.7	43.8	58.7
Series 3, yellow	46.6	37.9	41.6	40.3
Series 3, black	44.9	36.8	49.8	43.9
Series 3, cyan	45.5	44.1	53.7	42.1
Series 3, magent	42.5	28.1	39.7	51.5
Series 3, yellow	55.1	34.7	50.2	40.8
Series 3, black	54.9	31.9	47.6	41.4
Series 3, cyan	41.1	41.0	45.1	36.9
Series 3, magent	43.9	30.8	47.7	37.4
Series 3, yellow	44.7	34.9	50.2	35.7
Average	50.4	35.6	46.2	40.8
Standard deviation	6.6	8.7	6.0	6.2

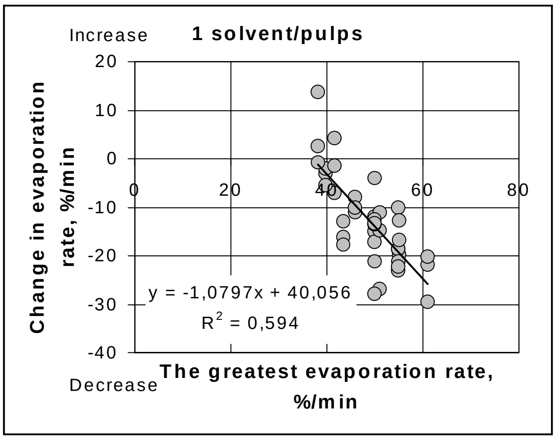

Fig. 5 Change of evaporation rate in ink/pulp-mixture as a function of evaporation rate of solvent.

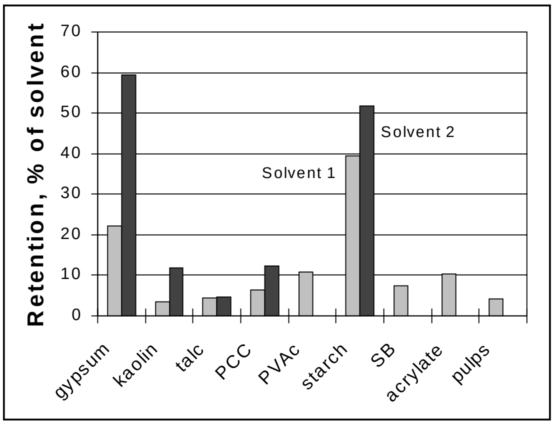

Fig. 6 Retention of solvents in paper components.

No distinct trend could be detected between the proportions of solvents and amounts of retention. Generally, the retention of water was greater than the retention of other solvents, with the other solvents having only a minor influence on water retention. The retention of water from mixtures of 1.5-pentanediol or DEG was somewhat greater than from mixtures of TEG.

Binder retained more water and organic solvents than pulps or pigments. The retention of organic solvents to pulps and pigments was minor. Pigments have greater water retention than pulps, which is due to the great water retention capacity of gypsum. Figure 7 shows the retention of water (the 1st solvent) and retention of organic solvent (the 2nd solvent) to the paper component in 3-component mixtures. Retentions were calculated from total and evaporated solvent amounts.

Evaporation Energies

The evaporation energy of the first solvent tends to be higher from ink/component mixtures than from pure inks. The energies of evaporation at the first peak tend to be higher in pulp mixtures. Some error in the data is caused by the fact that the substrate components were air-dried and thus contained some water, about 5 % on average, as discussed above. With some exceptions, the energies of evaporation at the first peak are fairly similar and representative of values for water. The evaporation energy of the first solvent is somewhat higher from model solvent mixtures than from mixtures of commercial ink and the paper component /Table 4/. The evaporation energy of the first solvent is increased more than the energy of the second solvent with commercial inks. In the case of the first solvent, the increase in evaporation energy is almost the same in ink/fibre and ink/pigment mixtures.

In the case of the second solvent, the increase in evaporation energy is slightly greater (about 10 %) in ink/fibre mixtures than in ink/pigment mixtures /Table 4/. No significant difference can be found between the effects of the mixtures. In the case of the second solvent, the increase in evaporation energy is greater in ink/pigment mixtures than in ink/fibre-mixtures. The evaporation energy of the second solvent is greater from 3-component mixtures than from the mixtures of commercial inks and the paper component. This may be due to the fact that a greater part of water evaporates with the second solvent from mixtures at a higher temperature. The retention of the first solvent and evaporation with the second solvent increase the measured evaporation energy values of the second solvent, especially in the case of gypsum. Generally, more water evaporates with the second solvent from the 3-component model mixtures than from the mixtures of commercial inks and paper components.

Differences between pigments are small (except for gypsum). Differences between pulps are small, too. Starch causes the evaporation energy of the first solvent to increase more than PVAc, SB or acrylate.

The rising temperature analysis gives systematically smaller energy values than isothermal analysis /Figure 8/. It seems evident that the evaporation energy of a solvent mainly depends on internal forces of the ink itself.

In isothermal DSC analysis solvents evaporate from mixtures at a rate which depends on temperature. Inks had the lowest evaporation energies from pine sulphate chemical pulp. This may be partly due to pore size differences and differences in specific surface areas of the studied pulps, because pores are likely to retain solvent. Chemical softwood pulps have larger pore volumes than hardwood pulp or mechanical pulps /15/. Within the range studied, the evaporation energies were highest at 20°C. Evaporation energies of the first solvent (water) from isothermal DSC measurements declined as a function of temperature, as was to be expected. The isothermally analysed evaporation energies are greater than those measured with increasing temperature.

Freezing Energies

Freezing energy and temperature are characteristic for every pure liquid. The freezing and boiling temperatures of a will mixture change depending on the proportions of components and chemical bonds between components. Chemically

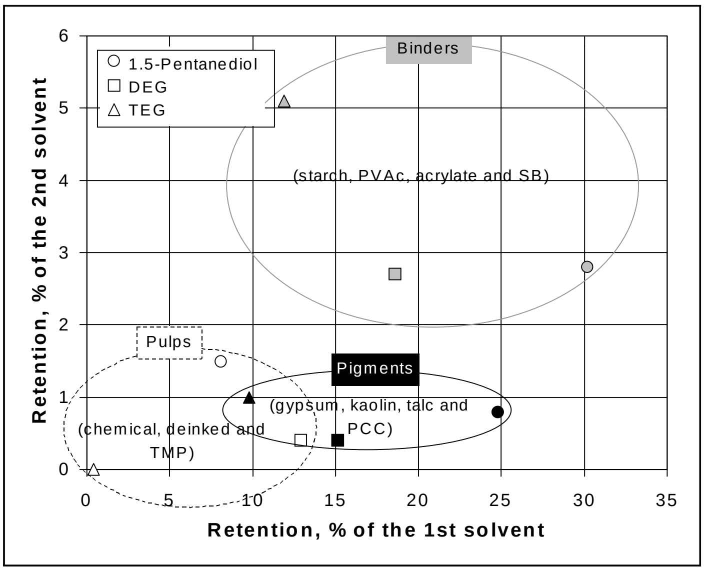

Fig. 7 Retention of solvents from 3-component mixtures.

Table 4. Evaporation energy of solvents from pure ink and from ink/paper component mixtures (*J/g*).

Sample	1st solvent	2nd solvent
Ink*	1500	500
Ink/pigment (kaolin, talc and PCC)	1860	600
Ink/ pulp (TMP, chemical and deinked)	1710	30
Ink/starch	2170	110
Water/1.5-pentanediol/pulp (TMP, chemical and deinked)	2230	830
Water/1.5-pentanediol/pigment (kaolin, talc, gypsum and PCC)	1810	2070
Water/1.5-pentanediol/binder (starch, PVAc, acrylate and SB)	2110	1080
Water/DEG/pulp	2440	610
Water/DEG/pigment	2130	1080
Water/DEG/binder	2300	550
Water/TEG/pulp	2510	170
Water/TEG/pigment	2190	800
Water/TEG/binder	2390	490

* Ink means average values of commercial inks

bound water has a lower freezing temperature than free water in a paper fibre.

Figure 9 illustrates changes in freezing temperature as a function of freezing energy, as measured from various ink/substrate mixtures. The substrate components were pulps (birch and pine chemical pulp, TMP, eucalyptus, deinked pulp) and PCC. Freezing energies and freezing points changed more in ink/substrate-mixtures than in water/substrate-mixtures, compared to plain water. FB caused the greatest change in the measured freezing energies. This suggests that the interaction between FB ink and substrate components is more intensive than the interaction between PFB ink and substrate components. Changes in freezing energies of precipitated calcium carbonate mixtures were smaller than those of pulp mixtures. A great change in freezing temperature or freezing energy indicates great adsorption forces.

Differences between freezing energies and temperatures of water/substrate mixtures and ink/substrate mixtures are due to dye/solvents interactions, whereas differences between freezing energies and temperatures of water and of water/substrate or ink/substrate mixtures are due to water-substrate interactions.

Thermal data and smearing tendency of prints

Drying of ink can be separated into setting and drying stages. In the setting stage, ink forms a set-off resistant layer and in the drying stage, ink forms a rub-off resistant layer. The solvent of the ink partly evaporates and partly penetrates into paper in the setting stage. Dye or pigment remains mainly on paper component surfaces. Precipitation or adsorption binding may occur during the drying stage, when drying conditions change. A print´s tendency to smear (set-off and rub-off) means that a reader´s hands and other surfaces may be soiled. Generally, the smearing tendency of prints diminishes as a function of time.

Figure 10 shows set-off (offset) and rub-off (smudge) smearing from PCC pigmented paper as a function of time. In terms of density units, ink jet inks have greater set-off than rub-off smearing tendency, which may be due to hydrophility of dyes or pigments. The same trend was found with all the studied papers.

Some prints, printed with magenta ink and talc-based papers, were totally dry just after printing (3 *s*) and some were all wet after testing (51 *s*). The pigmented ink smeared most in all the papers. The magenta ink smeared the least. The drying of inks was found to be slowest with PCC and kaolin-filled papers.

PFB, which precipitates in neutral or acid conditions on the paper, and pigmented ink have the longest drying times in rubbing. This is probably because their dye and pigment remain mostly on the surface of the paper. In this case rubbing occurs easily. The rubbing tendency of magenta ink and FB is minimal. This may be due to penetration of dye with solvent deep into the paper. In the case of set-off smearing, dye-substrate component interactions seem to have a greater effect than penetration of solvent. In the case of rubbing, a connection between drying time and retention is

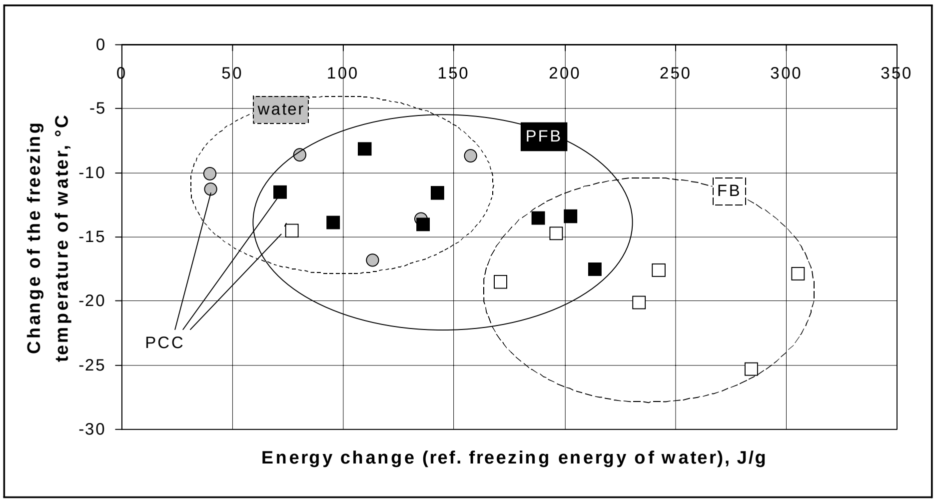

Fig. 9 Changes in freezing temperature and energy in mixtures ref. water.

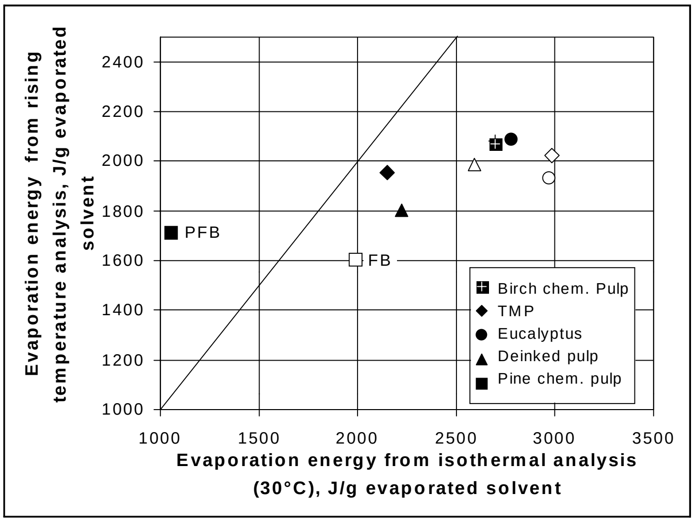

Fig. 8 Evaporation energies of ink/fibre mixtures measured isothermally and with increasing temperature.

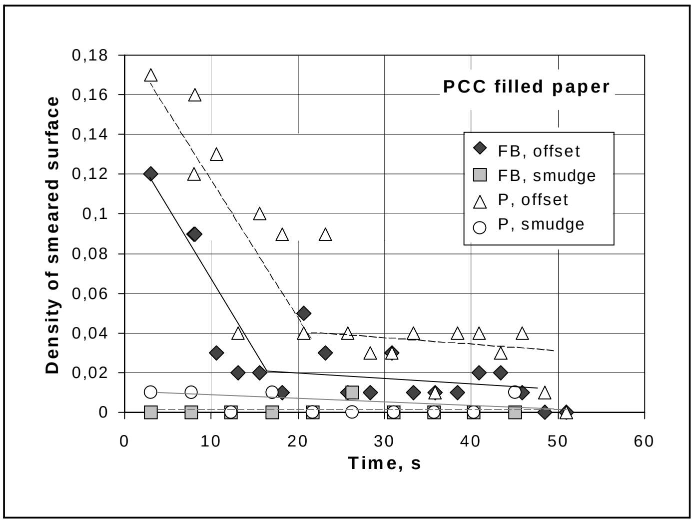

Fig. 10 Smearing as a function of time.

evident. If solvent is strongly retained in paper, the print dries fast, even if the evaporation temperature is high /Figure 11/.

Obviously, a great evaporation energy suggests strong interactions between solvent and substrate components. This reduces the smearing of prints. It was difficult to estimate the exact changes in evaporation energy in mixtures, because it was impossible to weigh the sample during DSC measurement. The estimation of the evaporated proportion of solvent in DSC measurement from TG measurement caused variations in results. Correspondingly, a great change in freezing energies between ink and an ink-solvent mixture indicates interactions between the solvent and substrate components. This is one reason why Food Black 2 dye smeared less on PCC-based papers than Projet Fast Black 2 dye.

CONCLUSIONS

The experimental data show that the thermal methods employed provide information on solvent/media- and dye/media-interactions, solvent retention and affinity to dye. Differences were found in the evaporation energies of solvents from various mixtures, in the evaporation rates of solvents and in the retention in the substrate component. The evaporation energy from a mixture and the retention of solvent in a substrate showed a distinct trend: a large evaporation energy corresponds to a large retention capacity.

Evaporation from mixtures of ink and substrate components was different from evaporation from the ink as such. The energies of evaporation were highest in mixtures of ink and starch and lowest in mixtures of ink and PCC. The evaporation rate of the first solvent (water) was reduced by more than the evaporation rate of the second solvent. Evaporation energy from ink/component mixtures was higher than from pure inks. The energies of evaporation at the first peak tend to be higher in pulp mixtures than in pigment mixtures. The second solvent in ink has a significant effect on retention of water and accordingly on the drying properties of a print. Obviously, the evaporation energy of a solvent mainly depends on the internal forces of the ink itself. Freezing energies and freezing points changed more in ink/substrate mixtures than in water/substrate mixtures compared with plain water. Differences in the freezing energies and freezing points confirmed that there are certain interactions both between ink and substrate components and between dye and solvent.

The precipitating ink (PFB) and pigmented ink had the longest drying times. This may be due to the multilayer precipitation of dye or pigment on the surface of a print. In most of the experiments, a high evaporation temperature resulted in a low retention of solvent. In the inks with limited smearing tendency the dye probably penetrates with the solvent deeper into the paper.

ACKNOWLEDGEMENTS

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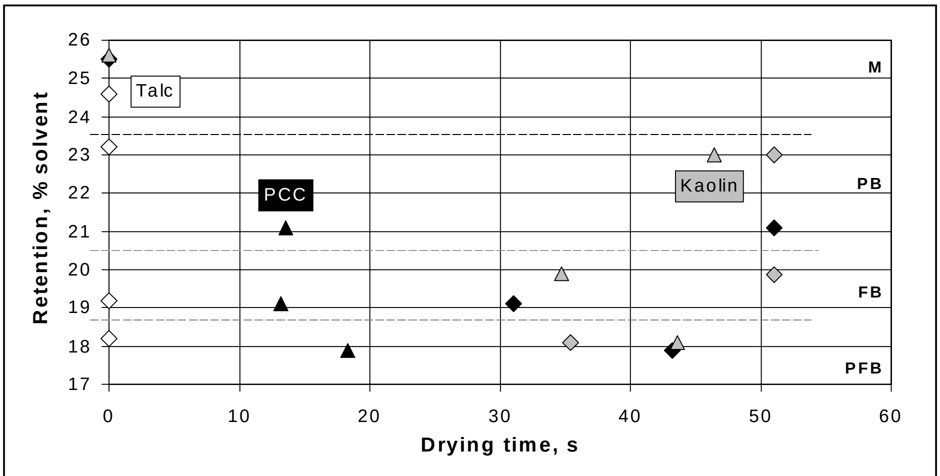

Fig. 11 Retention as a function of drying time (Triangles mean drying time in offset and quadrangles in smudge).

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The Quality of Image Reproduction: The Selection of Metrics for Analysis

Heikkilä, I.*

Kuvareproduktion laatu: mittojen valinta analyysiä varten.

ABSTRACT

This study discusses the criteria for a quality analysis of image reproduction. It is determined that the objective of image reproduction is to reproduce the visual information that is available in an original image. The visual information of an image is in the colours of image points and in the spatial structures that result from the colour fluctuation across the image. The quality of the image reproduction is often described in terms of the quality of the colour reproduction. It is, however, true that minor errors in the colour reproduction may cause significant errors in or even vanishing of the spatial structures of an image. This therefore suggests that, when the quality of the image reproduction is analysed, also the structure reproduction has to be analysed with regard to its quality.

Monocular sources of visual information are reviewed to find criteria for the quality analysis of the structure reproduction. It was found that the characteristics of many sources of visual information relate to the sharpness of edges, the size of details, or to the evenness. These metrics are also proposed to be used for the analysis of the quality of the structure reproduction. Discussions about the low-pass filtering properties of the human vision suggest that the spatial structures resulting from the luminance fluctuation across the image are of special importance.

TIIVISTELMÄ

Tässä artikkelissa tarkastellaan kuvareproduktion laatukriteerejä. Tarkastelu perustuu määritelmään, jonka mukaan kuvareproduktion tavoitteena on originaalikuvan visuaalisen informaation reproduktio. Artikkelissa todetaan, että kuvassa oleva visuaalinen informaatio sisältyy yksittäisten kuvapisteiden väreihin ja niistä muodostuviin laajempiin kokonaisuuksiin, spatiaalisiin rakenteisiin. Kuvareproduktion laadun tarkastelu perustuu usein värireproduktion laadun tarkasteluun. On kuitenkin niin, että jo hyvin vähäiset värireproduktion virheet saattavat aiheuttaa hyvinkin suuria virheitä spatiaalisten rakenteiden reproduktioon. Kuvan spatiaaliset rakenteet saattavat joskus jopa hävitä pienten värireproduktion virheiden seurauksena. Onkin ilmeistä, että kun kuvareproduktion laatua tarkastellaan, on tarkasteltava sekä värireproduktion että rakenteen reproduktion laatua.

Artikkelissa tehdään kirjallisuuskatsaus monokulaarisiin visuaalisen informaation lähteisiin. Niiden perusteella valitaan mitat, joita voitaisiin käyttää rakenteen reproduktion laadun määrittämisessä. Työssä todetaan, että kuvassa esiintyvien reunojen terävyyden, yksityiskohtien koon ja tasaisuuden virheetön reproduktio on erityisen tärkeää, jotta kuvassa oleva visuaalinen informaatio toistuisi. Kyseisiä mittoja ehdotetaan myös käytettäväksi rakenteen reproduktion laadun määrittämisessä. Artikkelissa tarkastellaan myös värien alipäästösuodattumista ihmisen näköjärjestelmässä. On ilmeistä, että kun rakenteen reproduktion laatua määritetään, päähuomio olisi kiinnitettävä kuvassa oleviin vaaleusvaihteluihin.

INTRODUCTION

The term digital image refers to a three-dimensional matrix, in which the rows and the column indices identify the spatial location of an image point, and the third dimension is used to determine the colour at each image point. When the quality of the image reproduction is analysed, often only the quality of the reproduction of the third dimension – or the quality of the colour reproduction – is analysed. For that purpose, there are widely accepted methods to calculate the colour difference between each image point in the original and in the reproduced images. It is, however, true that, in an image, not only the colours of individual points, but also the spatial correlations or the spatial structures formed by the individual points are of importance. Minor

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errors in the colour reproduction may cause significant errors, or even vanishing, in the spatial structures of an image. This suggests that also the reproduction of the spatial structures should be analysed for quality. But, how should the spatial structures be described?

Perhaps the simplest way to describe the spatial structures of the original and the reproduced images would be applying the methods of feature and structure analysis discussed in the literature (see /1/ and /2/ for reviews). Undoubtedly, this approach would describe all of the structures in the images, but several problems may arise. For one, there is the need to determine the acceptance criteria and the limits of image reproduction, since in the perception, human visual system exhibits a strong disregard for irrelevant variables, and thus all of the spatial structures are not utilized in the perception. For instance, as pointed out in /3/, slow and gradual changes in the surface spectral power distribution are often factored out, as they may be attributed to the uneven illumination.

This suggests that the structures which are of greater importance to the perception should also be weighted accordingly, when the spatial structures are determined. This can be done by using some properties of the human vision, when the metrics are selected. For instance, there is evidence that the visual system determines spatial derivatives of the retinal image at least to the fourth order /4/. In fact, the first derivatives has been used in various applications /4,6/; it has been found that the physical sharpness of edges relates to the apparent sharpness of the image. In /4/, an analysis of the image structures, that utilize also higher order spatial derivatives, has been developed. The properties of the human vision could also be used, when the acceptance criteria for structure reproduction are determined. For instance, the selection of the acceptance limits might be easier by means of contrasts. Rather than absolute luminance levels, the contrasts are of importance to visual processing.

The properties of the human vision have been used even more in the analysis of the differences between two images. In those cases, the images are first transformed into a "perceptual domain", where their differences are analysed. Weighting of the image frequency spectrum by human visual modulation transfer function /7,8/ is used widely. This concept is used because there is a large fall-off in human contrast sensitivity as the spatial frequency increases. As pointed out in /9/, this dependence is caused by several reasons, including the optical point spread in the lens, as well as some neural factors.

The approach of "perceptual domains" could be extended to cover some other properties of the human vision as well. A useful approach might be to implement the concept of neural images and to apply the methods of computational vision models. The concept of neural images is based on the assumption that the light sensitive neurons in the retina are specialized for different tasks. One neural image may represent the activity of a group of specialized neurons, and the different types of neural images represent different properties of the image. One type of the neural images is assumed to represent the edge locations of the viewed image. Another type of neural image may represent the encoding of the local mean intensity, such as might be used to regulate visual adaptation to the illumination variation in the image. The other types of neural images may represent aspects of colour, motion and depth, for instance. Also, the multiresolution theory is based on a neural representation that consists of a collection of component – images, each one sensitive to a narrow band of spatial frequencies and orientations /9,10,11/. Some of the discussed aspects of early vision have already been used /12,13/ to estimate the visibility of distortions.

The concept of "perceptual domains" has several drawbacks in the analysis of spatial structures – or the quality of the image reproduction. Perhaps the most serious problems relates to the assumptions made when the images are transformed into the "perceptual domain". The values of visual parameters of a "standard" or "average" observer are used in the transformation. As pointed out in /14/, there are significant variations in the observer's contrast sensitivity functions and in other critical visual parameters, and also the weighting of the different types of distortions may vary depending on the observer. Besides, the viewing distance (the retinal size) and the viewing angle (not necessarily perpendicular) are fixed for the transformation. They are not standardized or fixed in the real perception of images, and they may be continuously adjusted by the perceiver according to the size of the field perceived or to eliminate the effects of surface gloss. This suggests that, the concept of "perceptual domains" for the quality analysis of the image reproduction is limited, at least in general use.

There is still another relevant basis for the selection of the metrics to describe the spatial structures of an image. The colours and the spatial structures of an image represent visual information frozen from a scene into the image. Correspondingly, we can determine that, the objective of image reproduction is to reproduce the visual information that is available in original image. Based on this determination, in analysing the quality of the image reproduction we should establish whether there is available similar visual information in the original and in the reproduced images.

SOURCES OF VISUAL INFORMATION IN IMAGES

This section discusses, monocular sources of visual information – i.e. sources which may be available in images. The ultimate purpose of this chapter is to select, based on the sources, a few metrics which will be used to describe the spatial structures in the images.

When looking at a scene, the intensity as well as the wavelength distribution of the light that falls in the eye from different directions vary often widely. The sharp changes, or discontinuities may be perceived as edges:

Visual edges. Four different spatial arrangements can create visual edges. The first two types of visual edges relate to the plane. An illumination edge (1) results from the different amount of illumination that falls on the different parts of a surface, while a reflectance edge (2) results from the different reflectances of two surfaces. The other two types of edges appear when the edges are not on a plane. The two surfaces may be at different distances from observer, or they may be at different angles (walls of the room). A depth illumination edge (3) results from the different amount of illumination that falls on the two surfaces, and a depth reflectance edge (4) results from the different reflectances of the surfaces /11/. In a real scene, many visual edges are combinations of the different types of edges /11/, and several types of edges may also produce luminance and chromaticity changes in the same region but at different scales /10/.

The visual information in the edges may relate to two types of discontinuities. The first is the sharpness of the edge. It may vary from the sharpest reflectance edge between two physical objects to a smooth illumination edge on the boundary of an shadowed area /11/. The second edge property that may be the cue is the type of the discontinuity. The reflectance edges often contain a discontinuity in luminance and chromaticity, while the illumination edges mainly contain a difference in luminance. The visual edges enclose regions which represent visual surfaces. The surfaces may vary in several properties:

Spatial dimensions. The visual surfaces vary with regard to spatial properties, such as the length, size, shape, position and symmetry.

Spectral reflectance of the surface. The interactions of light with the bulk matter include diffuse and specular reflections, scattering and internal reflections, emissions though fluorescence, absorption and transmission. Since the interactions are dependent on the wavelength, the spectral reflectance of a surface is an important cue to the physical and chemical properties, and the composition of the surface.

Texture of the surface. Almost every object shows a structure – or a texture – on multiple scales, and the visibility of the texture on a given scale relates to the viewing distance. For instance, a tile surface shows a strong, randomly regular structure on a micro scale, while the macro scale texture of a tile wall is deterministic and periodic. Finally, when the viewing distance is long enough, all the textures of the wall are averaged out, and the surface appears to be very uniform.

The problem of texture perception may be formulated either in statistical terms, or in terms of the detection of the underlying texture elements or textons (see /15 and 16/ for reviews on the theories of visual texture perception). Several texton properties which are of importance to perception have been discussed in the literature. Some of them, such as the size, shape, local contrast, lightness, chromaticity, flicker, motion, depth and spatial organization, are clearly defined, while other properties, like those relating to the ends of the lines or terminators /15/, are less clearly defined.

Marking of the surface. There may be two types of markings on visual surfaces. The intrinsic markings are independent of the viewing and lighting geometry, and include markings due to reflectance variations, as well as surface cracks. The nonsurface markings result from viewing and lighting, and include self-occlusion and shadows. The surface contours project from the intrinsic markings of the surface, and also they may provide information about the three-dimensional shape of the surface. As used by Knill /17/, the scale might be distinction between marking and texture. While surface markings are extended over a surface, texture markings have small textons.

Orientation and degree of the curvature. Visual surfaces may vary also in the orientation and in the degree of the curvature. These relate to the perception of depth and will be discussed below.

In addition to the visible edges and surfaces, there is a huge amount of visual information in an image that act as cues to the depth. These cues are called monocular depth cues or pictorial cues. In the literature, there are lots of discussions about the relative importance of the different depth cues (for a nice example, see /18/); clearly the importance of a given depth cue varies with the type of stimulus. The list below contains the principal depth cues and mainly follows the nomenclature used by Wickens /19/. Figure 1 gives examples of depth cues.

Texture gradient. Information in texture gradients is commonly decomposed into three quasi-independent cues: perspective scaling (or scaling), foreshortening (or compression) and density (or position). As pointed out by Sakai /20/, the studies have shown that the texture compression is the dominant cue to the surface curvature, whereas the changes in the two other components play a dominant role in determining the depth.

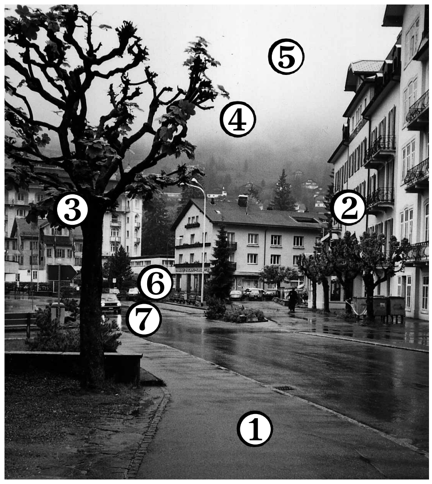
The use of a texture gradient as a cue to the curvature and the depth is based on assumptions about the statistical properties of the texture. The minimum assumption /21/ may be homogeneity – the texture is assumed to be spatially stationary in a global scale, and hence gradients in perspective scaling, foreshortening and density arises due to projection. The second assumption may be isotropy. Since it refers to the lack of directional bias in the statistics of a surface texture, the deviation from isotropy can be used – even locally – as a cue to the orientation and the curvature /22/.

Linear perspective. Two converging lines appear to be parallel and resending in depth, since the sizes are scaled as a function of the distance. This transformation is described by the laws of perspective on the principles of Euclidean geometry.

Interposition. An object that is partially obstructed by another object appears to be more distant. When the shapes of objects are known, the interposition is a very sure cue to three-dimensionality. Even though this is true, the impression of depth created by the interposition alone is not usually very strong. It has, however, been shown that the sharpness of the depth reflectance edges may be a cue to the relative depth of the objects /23/.

Light and shadow. Shadows are often studied in terms of intrinsic and extrinsic shadows. Intrinsic shadows are formed by the object itself, and they provide perceptually salient information about the shapes of the objects and about the direction of illumination on a scene. Extrinsic shadows are cast by one object on another. They are very important cues to the relative positions and orientations of the objects /24/. Shadows are therefore among of the most important cues to three dimensionality. It is important to note that, shadows may give a very high contrast.

Another cue that relates to lighting geometry is shading. However, information provided by shading is qualitatively very different from the information provided by shadows. Shading is local in nature, and it can be specified by the local surface reflectance properties and by the angles between the surface normal and the directions of the light source and the viewer /25/. The primarily role of shading in the perception of depth may be to enhance information from the other cues. Shading alone does not provide enough



1. Texture gradient
2. Linear perspective
3. Interposition
4. Aerial perspective
5. Height in plane
6. Retinal image size (the size of the car is known)
7. Light and shadow (reflections from the paved road).

Fig. 1 Examples of monocular depth cues.

information for a correct perception of depth.

Aerial perspective. More distant objects tend to be "hazier" /19/. This "haziness" results from the scattering of light in the air, and it result more in lower contrast than in blurring. In fact, it has been proposed that the contrast may be a monocular depth cue, simulating haziness of the aerial perspective /26/. Shorter wavelengths scatter more in the air, and thus haziness causes also changes in the colour.

Proximity-Luminance covariance. Closely related with textural gradients is that brighter objects are typically also closer, and that continuous reductions in the intensity of lighting are assumed to signal receding with the distance /19/. Some aspects of proximity-luminance covariance have been discussed in /27/.

Height in the plane. Since objects are normally viewed from above, objects that are higher in the visual field are assumed to be farther away /19/.

Retinal image size. When the real size of the object is known, the smaller the retinal size is, the farther away the object is assumed to be /19/.

The discussion above relates to the visible edges and surfaces, and to some spatial aspects of the image. Although the main stream of account of perceiver is concerned with them /10/, the image may also contain other important information about the visual world, for example light sources. In the scenes, the light sources are often very bright, compared with the average intensity in the field. Like shadows, also the light sources may give very high contrasts – contrasts which are not reproducible. The second light source related effect with very a high contrast are specular reflections from surfaces. In specular reflections, the colour of the reflected light matches the colour of the light source. The size and the shape of the total reflection point provide information about the surface curvature.

Transparency is a surface property not discussed above. As pointed out by Metelli /28/, to perceive transparency, the viewer needs two types of cues: cues to the transparent medium and cues to the objects or the background behind the medium. According to this definition, the air and plate glass are not perceptually transparent unless there is, for instance, fog in the air, or marks or reflections on the glass. Due to this requirement of a light mixture, perceptual transparency is most likely when the luminance contrast of the background, viewed through the transparent medium, is less than or equal to the contrast of the background viewed directly /28,29/.

When a natural scene is perceived, the observer can also use the limited depth of the field (by two different means /30/), accommodation, convergence, motion and binocular vision. However, when viewing an image, they are in conflict with the monocular depth cues. Therefore, an image can be perceived as a three dimensional space or as a flat surface. The limited range of contrasts that can be reproduced and the frame and the surround of the image are also cues to flatness /11/. Unfortunately, they are not the only cues to flatness. Distortions in the image reproduction, such as noise, may give a direct cue to flatness, but they may also cause conflict between monocular depth cues. For instance due to the distortions, the impression to depth from the linear perspective and the texture gradient may be different.

Perhaps the strongest effects are caused when the distortions interact with or mask the visual information of the original image. In the image reproduction there are sources of errors that produce very deterministic, even sinusoidal, noise patterns as well as sources that give random noise. In fact, both mask types have been used in visual masking experiments. Also, experiments have been made to find out about the masking effects between isoluminant and isochrominant gratings /31/.

As determined in this study, the goal of the image reproduction is to reproduce visual information that is available in original image. Thus, also the noise, if not removed from the original, should be reproduced. The same approach is proposed here also to other types of distortions in an original image. This approach is relevant as distortions, including noise-like effects and blurring, may also be wanted. For instance, the limited depth of focus is sometimes used by photographers to cause blurring in some parts of the image.

QUALITY OF IMAGE REPRODUCTION: SELECTION OF METRICS

There are many sources of visual information included in the intensity and the wavelength distribution of the light that falls in the eye, and in their variation with the viewing direction. In the images, the intensity and the wavelength distribution are reduced to the values of the three channels of red, green and blue. They represent colour, which is undoubtedly a very important cue source of visual information. There are widely accepted methods, for instance the CIELAB colour space with the colour difference formulae, for the quality analysis of colour reproduction.

Correspondingly, the variation of the intensity and the wavelength distribution of light with the viewing direction is reduced in the images in the spatial variation of the values of red, green and blue. It is true that, if there are no errors in the colour reproduction, there are no errors in the reproduction of spatial structures. Since the case of no errors in the colour reproduction is more or less hypothetical, minor errors are practically accepted and, as pointed out earlier, minor errors in the colour reproduction may cause significant distortions in the spatial structures. Consequently, the quality of structure reproduction has to be analysed. In this study, based on the sources of visual information, three metrics were selected and proposed for the quality analysis of structure reproduction:

Edge sharpness. The reproduction of edge sharpness is strongly related with the reproduction of many sources of visual information. Sharpness is a cue to the type of the edge (reflectance edge, illuminance edge). Edge sharpness is essential to the perception of surfaces (textures, markings); it is also important for the perception of depth (texture gradient, interposition, light and shadow).

Size of detail. The reproduction of the spatial size is also related with the reproduction of many sources of visual information. Surfaces, textons and surface markings vary in size; the size and scaling of the size are also important for the perception of depth (texture gradient, linear perspective, retinal image size).

Evenness. Evenness is also an important characteristic of many sources of visual information. It may be an important cue to surfaces (lack of textures and markings), to transparency and blurring, as well as to depth (a lower contrast due to the aerial perspective).

We also find that the proposed metrics become easily distorted by the typical errors of printing and displaying. The neighboring effects are some of the most typical errors in printing and in displaying. The output colour of an image point depends on the input value of that point as well as on the values of the neighboring points. These effects easily cause strong distortions in the reproduction of edge sharpness. The reproduction of the smallest image details in printing and in displaying is also a relevant issue. If the image resolution is higher than that can be reproduced in printing or in displays, the smallest image details will not be reproduced. The reproduction of evenness may be easily distorted by the noise of the image reproduction. Noise may mask evenness as well as smallest image details /32/. Therefore, the three proposed metrics relate to the characteristics of visual information, but they are also sensitive to the typical errors of printing and displaying.

The principle of the reproduction of colour in printing and displays implies that the reproduction of lightness and chromaticity relate to one another: When distortions occur, errors are not isoluminant or isochrominant. Consequently, it is necessary to discuss the relative importance of errors in luminance and chromaticity in the reproduction of spatial structures.

Some psychophysical measurements may guide this discussion. The contrast sensitivity threshold, both for luminance and chromaticity, of observer depends on the spatial frequency. The threshold is determined by means of sinusoidal stripe patterns. A grayscale pattern is used for luminance sensitivity measurements. For colour sensitivity measurements, isoluminant colour gratings, that varies in saturation between the complementary colours, is used. The two colour contrast sensitivity thresholds are determined for the pair of red and green, and for the pair of yellow and blue. In all cases, the contrast sensitivity threshold, which is the contrast below the pattern becomes invisible, is plotted against the spatial frequency. A very clear result of these tests has been that, human vision is much more sensitive to the contrast in luminance than to the contrast in chromaticity at high spatial frequencies /33/. The difference is significant: the apparent spatial sharpness of a colour image mostly depends on the sharpness of the luminance component.

This property of the human vision has been used in several applications. For example, a composite PAL video signal consists of a luminance signal and two colour difference signals. The bandwidth of the luminance signal is 5 MHz, but it is only 1 MHz for the two colour difference signals together. This is achieved by coding only the lowest spatial frequencies to the colour difference signals. In fact, further degradation of the edges will occur on account of the definition of the standard /34/. Although this impressive example is from moving images, where the spatiotemporal frequency response of the human visual system is of importance, the images have also parts which are not moving. This property of the human vision is also used in image compression algorithms (see /33/ for a short discussion), for instance, in the algorithm defined by the Joint Photographic Experts Group (JPEG).

The lowpass filtering of the human visual system has also been used in the analysis of the visual noise of the colour halftone screens /35/. The results show that the fluctuation of the luminance component is dominant in the perception of noise: the magnitude of the visual graininess of colour halftone screens can be predicted by using only luminance fluctuation data. These discussions suggest that, to analyse the quality of the image reproduction, attention should be paid mainly to the spatial structures that result from the luminance variations across the image.

CONCLUSIONS

It was determined in this study, that the objective of the image reproduction is to reproduce the visual information that is available in the original image. It was also pointed out that not only the colours of the individual image points but also the fluctuations of colour across the image are very important sources of visual information. Therefore, to analyse the quality of the image reproduction, it is necessary to analyse the quality of the colour reproduction as well as that of the structure reproduction.

There are commonly accepted methods for the quality analysis of the colour reproduction. To select the metrics for the quality analysis of the structure reproduction, monocular sources of visual information – i.e. sources that may be available in the images – were reviewed. Based on these sources, three metrics were proposed for the quality analysis of the structure reproduction, the sharpness of edges, the size of details and the evenness.

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