Soft proofing using Liquid Crystal Displays

Colour management for media production processes

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Abstract

Development of colour management systems, the level of standardisation, as well as the embedding of facilities for colour management into computer operating systems and software, enables successful future interoperability of colour reproduction in the graphic arts industry. Yet colour reproduction from one medium to another, still gives rise to inconsistencies.

This thesis investigates colour management and control processes in premedia and press process workflows in graphic arts production, including standards, instruments and procedures. The goal is to find methods for higher efficiency and control of colour print media production processes, aiming at increasing colour consistency and process automation and of reducing overheads. The focus is on the control of colour data by displays in prepress processes producing low quality paper products. In this respect the greatest interest of this thesis is on technical and visual characteristics of displays with respect to the reproduction of colour, especially desktop Thin Film Transistor Liquid Crystal Displays (TFTLCD) compared to portable TFTLCDs and Cathod Ray Tube (CRT) monitors.

In order to reach the desired goal, this thesis is based on a literature survey and empirical studies. The empirical studies include both qualitative and quantitative methods, organised into three parts:

- Colour process management: Analysed case studies of the implementation of colour management in entire graphic arts production workflow processes.
- Display technology: LCD and CRT displays have been examined through measurements to establish their fundamental strengths and weaknesses in reproducing colours.
- Comparison of reproduction: A perceptual experiment has been conducted to determine the ability of the disparate components included in a colour management system to co-operate and match reproduced colour, according to the perceived preference of observers.

It was found that in most cases consistent colour fidelity depends on the knowledge and experience of the actors involved in the production process, including the utilisation of routines and equipment. Lack of these factors is not necessarily fatal for the final low quality paper colour product, but obstructs the automation. In addition, increased digitalisation will increase the importance of displays in such processes. The results show that CRTs and desktop LCDs meet most of the demands of colour reproduction in various areas of low quality paper production processes, e.g. newspaper production. However, some fundamental aspects, such as low digital input values, viewing angles and colour temperature, matters that concern characterisation and calibration, still need to be developed. Concerning soft proofing, the matching correspondence between hard and soft copies gives similar results for both CRT and LCDs for high-quality paper originals, if the luminance is decreased on the LCD (to luminance levels of CRTs). Soft proofing of low quality papers gives equally lower matching agreement for both CRT and LCD, in this case when the luminance of the LCD is set higher (e.g. about twice the levels luminance levels of CRTs).

Keywords: Displays, LCD, CRT, premedia, prepress, soft proof, workflows, newspaper, colour management systems, colour control, colour reproduction
List of papers

This thesis is a monograph, the content of which is based on and extends the work presented in the following publications:


The following publication is related to but not covered in this thesis:

Preface

Soon I can (hopefully) look back at these three years of blood, sweat and tears and exclaim – “Yes!” “I did it!” – and with a huge amount of relief. I really (will avoid the word “love” here) like the way of living that research implies, since it fits my changeable level of ambition, as well as the subject of colour, where there are no limits for further expeditions. However, these years have been very turbulent, and unfortunately it has taught me things I could have lived without. On the other hand, things that I could not have lived without are people that have helped me during my work, both in laughing and serious matters. I would probably not have made it this far without support and help from my advisor Doctor Stig Nordqvist at the Swedish Newspaper Publishers’ Association (TU). As well as providing professional support, guidance and excellent contacts he is an optimistic fella and creates a great social environment and is very encouraging.

Other persons essential for bringing this thesis project to an conclusion are Professor Nils Enlund at the department for Numerical Analysis and Computer Science (NADA), Media Technology and Graphic Arts at The Royal Institute of Technology (KTH) who at the last minute stepped in as my supervisor and the Dean at NADA, Ingrid Melinder, who both helped steer me into harbour.

Since this project has been conducted at three different places; at the department of Numerical Analysis and Computer Science – Media Technology and Graphic Arts at KTH, at the former Research Institute for Media Technology and Communication (Framkom) now Swedish Pulp and Paper Institute (STFI) and the at the Media Technology group at the department of Science and Technology at Linköping University (LiU), there are quite a number of people who deserve many thanks for creating a grand working atmosphere. At first I thought of just thanking you all, but I cannot resist mentioning people that have a big finger in the project pie. So special thanks to: Christer Lie and Ester Appelgren at KTH for many interesting talks and less serious giggles and Ingrid Andersson, Lasse Forsberg and Mattias Jonsson at former Framkom, for great help in the battle with fussy and tricky equipment as well as entertaining coffee breaks.

At another research institute in the “hood” I would like to thank (soon to be!) Doctor Siv Lindberg and Doctor Christian Persson, both at STFI, for their help and support. Christian has also given very thoughtful comments on the final work with the thesis draft, as well as has Professor Caj Södergård at VTT Information Technology, that have been very helpful. Thank you!
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There is also a large number of benevolent employees at premedia, prepress, press, supplier and manufacture: companies from the media and graphic arts industry in Sweden, who have kindly have assisted me with the “latest” from the print production and the hottest gadgets. Without your help I would have had a much harder time!

My family are of course ultimately responsible for my position. My mother Ingegerd, the best hardware and software supporter I have ever met (which says a lot since I worked in the engineering field for nine years), my father Bosse who is invaluable regarding (theoretical!) academic matters and the king of graph polishing. My sister Åsa who, when not throwing heavy objects at me, is a doll! My aunt Margaretha and her husband Sören who provide an extra home and make food that is divine. And of course the cats Pelle&Putte and the dog Bimbo. Thank you all for being there and believing in me!! Even when it involves Vasaloppet or providing cat food…

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Sara Leckner, Göteborg, January 2004
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CHAPTER 1

Introduction

“Does this sample have the same colour as the one I saw yesterday – or last week, or last year?” “Does this batch of material have the same colour as a standard?” “Does this reproduced image match the original?”

Historically most of these questions only had subjective answers. Today, through the application of the principles of colour technology and the use of colour measurement, it is possible to provide objective answers. However, there are no simple answers. Since colour to a great extent is a psychophysical phenomenon, colour management requires involvement by both man and machine, factors that mutually embrace pros and cons concerning colour management control. These colour control factors are the key subject matter of this thesis, investigated and analysed throughout it.

[Comic strip image]

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1.1 Fundamentals of the colour print process

Colour management is required to provide predictable and consistent colour results throughout a print production, i.e. from image input into the digital system, explained in Section 1.1.1, through to the reproduction by an output medium, with maximum throughput and minimum interference of operating skill. The premedia process, i.e. the part that takes place prior to printing, consists of systems being able to integrate different imaging peripherals, delivered from different suppliers, and to reproduce coloured media at printing houses located over a large area. Hence, the objective of any colour management system is to provide a means of managing colour consistency and image quality throughout a system made up of disparate components [Wallner 2002].

The new developments in colour management systems have come about during the past decade through co-operations between leading companies in the desktop computer industry and in the colour reproduction industry. Device characterisation, gamut mapping, colour appearance and additional principals included in the colour management systems are well established [Wallner 2002]. What still can give rise to inconsistencies is the level of agreement and/or the lack of standardisation across the industry, as well as the embedding of the colour management facilities into the software of an operating system and the continuous development of new technology. At present, in print production processes, colour fidelity diminishes, partly due to lack of routine procedures and efficient use of high-end equipment and standard methodology. These inadequacies reduce the reliability of the colour reproduction process and result in customer complaints, non-remoteness, non-automation and inflexibility of the colour production.

1.1.1 Colour management and print production processes

Colour management is defined as the use of appropriate hardware, software and methodology to control and adjust colour in an imaging system [Giorgianni 1958], Figure 1.

A colour imaging system (e.g., scanner, displays and printers connected) that is colour managed delivers acceptable colour quality for the system’s intended application. A colour management system has to face tricky challenges on its way to an adequately performed task. One challenge is that the colours are being produced not by a colour
technologist who understands the material and process, but often by a layman. The colour management system is expected to make up for any problem caused by lack of knowledge. A second challenge is the ease of evaluating colour accuracy. If the samples can be evaluated side by side a quick indication of the colour management can be achieved. A third challenge arises if the samples (e.g. the original and the reproduction) are of different media, which is often the case in image reproduction. The fourth challenge is the expectation that colour should be consistent and accurate no matter what device is used. [Berms 2000]. Solving these challenges is a current topic of research of development and the vision of this thesis is to assist in some way. In this thesis the colour management system is incorporated into the media process of print production.

The print process consists principally of three parts: prepress, press and postpress. Each part is divided into smaller parts. For example the prepress process can be divided into image processing, editing, repro etc. Figure 2 shows the parts, Image processing and Advertisement flow (prepress) and Printing flow (press), dealt with in this thesis. Colour management in print production is thoroughly discussed in Chapter 3. Principals that affect the colour management system are the dependence on manufacturer, technology and conditions of the hardware and software, e.g. the monitors, printers, presses, ICC profiles, as well as environmental conditions and standardisation of the equipment discussed throughout the thesis.

Figure 2. Colour management in different parts of a print production process. This figure shows a general outline of the prepress and press workflows in newspaper production.
1.1.2 Proofing - remote, hard and soft

Proof and proofing are practicable tools to control colour. Here the designation for proofs is as follows:

Proofing refers to the ability to simulate as closely as possible the colour images displayed on monitors or hard copy proofing systems to the images reproduced from the same digital file by a printing system, i.e. to produce a match. Matching is further discussed in Chapter 5.

Soft proofing is referred to when a monitor is used to reproduce the proof.

Hard copy proofing is referred to when the proof is printed on a material, commonly paper, by a proofing or printing system. There are sub-classifications of hard copy proofs such as contact proofs (mainly show layout and copy correctness), digital proofs (show colour correctness printed directly from file, on ink jet, laser and similar printers), laminate proofs (show colour correctness more accurately by the use of final printing parameters, fused or laminated together) and contract proofs (looked on as print contracts between printer and client).

Remote proofing is when image data are proofed in a location different from where it is produced and/or printed. The remote distance could be in-house (e.g. different floors or rooms) as well as across continents (e.g. a file sent from Sweden to China to be printed).

The requirement for reliable digital proofs is increasing in the graphic arts industry due to a higher extent of automation and the transition to Computer to Plate (CtP), digital printing and electronic publishing. Remote proofing is, and will continue to be, an important part in the print production due to the increased ability to transfer large image data sets electronically over wide geographical distances. Instead of hard copy proofs printed and posted, the data files are transferred electronically and proofed at another place in the company, at the customer’s office or at the printing company. In a successful process, the transfer format as well as the transfer technique is stable with regard to the content of the document e.g. the colour information. The media devices of the geographically remote users have to be of guaranteed quality and standard procedures such as calibration must be adopted to ensure accurate determination and subsequent reproduction of the image at remote users’. Remote proofing implies fast and smooth communication between advertisement-, premedia-, and printing companies. However, successful and consistent communication requires development of the colour management process.
Until recently, proofs have generally been produced by the person who also makes the adaptations of the medium where the image will be reproduced. However, today, when the image originator generally might not know in which medium the image will be reproduced, remote proofing is an attractive method for digital automation. What makes this process complicated and rather complex is that along with the increasing importance of consistent colour reproduction, the colour image has to be reproduced across different media, devices and locations. This requires accurate procedures concerning standards, devices, routines and knowledge involved in the process, currently not guaranteed. Without such procedures colour fidelity is very much localised.

Hard copy colour proofing is traditionally viewed as a more accurate proofing method than soft proofing, and it is the chosen method when the printed product needs to be accurately colour proofed (e.g. when a contract proof is needed). However, hard copy proofing is expensive, as it requires advanced equipment and materials. Since the entire premedia process is on its way to full digitalisation and automation and the display and colour management system technology is constantly developing; the use of soft proofing for rapid print processes will be inevitable as a colour control application. The fidelity of proofing and proofs is further discussed in Chapter 3 in general and Chapter 5 in particular.

1.1.3 Monitors in colour management

The Cathode Ray Tube (CRT) has been used for a number of years in the graphic arts industry for visual matching, image processing and soft proofing in cases where correct colour reproduction is essential. The factors that have an impact on the colour reproduction on a CRT are well known, but the CRT technology is not optimal. Display technology is further discussed in Chapter 4.

The Liquid Crystal Display (LCD) technology has quite recently reached a level of high technical sophistication and is therefore becoming an appropriate alternative for professional colour image work in the graphic arts industry. However, colour reproduction for LCD panels is different from that of a CRT display. A list of some factors influencing colour performance of Thin Film Transistor (TFT) LCD technology, includes backlight and colour filter characteristics, quality of panel drive electronics, analogue and digital graphics adapter electronics, LCD array design, pixel/cell design and liquid crystal mode [Wright et al. 2000]. This dissimilarity in monitor technology results in different procedures and specifications for calibration and characterisation of the panels. Since the high-end LCD technology is still quite new, some of these characteristics have been investigated but some have not. While some trends are common to all LCDs, presently there are no standard characteristics, such as those exhibited by
CRTs [Wright et al. 2000]. There are significant differences between desktop LCD and portable LCD, concerning colour rendering, discussed further in Chapter 4.

1.1.4 Other principles

The colour reproduction in a colour management system is highly dependent on the algorithms used in the colour transformations. There are many differently optimised International Colour Consortium (ICC) profiles, [ICC 1:2001-12] and ICC proofing tools available on the market. Besides the algorithms to create the ICC profiles, the ICC profile specifications (tag formats, the Profile Connection Space (PCS) definition) and different Colour Management Module (CMM) implementations do not guarantee interoperability.

Standard methodology is an important part of stable and automated print production processes. Standards for the graphic arts industry are and have been proposed by, for example, the International Organisation for Standardisation (ISO), the American National Standard Institute (ANSI) and the Japanese Standard Organisation (JIS).

1.2 Scope of the thesis

This thesis is a result of a research project dealing with colour management control processes, in premedia and press process workflows, in graphic arts production.

1.2.1 Problem statements

The work started out with an effort to delineate the general status of colour processes in today’s graphic arts production, in order to identify possible inefficiencies and bottlenecks, concerning colour management and colour control. Thus, the following problem statement can be made:

(I) What techniques and equipment exist for colour management and how are they utilised? How do the processes differ for different products? How efficient, optimised and flexible is the colour process, especially when considering soft proofing, displays and their utilisation? How do the above aspects affect the final colour product, the automation throughout the workflow and the overhead costs?

Once this statement has been addressed the research criteria can be narrowed down and candidate mechanisms for further analysis and evaluation can be chosen. For example the colour process and the utilisation of soft proofing in the production workflow has been elucidated. Yet, reliable utilisation of soft proof and
image processing requires reliable displays. When these candidates have been identified the following problem statement must be considered:

(II) How well do displays reproduce colours? To what extent does the reproduction diverge from the manufacturers claims? What hardware aberrations are most troublesome for the colour reproduction? How does LCD colour reproduction distinguish between CRT displays? What characteristics have to be observed in colour processing work? That is, what can be corrected and to what extent, by software, hardware, manually or physically?

It is of course desirable to have efficient software and hardware mechanisms for colour handling and colour control. However, since it is the human perception of the perceived colour that will finally matter, the final problem statement to be considered is:

(III) To what extent do hardware and software render correct colour? That is, to what degree does cross-media matching work? How practicable is proofing? How much do different devices and techniques affect the colour correspondence? That is, what are the influences of different display techniques and software and the influences of different printing techniques and paper qualities?

These problem statements have formed the foundation of the thesis work, and, hopefully some light is shed upon these problems. In the next section there is a more detailed account of the goals and activities that guided and geared the work presented.

### 1.2.2 Goals and activities

The main goal of the work presented is to develop methods to increase automation, control and stability for dependable workflows in print production processes. In this respect, the focus has been put on colour management systems and methods applied to control the colour data throughout print production processes, essentially through soft proofing in low quality paper print productions. The principal interest is in displays, in particular desktop LCDs, in rendering and control of colours.

The research generated has mainly been divided into three activities:

**Activity I.** Analysis of colour management systems in real time print production processes.

**Activity II.** Measurements of basic colour properties of high quality display technologies.
Activity III. Experiments of colour management systems in preference to human perception.

Activity I provides an overview of the standards, instruments and procedures that comprise the colour production throughout a print production process. This means the level, consistency and control in the endeavour to attain colour fidelity, from original to print. The utilisation of soft proofing in particular. The thesis aims to point out bottlenecks and possible ways of increasing efficiency, stability and automation, generally and for different colour production processes.

Activity II looks more closely into the technical aspects and what can be expected of high quality displays used for colour quality work. The aim is to establish the status of display technology characteristics and the kind of adjustments that must be considered to achieve approved colour quality.

Activity III is focused on the ability of the various components included in a colour management system to co-operate and match the reproduced colour. The focus is on the comprehension of human perception regarding colour management.

A more detailed description of the methodologies used is presented in the next section along with a brief description of the reliability and validity of the methodology.

1.2.3 Methodology

Colour is a physical, psychophysical and a psychological phenomenon. Therefore research in colour reproduction and colour appearance can benefit from using both quantitative and qualitative methods. The methods employed in this thesis include measurements, both visual and instrumental, interviews, questionnaires and participatory observations. At first a description of methods used for each activity will be presented, followed by a more general description of the research methodology and the reliability and validity connected to the choice of methodology.

1.2.3.1 Practical methodology

1.2.3.1.1 Activity I

Activity I has been approached by case studies, mainly conducted through participatory observations including interviews, along with questionnaires concerning the prepress routines used in print production processes.
To cover conventional low quality paper print processes, three types of cases have been chosen. These includes companies in:

(1) Advertisement premedia.
(2) Production of premedia for journals.
(3) Newspaper premedia and printing.

The investigated companies use coldset web offset printing or in some cases heatset (sheetfed) to produce their final product (i.e. newsprint and uncoated/LWC paper qualities). Coldset web offset print production is chosen as the main focus of interest, in favour of production processes utilising high(er) paper qualities, due to the rapid process throughput and consent to greater colour tolerance variations. As a consequence, managers of such productions are more inclined to try new methods and equipment, since the process allows greater margins of errors. Such processes include the production of daily newspapers and advertisements printed on newsprint and uncoated paper qualities.

The companies were chosen on the basis of being large (L) and middle sized (M), Table 1, and particularly interested in development of colour management. This means that they are either interested in further development of their colour management or distinguished for their colour management methods.

24 media companies were included in the main investigation, i.e. the case studies (10) and questionnaires (14), of production processes and use of proofs, Table 1. The selected companies put different emphasis on premedia (PP) or press (P) processes, or handle both (PP+P) processes.

As to the newspaper processes (PP and P), the main production concerns newspaper production, although they also handle advertisement (ad) materials, mainly through printing (P). The six newspaper investigated have a total circulation of approximately ¼ a year of the total amount of newspaper circulation in Sweden, (approximately 4 million copies a year [TU 2002]).

Additional information of the use of hard copy proofs and the accuracy of such proofs, considered to be of high quality (e.g. laminate and ink jet qualities), was used as comparable information in the study of low quality papers. This information was obtained through interviews and measurements of sample hard proof printouts, by companies doing prepress work for products of higher paper qualities mainly (such as coated paper qualities and other materials), Table 1.
Table 1. The production processes investigated in Activity I.

| Participatory observations and interviews |  |
|-------------------------------|---|---|---|---|
| Product | Size** | Media *** | No | Period |
| Newspaper | L | PP | 3 | Nov 2001-Feb 2003 |
| Newspaper/Ads | M | PP+P | 2 | Nov 2001-Feb 2003 |
| Newspaper/Ads | M | P | 1 | Feb 2003 |
| Journal | L | PP | 2 | Aug 2002-Feb 2003 |
| Ads | L, M | PP | 2 | Dec 2002-Feb 2003 |

| Questionnaires |  |
|----------------|---|---|---|---|
| Product/Size | Media | No | Period |
| Newspaper/Ads | L, M, S | PP+P | 14 | Feb 2003 |

| Interviews |  |
|-------------|---|---|---|---|
| Product | Size | Media | No | Period |
| Ads | M, S | PP | 8 | Dec 2002 |

*Ad stands for where the final product is an ad or an amount of ads, like a leaflet.

**Size stands for L (Large sized publication company, Sweden); newspaper = >100 000 circulation/day, Journal = >100 000 circulation/year, M (Medium sized publication company, Sweden); newspaper = >50 000 circulation/day, Journal = >50 000 circulation/year, S (Small sized publication company, Sweden); newspaper = <50 000 circulation/day, Journal = <50 000 circulation/year, [TU 2002], [TS 2002]. The size definition of Ads is made on an average estimation on the investigated companies working mainly with prepress for ads and by [Grafiska 2003], hence in investigated cases: L = >100 000 produced ads/year, M = 50-200 produced ads/year, S = <200 produced ads/year.

***PP stands for print process and PP stands for prepress process.

1.2.3.1.2 Activity II
Activity II measure displays under controlled conditions. The displays are applied for high-quality colour image processing; CRT displays and desktop TFTLCDs. Not all CRTs have the technical properties necessary for professional image processing and the same is true for the LCDs. High-quality means that the display inherit characteristics of a wide colour gamut, additive colour mixing, stable white point and brightness, little colour shift, high resolution and smooth gradation and that it is preferably hardware calibrative.

Throughout this thesis the acronym “LCD” stands for a high-quality desktop TFTLCD and “CRT” stands for a high-quality CRT monitor, if not otherwise stated. Portable LCDs that are also TFT, but usually of Twisted Nematic (TN)-technology, are sometimes used in professional colour image work and are therefore interesting as a comparison to the desktop LCD and its reproduction abilities. The portable LCDs are denoted “portable” or “notebook” LCDs.

Data collected by measurements conducted on displays are made on Barco and Radius CRT monitors and Eizo and Apple LCD displays. Additional measurement data are acquired through documentation and literature.

1.2.3.1.3 Activity III
Activity III is performed through perceptual experiments conducted under controlled conditions. In the experiments the level of correspondence between hard and soft copies is evaluated. The hard and soft copy parameters examined are
coated and newsprint paper qualities printed in digital and offset presses and soft copies reproduced on CRT and LCD monitors. The strengths and weaknesses of the hardware and software used for colour management control are examined and judged by observers skilled in graphic arts.

1.2.3.2 Research methodology

Information about the condition of real time colour management processes have been obtained by qualitative methods, mainly conducted in the form of case studies. The case studies are based on semi-structured [Westlander 1999] interviews and documentation of discussions, attitudes and reflections, [Gummeson 1991], as well as participatory observations. Case study methodologies are suitable in studies of situations of change, such as in real time processes put into practise, since they allow questions such as “how” and “why” to be asked [Yin 1994] to respondents included in the process. In such situations it is difficult, if not impossible, to conduct traditional positivistic-based research. The methods are determined by what the problem looks like, the question it raises and the kind of results that are desired [Merriman 1994].

Participants interviewed, principally persons from the case studies, were mainly qualified premedia and press employees at media and newspaper companies, which have a reputation for good colour management. The interviews were guided, but the interviewees were able to speak freely to avoid the author’s opinions and preconceived ideas influencing the answers. In the participatory observations, interviews were followed up with one or more of the participants.

Questionnaires answered by media companies are used as the basis of Chapter 3: Overview of colour management of presented cases and Colour fidelity control in the premedia process. Questionnaires were sent to 98 print-related media companies (mainly newspapers) chosen because they are members of the Swedish Newspaper Publishers’ Association (TU). The number of questionnaires retrieved (14) did not allow for statistically based conclusions, but the results were sufficient to support earlier assumptions, based on numerous interviews. Thus, the answered questionnaires were regarded as suitable for qualitative judgements. Quantitative methods have been used to obtain the empirical data. Measurement sessions have been guided by references, such as Fairchild and Wyble (1998b), Gibson and Fairchild (2000a), Silverstein and Fiske (1993), Kwak and MacDonald (2000, 2001), to mention a few. The psychometric experiments are based on ISO (3664, 13655), ISO/DIS (3664:1998), ISO TC130 WD (12646) standards, and methodology formulated by Engeldrum (2000).
Additional essential sources of wisdom throughout the research are collected from literature, the Internet, seminars and conferences, especially within areas of colour science and media technologies.

1.2.3.3 Reliability and validity

The final product of the media production processes of interest, is a printed matter, mainly printed on paper. The specific interest is also narrowed down to production on lower paper qualities, such as newsprint, uncoated, Light Weight Coated (LWC) or similar paper qualities. For products printed on coated or fine paper qualities or on materials other than paper, the premedia and press process may differ from the ones discussed in this thesis, even though the general approach remains valid.

Since the selection of companies studied is limited, and concentrated to the Swedish market, the conclusions derived may not be valid for all newspaper and media companies throughout the world. However, print production companies in Sweden maintain a generally high colour standard in their final products and they are interested in developing their colour management systems and processes.

The internal and external validity and the reliability of the results, particularly the qualitative studies, are dependent on the condition and subject of change. The reliability, defined as the possibility to repeat the studies and achieve a similar result is therefore reduced over time. Reliability is generally difficult to achieve in the kind of studies presented here, as the behaviour of companies and equipment change over time with the overall change in the market and in the technological and societal development [Fredberg 2003]. Thus, the reliability of this study could be regarded as a general study in this area. The reliability would be further increased by the fact that the multiple companies and displays studied show relatively few differences.

Internal validity is defined as the correspondence between the research results and reality. In the studies presented it should be increased by (1) the variety of methods used and (2) the number of case studies to which the theories presented seems to apply. The external validity refers to the degree to which the results can be generalised. In the design of the studies, more than one type of media companies, one-size companies or one evaluation method and parameter were included to sustain the validity. [Fredberg 2003].

In the next section the main contributions are briefly presented.
1.2.4 Main contributions

A key driver has been that the results should provide an increased understanding of colour management and colour control in print production workflows in general and to make colour obstacles involving soft proofing and use of display in such processes more accessible. The strategy model employed is not intended to be a static replication or snapshot of the market development, but is intended to be used in times of change.

Figure 3 illustrates the course of events where contributions put forward in this work are addressed.

![Diagram of Colour Processing and Management](image)

**Figure 3.** The development of the work.

**Evaluation and presentation of the colour process.** Status overviews of the control of colour management for different processes are presented. These processes are based on different products but, principally, the colour management can be generalised to fit all processes. The neglect of factors affecting the colour performance in such processes are rather modest and have no severe influence on the colour output, but have an impact on the maximum throughput and minimum operator interference.

**Bottleneck detection and efficiency strategy.** The use of standards, colour management and equipment is analysed and discussed with regard to the colour quality, throughout the production workflows. Many bottlenecks occur through lack
of knowledge, equipment and routine procedures. This is rather obvious and fairly easily rectified, increasing automation and the colour consistency.

**Use of proofing.** Soft copies are not as yet much used as colour proofs in the workflows discussed. Workflows with greater tolerance levels for colour variations, such as repeatable printing productions, like newspaper and journal productions, would benefit from higher integration of soft proofing methods, especially if the soft proofing is integrated along the whole production process, i.e. prepress and press. Flat panel displays work well in such workflows.

**Evaluation of technical display characteristics.** Fundamental display characteristics influencing the colour reproduction are detected and discussed, for high-quality displays in general and LCDs in particular. In many ways LCDs are superior to CRT in high quality colour rendering. Yet, CRT monitors retain a dominant position for colour-critical work in graphic arts production due to LCD characteristics influencing the propriety of the calibration and characterisation.

**Evaluation of perceptual display characteristics.** The level of cooperation and the matching ability between hardware and software in cross-media comparisons are presented and the reliability of soft proofing determined. CRT and LCD work approximately equally well as soft proofing media for various paper qualities, depending on the luminance level adjustments of the LCD.

### 1.2.5 Thesis structure

The reminder of this thesis is structured as follows:

- **Chapter 2** covers the work related to the content and provides an overview of colour theory used as a foundation of the work presented.

- **Chapter 3** presents the target production workflow processes that form the basis of the process models and associated assumptions used. This chapter also further describes the colour management in prepress and print production and points out probable instabilities and bottlenecks in such processes related to colour management.

- **Chapter 4** presents an examination of LCD and CRT display technology based on measurements. This chapter contains an overview of fundamental aspects of the characteristics of colour displays, fundamentally and perceptually, individually, and compared to each other. The focus is on technical aspects influencing the colour performance, particularly LCD desktop displays.
1.2 · SCOPE OF THE THESIS

Chapter 5 describes a perceptual experiment conducted to determine the ability of the disparate components embedded in colour management systems to co-operate and match reproduced colour. In this chapter the focus is on the human perception of the performance of a colour management system.

Chapter 6 summarises the work presented and lists the conclusions to be drawn from the results obtained.

After Chapter 6 the Bibliography can be found along with an Appendix, which contains basic display technology and measurement set-up.
CHAPTER 2

Frame of reference

This chapter contains an overview of previous work in the area related to print process management and display systems. More specifically it tries to show how the present work fits in. Moreover, this chapter includes a basic theoretical background of the colour science used.
2.1 Related research

The effects of mixed adaptation, colour appearance models and colorimetric thresholds in cross-media colour reproduction, have been studied by several researchers, exemplified by Katho (1994), Song and Luo (2001), Sueprasans and Luo (2001) and Henely and Fairchild (2000). Most work related to these topics has been concerned with colour appearance aimed at a cross-media colour reproduction performed by a layman, i.e. a person not skilled in professional image reproduction, and who is not included in a process where correct colour reproduction is essential. An example could be a person working in an office or being at home, evaluating colour reproduced on the Internet or as printed images in non-standardised ambient light and/or on a non-calibrated display. Hence, it is commonly stated that if using a colour management system under strictly controlled viewing conditions, a soft copy device will successfully match the colour appearance of a hard copy original. The thesis deals with a refinement of that assertion, claiming that in order to achieve successful matching across media, there are a variety of factors, more than standard light and colour management systems, that have to be considered.

Research concerning LCD technology has been carried out during a few years. Important work includes fundamental colorimetric LCD-issues by Silverstein and Fiske (1993) and Marcu et al. (2002). Characterisation and calibration issues have been presented in Fairchild and Wylie (1998b) and Kwak and MacDonald (2000). Work concerning colour management has been presented by Yoshida and Yamamoto (2002a, 2002b) and special topics like contrast ratio by Kubota (1995) and viewing angle by Wright et al. (2000), among others. In contrast to the present work the focus has been on colour management related to LCDs in general, without distinction between portable or desktop LCDs or if the user is skilled or not in professional image processing, aspects that require different handling.

The academic field of media management and colour processes in media and graphic arts production is quite new. Literature related to (mainly newspaper) media management includes productions such as Alström et al. (2001), Rosenqvist (2000) and Sabelström-Möller (2001) who discuss convergence aspects in media technology; Fredberg (2003) is concerned by the economical strategies and Rehn (2001) and Nordqvist (1996) address aspects of the (newspaper) print production process, but focus on other parts than the colour control; Tran (2003) discusses colour based image retrieval for newspaper layout. All these works touch developments of (print) media management and processing which are related to this thesis, but they do not explicitly handle the focal point of the thesis: colour management by soft proofing.
2.2 Theoretical background

The concept Colour can have many meanings. Colour is what we see – the result of optical interaction of lights and colorants (dye, pigments, phosphors, etc used in the process of colouring materials) as detected by the human eye - the response process - and interpreted by the brain - the perceptual process, which includes psychology, since colour only exists in the mind of the viewer [Berns 2000]. The response of colours includes (usually) three factors: the light source, the object (which can be left out if the light source is emitting light) and the sensor. Hence, without any light there will not be any colours for us to see, since we do not actually see the coloured objects, but the light reflected from, transmitted through and/or emitted by the objects, Figure 4.

![Figure 4. Lights reflected from, transmitted through and/or emitted by the object.](image)

Thus, the colour sensation is essentially dependent on the characteristics of the illuminated light. An illuminant is light, defined by a relative spectral power distribution that may or may not be physically realisable as a source. The spectral power distribution curve is light from any source described in terms of relative power (amount of light), plotted as a function of the wavelength. If an illuminant is made available in physical form, it becomes a standard source. A source is a physically realisable light, whose spectral power distribution can be experimentally determined. When the determination is made and specified, the source becomes a standard source [Berns 2000].

Blackbodies are an important group of light sources, hollow heated chambers, which emit light according to Planck's law (distribution of radiative intensity with wavelength). They are important because their spectral power distribution, and therefore their colour, depends only on their temperature, called their colour temperature usually expressed in Kelvin (K) [Berns 2000], and not on their spectral composition. Many non-blackbody light sources can be described by the colour temperature of the blackbody that they resemble, called the correlated colour temperature (CCT). A number of spectral power distributions have been defined in this way by the Commission International de l’Éclairage (CIE) called standard illuminants. The standard illuminants D and C are commonly used in the
graphic arts, which enables daylight spectral power distributions to be calculated for a wide range of correlated colour temperatures. Figure 5 shows the difference in colour appearance depending on display CCT.

Figure 5a, b and c. Differences in colour appearance for display temperatures of D50 (5000K (a)), D65 (6500K (b)) and 9300K (c) are simulated.

Depending on the light source the spectral power distribution of the stimuli will vary for the same object, Figure 6. The spectral power distribution of a stimulus, is the product of the spectral power distribution of a light source and an object, and is calculated by multiplying the power of the light source and the reflectance of the object at each wavelength. Standard illuminants are used when it is common that pairs of colours with different spectral reflectance curves can match under one set of viewing and illumination conditions, but fail to match under another. This phenomenon is called illuminant metamerism [Berns 2000].

Figure 6. Spectral power distribution for a violet flower, illuminated with two different light sources: a fluorescent cool white and a standard illuminant C source. Modified from [Tran 2002].

However, even if a standardised illuminant is used, a match for one person might not remain a match when viewed by another person [Berns 2000], due to the individual properties of the human physiology and referred to as psychophysical metamerism.

To make all specifications consistent, the average observer was standardised into the colour matching functions $X(\lambda)$, $Y(\lambda)$ and $Z(\lambda)$. The standardisation was
based on colour matching characteristics, representative of the human population with normal colour vision, called the standard observer (CIE 1931 and redefined in 1964). Further discussed in Section XYZ.

The graphic arts industry has standardised a set of viewing and illuminating conditions for visual observation [ISO 3664], [ISO/DIS 3664] which specify CIE illuminant D50 at two luminance levels, 2000 ± 250 lux for critical applications (light tables) and 500 ± 125 lux for practical applications (light boxes). Reflection prints are viewed at 45° to eliminate specular reflection. For spectral and colorimetric measurements and calculations, bi-directional geometries are specified along with the use of CIE illuminant D50 and the 1931 standard observer [ISO 13655]. Unfortunately, because viewing booths do not closely simulate D50, the correlation between colorimetric calculations and visual observations can be poor. [Berns 2000].

Colour perception is very complex with many physiological and psychological factors affecting judgements despite standard methodology. Here follows a few examples:

**Figure 7.** Chromatic adaptation: Changes in the visual system that approximately compensate for changes in the spectral characteristics of the illumination.

**Figure 8.** Light adaptation: Changes in the visual system that approximately compensate for changes in the level of illumination.

**Figure 9a and b.** Colour constancy: General tendency of the observed colour of an object to remain constant when the level and colour of the illumination is changed. By applying a mask with black paper above the lemon and garlic in Figure 9a shows that viewing an object without seeing the light source results in a different colour perception than viewing an object while seeing the source as shown in Figure 9b. [Berns 2000].
This means that the colour perception is dependent on the image content and surrounding colours.

2.2.1 Colour spaces

In order to talk about colour – as with any other form of communication – it is necessary to adapt a language that all parties are able to comprehend; a system for logically ordering and specifying colour stimuli according to different attributes. We define a colour model as a mathematical relationship between the input into a coloration system and the output expressed as colorimetric coordinates.

2.2.1.1 RGB and CMYK

For the graphic arts industry two main colour mixing systems are used: RGB (Red-Green-Blue) which is additive, resulting in white colour when all primaries are mixed together, and CMYK (Cyan-Magenta-Yellow-Key (Black)) which is subtractive, resulting in black when primaries are mixed together. The RGB colour system is commonly used in displays, cameras and scanners (input devices) and CMYK is used for printing (hard copy output devices). Both systems are device-dependent. This implies that the reproduced RGB or CMYK colours depend on the specific conditions of the device or materials used: fundamental structure, adjustments, age, pigments etc. In order to make device-independent colour encoding, CIE recommends the use of $X$, $Y$, $Z$, since the tristimulus values provide the most “fundamental” colorimetric definition. (The following systems are described on the basis of transformations from RGB.)

2.2.1.2 XYZ

The colour matching functions described in the earlier section can be used to calculate the tristimulus values, Figure 10.

![Diagram of light sources, object, and standard observer with tristimulus values formula](image)

**Figure 10.** The product of the light source, the object and the standard observer gives the recording of colour in $XYZ$. 
The tristimulus values describe the colour by the numeric triple X, Y and Z defined as:

\[
\begin{align*}
X &= k \int S(\lambda) R(\lambda) \bar{x}(\lambda) \, d\lambda \\
Y &= k \int S(\lambda) R(\lambda) \bar{y}(\lambda) \, d\lambda \\
Z &= k \int S(\lambda) R(\lambda) \bar{z}(\lambda) \, d\lambda
\end{align*}
\]

\[k = 100 \int S(\lambda) \bar{y}(\lambda) \, d\lambda\]  

(1)

Where X, Y and Z are the CIE tristimulus values, S(\lambda) is the spectral power distribution of the light source, R(\lambda) is the spectral reflectance of a reflective object (or T, spectral transmittance of a transmissive object), \(\bar{x}(\lambda)\), \(\bar{y}(\lambda)\) and \(\bar{z}(\lambda)\) are the colour matching functions of the CIE standard colorimetric observer, and k is the normalisation factor. By convention k is usually determined so that Y = 100 when the object is a perfect white. A perfect white is an ideal, non-fluorescent, isotropic diffuser with reflectance (or transmittance) equal to unity throughout the spectrum [Tran 2003].

In order to calculate RGB to XYZ, the spectral properties must be known. The spectral properties at any level of emission can be calculated knowing the scalar and the maximum spectral radiance. At typical viewing distance, the spectral radiance of any given pixel is a linear combination of three independent channels, assuming that the detector area integrates the three emissions within a pixel [Kang 1997].

\[L_{\text{pixel}} = R L_{r,\text{max}} + G L_{g,\text{max}} + B L_{b,\text{max}}\]  

(2)

This can be written as an additive combination of tristimulus values, transforming RGB to XYZ tristimulus values:

\[
\begin{bmatrix}
X_{\text{Trist}} \\
Y_{\text{Trist}} \\
Z_{\text{Trist}}
\end{bmatrix} =
\begin{bmatrix}
X_{r,\text{max}}, X_{g,\text{max}}, X_{b,\text{max}} \\
Y_{r,\text{max}}, Y_{g,\text{max}}, Y_{b,\text{max}} \\
Z_{r,\text{max}}, Z_{g,\text{max}}, Z_{b,\text{max}}
\end{bmatrix}
\begin{bmatrix}
R \\
G \\
B
\end{bmatrix}
\]

(3)

To find the primaries (RGB peaks) relative to the tristimulus values of the spectrum, the inverse transformation matrix is required:

\[
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix} =
\begin{bmatrix}
R \\
G \\
B
\end{bmatrix} = A^{-1}
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix}
\]

(4)
2.2.1.3  **xyz**

By performing two sequential projections [Fairman 1997], i.e. transforming the magnitudes of the tristimulus values into ratios of the tristimulus values, a two-dimensional map of colour is obtained, called *chromaticity diagram*. The *chromaticity coordinates* $x$, $y$, $z$ are related to the tristimulus values by taking the ratios of the tristimulus values to their sum, $X+Y+Z$. Two of the coordinates are needed since the sum of the chromaticity coordinates is 1. In addition one of the tristimulus values, usually $Y$ must be specified.

The CIE tristimulus and chromaticity system may be linearly uniform, but they are hardly perceptually uniform, meaning that a distance between two points at one area of the spectrum does not necessary equal the same perceptual colour distance in another part of the spectrum.

![2.2.1.4 LAB](image)

**Figure 11.** CIELAB colour system.

To get a more perceptually uniform colour space the CIE recommended 1976 CIELAB “whenever a three-dimensional spacing perceptually more nearly uniform than that provided by the XYZ system is desired”. CIELAB consists of three components: $L^*$, $a^*$ and $b^*$, describing the difference in lightness, $\Delta L^*$, redness-greenness, $\Delta a^*$, and yellowness-blueness, $\Delta b^*$, [Berns 2000], presented on each axis. A line of average constant hue angle between the standard and the batch provides a pivot point for rotating difference coordinates from $\Delta a^*$ and $\Delta b^*$ to $\Delta C_{ab}$ and $\Delta H_{ab}$. Differences along the hue-angle line are differences in chroma ($\Delta C_{ab}$) and differences perpendicular to the hue-angle line are differences in hue ($\Delta H_{ab}$), [Berns 2000], Figure 11.

CIELAB values are calculated from CIE XYZ by:

\[
L^* = 116 \left( \frac{Y}{Y_n} \right)^{1/3} - 16 \\
L^* = 903.3 \left( \frac{Y}{Y_n} \right) \\
\text{if } Y/Y_n < 0.008856 \\
\text{if } Y/Y_n \leq 0.008856 \\
\]

\[
a^* = 500 \left( f \left( \frac{X}{X_n} - f \left( \frac{Y}{Y_n} \right) \right) \\
b^* = 200 \left( f \left( \frac{Y}{Y_n} - f \left( \frac{Z}{Z_n} \right) \right) \\
\]

(5)
where
\[
\begin{align*}
    f(x) &= x^{1/3} & \text{if } x > 0.008856 \\
    f(x) &= 7.877 \times (X/X_n, Y/Y_n, Z/Z_n) + 16/116 & \text{if } x \leq 0.008856
\end{align*}
\]

The tristimulus values $X_n$, $Y_n$ and $Z_n$ define the colour of the nominally white object-colour stimulus.

To estimate the size of colour distance the *Euclidian distance* ($\Delta E$) equation is used. The CIE94 ($\Delta E^\ast$94) is an extension of the CIE 1976 ($\Delta E^\ast$76) colour-difference model with correction for chroma-dependent variation in colour-difference perception.

**CIE 1976 colour-difference:**

\[
\Delta E^\ast_{ab} = [(\Delta L^\ast)^2 + (\Delta a^\ast)^2 + (\Delta b^\ast)^2]^{1/2}
\]  

(6)

Where $\Delta L^\ast = L^\ast_{\text{hatch}} - L^\ast_{\text{standard}}$ and analogously for $\Delta a^\ast$, $\Delta b^\ast$, and below for $\Delta C^*_{ab}$ and $\Delta H^*_{ab}$.

**CIE94 colour-difference:**

\[
\begin{align*}
    \Delta E^\ast_{ab} &= [(\Delta L^\ast)^2/(k_L S_L)] + (\Delta a^\ast)^2/(k_a S_a) + (\Delta b^\ast)^2/(k_b S_b)]^{1/2} \\
    C^*_{ab} &= [a^*^2 + b^*^2]^{1/2} \\
    H^*_{ab} &= \tan^{-1}(b^* / a^*)
\end{align*}
\]  

(7)

Where $S_L$, $S_a$ and $S_b$ are weighting functions, $k_L$, $k_a$ and $k_b$ parametric factors, $\Delta C$ the chroma difference and $\Delta H$ the hue difference.

\[
\begin{align*}
    SL &= 1 & \text{kL} &= 1 \\
    SC &= 1 + 0.045 \times C^*_{ab} & \text{kC} &= 1 \\
    SH &= 1 + 0.015 \times C^*_{ab} & \text{kH} &= 1
\end{align*}
\]  

(8)

### 2.2.1.5 LUV

The CIELUV colour system was introduced by the CIE at 1976 and has similar qualities to CIELAB and can, as well as CIELAB, be applied to all types of coloured stimuli [Berns 2000] where it is a need for a perceptually uniform scale. CIELAB is predominately used with surface colours, whilst CIELUV is normally applied to industries such as television [Rhodes 2002].

**CIELUV values are calculated from CIE XYZ by:**

\[
\begin{align*}
    L^* &= 116 \times (Y/Y_n)^{1/3} - 16 & \text{if } Y/Y_n > 0.008856 \\
    L^* &= 903.3 \times (Y/Y_n) & \text{if } Y/Y_n \leq 0.008856
\end{align*}
\]
\[ u^* = 13L^*(u' - u'') \]
\[ v^* = 13L^*(v' - v'') \]
\[ u' = 4X / (X + 15Y + 3Z) \]
\[ v' = 9Y / (X + 15Y + 3Z) \]
\[ u'' = 4X_n / (X_n + 15Y_n + 3Z_n) \]
\[ v'' = 9Y_n / (X_n + 15Y_n + 3Z_n) \]

where the tristimulus values \( X_n, Y_n \) and \( Z_n \) are those of the white object colour stimulus.
CHAPTER 3

Colour control by proofing
- in the production processes of low quality paper products

This chapter investigates the utilisation of standards in the colour management systems of current practice, in premedia and printing processes, aspiring for colour fidelity from original to print, with focus on the production low paper quality products. Of special interest is the use of colour control methods, such as hard and soft copy proofing. The content is mainly based on case studies of present real-time colour reproduction processes at premedia and printing companies in Sweden.

Analyses show that the compliance with standard adjustments varies in premedia and press processes. Through soft proofing increased colour stability and automation would be achieved.
3.1 Tolerance levels for standards in premedia colour processes

Essential for the colour fidelity in the reproduction process is the calibration and characterisation of the hardware and software in the system, the quality of the devices, and their optimal utilisation. A large share of colour complaints is related to issues that could be solved by equipment calibration [McCarthy 2002]. Although calibration of each device is a local proprietary function, any device in a workflow that is not controlled can have an adverse impact on the colour results of the other devices in the workflow. Calibration accuracy and stability in each device involves control capability, such that the device can be maintained within its optimal operating range. Devices must reproduce the same colour in different places on an output device, across multiple output devices and from one day to the next. Stable hardware devices, easy-to-use built-in colour controls, and recalibration procedures can result in controllable devices. However, imaging systems are built with tolerances, based on specifications, and these tolerances differ across media markets, and between imaging component vendors. When colour is not fully specified in a document file, imaging components receiving the document must make certain assumptions. For these reasons, improved colour fidelity in an open system requires improved consistency between colour measurement tools. Still, the same image file sent to several consistent reproduction media may yield different results, leading to inconsistencies in the impact of the presentation. At present, colour fidelity diminishes in graphic arts workflows, among other things, because of lack of knowledge, routines and efficient use of high-quality equipment and standard tools. These inadequacies reduce the reliability of the colour reproduction flow and result in customer complaints, non-remoteness, non-automation and inflexibility of the colour media production.

The following chapters will discuss how conventional coldset and heatset print production processes handle colour, according to the operators and according to the author. Drawbacks as well as improvements of control parameters will be discussed with focus on newspapers print production processes.

3.1.1 Premedia and press process workflows

Three general case studies are presented to cover the subject: manufacturers working with advertisement premedia, production of premedia for weekly journals, and newspaper premedia and print production processes. The first two cases presented are specific companies, not generalised because each of them represents an interesting aspects of colour management and function as
3.1 TOLERANCES LEVELS FOR STANDARDS IN PREMEDIA

comparison to newspaper premedia, with different products but with similar process repeatability and print qualities. Each specific workflow however, is supported by a general knowledge of premedia workflows and is intended to be used in general. Specific media parameters and the design of each workflow is presented in Figure 12, 13 and 14. The third case presented is based on numerous companies and is generalised.

Besides internal control of the tolerances of colour reproduction, mentioned in the below section How colour is checked and controlled, the external input of colour material (mainly advertisements) is often provided by persons who are not skilled in media production or in printing methods and paper qualities. This makes the colour reproduction of the final product a crucial task. Generally, the final product is of good quality, considering the problems connected with uncoated and newpress paper qualities.

3.1.1.1 Case 1: Advertisement premedia

In this case the greater part of the colour management is premedia of advertisements, predestined be printed on uncoated, mainly coloured, paper.

Almost all colour advertisement production is made for one large customer, who in turn has advertising customers. This premedia workflow, Figure 12 works for these customers’ customers, mostly by composition of previously designed advertisement (ads). Each customer usually provides logotypes and/or various image media for the ads, though complete ready-for-the-press materials are seldom supplied. Before making the ads, the company usually receives a script, of a varying quality, from the main customer, which demonstrates the expected ad-layout (i.e. a pre-layout). There is no feedback to the actual customers, but only to the main customer.

Colour management started in 1995-96 with modest progress in later years, although colour management has become more stable since the company started using hardcopy proofing, according to themselves. The hard proof is not used during printing, but by prepress operators as colour proof and by customers as a receipt of print colour agreement. Besides proofing, the way to control the colour consistency of the colour management system, consists of permitting a restricted number of formats in the database system and repeatedly employing the same printing house. The colour fidelity all the way to the final product is considered to be very satisfactory, according to the advertising premedia company, despite the fact that the product is printed in a great number of editions and on low quality paper,
Figure 12. Description of premedia for an advertisement process workflow, with comments related to Case 1.

3.1.1.2 Case 2: Weekly journal premedia

The colour management process of this company, Figure 13, is interesting, since premedia workflows rarely use only soft proofing as a proofing method. The company produces the prepress work for nine weekly journals and papers. The journals in this case are to be printed in heatset on mostly LWC paper. As a comparison this is interesting, since this product (journals) demands higher print quality and the tolerance levels of colour variations are lower, emphasising better colour and quality correspondence between original and print.

The prepress operators of Case 2 deem accurate image processing to be more important than the performance of proofing in the strive for good colour reproduction. Besides correct image processing, this colour management workflow demands very precise colour transforming ICC profiles from their printing house(s), in order to offer colour fidelity to their customers.
The premedia production of this company is mostly performed in-house; the main customers are the editorial staff of the journals, located in the same building, excluding the separate advertisement department. The files ready for press are sent to the printing house electronically as Portable Document Format (PDF) or Tag Image File Format (TIFF) files. This company is very satisfied with the colour fidelity of the printed journals. However, for the edition printed on newsprint maintaining consistent colour is a more difficult task, caused by the paper quality and print method, since an accurately displayed soft proof is more difficult to achieve.

![Diagram](image)

**Figure 13.** Description of a premedia process workflow for production of weekly journals, related to the company of Case 2.

### 3.1.1.3 Case 3: Newspaper premedia

Newspaper production processes usually consist of either premedia and editorial processes or premedia and print processes, Figure 2 and Figure 14. Besides the production of newspaper, the first type of process usually produces supplement papers printed by different printing methods, usually on a weekly basis. The second type of process commonly focuses on print and produces (prints) besides a newspaper, a number of other printed matters, such as other newspapers, journals, folders and advertisements.
In a newspaper production process, the most important colour reproduction matter is the advertisements, since they are a main component of the newspapers’ income and misprints can be costly. In Sweden most newspaper companies use the TU standard, [TU 2003a], for handling of ad materials. Usually the advertiser sends a digital file with the ad ready for press. Unfortunately, many advertisers are not skilled in the graphic arts, which may result in a time consuming restructuring of the ad materials. In order to avoid this, some newspaper companies offer technical support to their customers, as well as the possibility to look at a low resolution composite file over the Internet, soft proofing, but without colour management. Most press processes use CtP and the final print is typically controlled by grey balance bars and hard copy proofs.

Many newspaper companies are committed to present and future developments of their graphic arts production. At present, the “human factor” is the greatest source of mistakes in colour prin: quality in these processes, according to the operators.

Figure 14. Description of a premedia process workflow of newspaper production, Case 3.
3.1.1.4 Overview of colour management of presented cases

This section presents general opinions concerning the colour management efficiency and fidelity in prepress and/or press processes based on statements by prepress operators and managers from the companies investigated in the case studies, and by answers received from sent-out questionnaires. (For details see Chapter 1: Methodology). The following headings present the matter to be discussed:

- Customer complaints of printed matters in the media processes
  All investigated companies claim to have very few complaints from customers (in relation to their circulation Table 1.) according to the answers received from the questionnaire, presented in Figure 15. The complaints are generally not related to colour issues according to the printers of the companies, but to misregister, smear, tinting and false spreads. A few complaints are related to the advertiser's unawareness of the actual quality of a coldset print.

- Bottlenecks in the media processes
  The greatest bottleneck is in the quality of the materials received from the advertisers. The materials are often incorrect and may contain erroneous formats, images of too low resolution, missing parts (images, fonts), insufficient image quality or non-separated images, and so on. Often the premedia division or company offers a service of correcting or making ads on behalf of the customer and/or supports the customer in other ways, e.g. by purchase and support of displays and software.

  ![Figure 15. The frequency (in relation to circulations) of complaints related to colour, according to the prepress operators at investigated companies.](image)

- Process strength
  Flexibility is considered an important strength in the colour management process. In the press process this consists of an ability to print new editions with short
notice and still get the edition distributed in time. In the prepress process the ability to get material of low quality passed for press, as well customer support of colour management and the constant development of colour management systems, is considered an important strength in order to reach quality requirements, according to process operators.

![Figure 16. The satisfaction with existing reproduction workflow according to (the 20 investigated) newspaper companies.](image)

- **Ongoing/Future developments in process workflows**
  Numerous premedia and press managers are satisfied with their reproduction processes, according to Figure 16. However, automation and increased efficiency of process configurations and control routines, as well as increased knowledge of colour management, need to be developed. Moreover, additional integration of advertising customers into to the premedia process is desirable, for example by developing existing web-based advertising systems, principally resulting in increased automation.

  Halftoning made by hybrid screening is not yet used much for newsprint, but is of increasing interest for the printing houses. Currently it is (too) expensive and includes difficulties like reinforced sharpness.

  Furthermore, convergence of the traditional print process and other media is of increasing interest for newspaper companies and related companies [Smith 2002]. This increases the requirements of adequate colour management for a great amount of cooperating factors in the media production.

### 3.1.2 How colour is checked and controlled

The traditional graphic arts workflow consists of three major production areas: prepress, press and postpress processing. Major premedia functions include design, image, editing, and proofing. From this point of view, prepress could be
defined as premedia. Because, to a large extent, the creation, design and layout processes in media production are, initially, independent of the medium reproducing the final product. For printed media production, premedia means some additional prepress preparations, depending on the equipment used for production, the required quality, etc [Kipphan 1997].

At present, the colour production of the newspaper and journal industry is driven primarily by requirements of high-quality advertisements.

Efficient attainment of desired colour in prepress depends on accurate capture, followed by visual adjustments that are sometimes guided by a proof simulating the final output. Print operators mainly control the colour by grey balance bars, visually judged and/or by measured density, in many cases together with a hard copy proof. In many markets, such as publication of advertisements, the requirement of reproducing an ad identically across a multitude of output devices means there is a need for well functioning and well-managed standard colour methods (for details regarding standards methods see Chapter 2: Theoretical background). In many colour workflows, the general opinion concerning the colour system is that prepress responsibility is fulfilled if the proof accurately simulates the intended characterisation. The responsibility of print manufacturing is fulfilled when the final printed product matches a valid proof [Kohler and Rodriguez 1999].

**Figure 17.** Display types used in workflows.

**Figure 18.** Time of use of displays in colour workflows and age of these displays.
3.1.2.1 Colour fidelity control in the premedia process

This section presents the impact of calibration tools and routines used in (print related) colour workflows, based on answers from prepress operators and managers at 14 newspaper companies in Sweden, for details see Chapter 1: Methodology. Hence, the Figures 17-26 summarises these answers (where the 14 companies are designated as users). The questions asked were based on standard issues related to the workflows. The answers can be summarised as follows:

LCD displays are as yet less used than CRT displays, Figure 17, and almost never when colour control is used for image processing. The only premedia employing LCD displays for colour related work are newspapers.

Many workflows have new (one to two years old) display devices, but the frequency of exchanging the displays varies, as seen in Figure 18. Replacements are made when a display seems unstable rather than after a certain period of time.

![Figure 19. Display set-up used in workflows.](image)

Less than 40% of the workflows use the graphic arts standards as set-up for their displays Figure 19, the rest chose another set-up, because it fits them better. The prepress operators do not consider calibration of their display important or they lack the knowledge of carrying out calibration. Surprisingly enough, they all calibrate their displays, or state they do, Figure 20. Display calibration is considered to be very important or quite important, Figure 21.

![Figure 20. Frequency of display calibration for displays used in workflows](image)
3.1 - TOLERANCES LEVELS FOR STANDARDS IN PREMEDIA

Many newspaper companies commonly use proofs, Figure 22, as a control method in the printing production workflow. In soft proofing usually no colour management is (yet) involved. Proofs are considered quite important for control in colour production and the resemblance between the proofs and the proofs’ match with the final print, is considered to be slightly divergent, Figure 21.

![Graph showing the level of importance of proof for production, resemblance proof vs print, importance of illumination, and importance of display calibration](image)

**Figure 21.** The importance of using proofs, standard illumination, display calibration and matching ability of proofs, according to operators of production workflows. (The level 5 is considered as very important/corresponding and level 1 not important/corresponding at all).

As for standard illumination, about half of the companies claim that they use standard illuminants, Figure 23.

![Pie chart showing proof types used in workflows](image)

**Figure 22.** Proof types used in workflows.

**Figure 23.** Whether standard illumination(s) is used in workflows.
Most of the companies use neon tubes with no interference of daylight, Figure 24, although about 40% do not know the temperature of the illumination, Figure 25.

![Figure 24. Types of illumination(s) used in workflows.](image)

Whether the standard illuminants produce the right spectral and intensity values is not often controlled, Figure 26.

![Figure 25. Illumination set-up used in workflows.](image)

Surrounding characteristics and configurations of devices, Table 2, play an essential part in the appearance of colour. Two of the same colour patches presented on an identical medium and with identical viewing geometry usually do not match visually if the surroundings are different, even though they are measured to have identical XYZ values [MacDonald 1996].

![Figure 26. How often the illuminants are controlled in keeping standard values.](image)
### Table 2. Characteristics of different media [MacDonald 1996].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Real scene</th>
<th>CRT display</th>
<th>LCD display</th>
<th>Print in office</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of medium</td>
<td>Mixed</td>
<td>Self-luminous</td>
<td>Lamp</td>
<td>Reflective</td>
</tr>
<tr>
<td>Dimensions</td>
<td>Dynamic 3-D</td>
<td>Dynamic 2-D</td>
<td>Dynamic 2-D</td>
<td>Static 2-D</td>
</tr>
<tr>
<td>Illuminant type</td>
<td>Sun+light</td>
<td>Self+ambient</td>
<td>Self+(ambient)</td>
<td>Lamps-Daylight</td>
</tr>
<tr>
<td>Luminance (cd/m²)</td>
<td>1000-5000</td>
<td>50-120</td>
<td>200-500</td>
<td>150-500</td>
</tr>
<tr>
<td>White point (K)</td>
<td>2000-10000</td>
<td>5000-9300</td>
<td>5000-9300</td>
<td>2700-4500</td>
</tr>
<tr>
<td>Surround</td>
<td>Light</td>
<td>Dark-light</td>
<td>Dark-Light</td>
<td>Light</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>1000:1</td>
<td>100:1</td>
<td>400:1</td>
<td>50:1</td>
</tr>
<tr>
<td>Spatial resolution</td>
<td>Ideal</td>
<td>Low</td>
<td>Low</td>
<td>Very low</td>
</tr>
<tr>
<td>Colorants</td>
<td>Mixed</td>
<td>Phosphorous</td>
<td>Filters</td>
<td>Ink pigments</td>
</tr>
<tr>
<td>Colour gamut</td>
<td>Very large</td>
<td>Large</td>
<td>Large</td>
<td>Medium</td>
</tr>
</tbody>
</table>

Unfortunately, typical real-world viewing conditions cannot achieve all conditions and colours that make identical XYZ values look different in practice and vice versa.

#### 3.1.2.2 Colour fidelity control in the press process

Almost all of the 172 newspaper companies in Sweden, [TU 2002], use the same printing method; coldset web offset printing. They also use mainly the same paper quality and European Standard ink, printing at one or more of the 61 newspaper printing houses [TU 2002].

There are cost advantages of using coldset instead of heatset. Coldset makes it possible to print on lightweight newsprint qualities. This reduces the cost of the paper and distribution, which constitutes 29 of the cost of producing newspapers [TU 2002]. Since the heater, requiring as much energy as the press, is left out, the energy cost is reduced. The disadvantage of coldset printing is the difficulty to get correct colour reproduction because of the low-quality surface of the paper and the fact that the ink never dries, which causes unwanted effects like smear.

Colour control by grey balance, is principally used as colour control method in newspaper printing. Grey balance usually consists of a number of bars placed at the border of the page across the printing direction. The standard, advertised by the TU, recommends a grey balance mix consistent with 30% of cyan colorant and 22% of magenta and yellow, which should correspond to the amount of black colorant [TU 2003b]. The TU recommendation advocates colour control without any proof, and the grey balance bars are supposed to be mainly controlled visually.
When the colour conception of a page visually gives an impression of a more than normal deviation, density measurements are made. Grey balance has many advantages in time-strained press workflows, such as newspaper printing. However, the colour fidelity in this workflow is affected, because the number of grey balance bars is often a compromise between layout and the number of colour keys used on the press. Thus, there are usually too few grey balance bars to cover the page evenly. Another problem could be the ambient light, beneath which the colour prints are being viewed. The light in the press control room usually originates from non-standardised light tubes. This means that the spectral and intensity levels vary, resulting in colour infidelity. When the colour is controlled by density, full tone surfaces are measured. The Swedish recommendation for newsprint specifies density means for the chromatic colorants (C, M, Y) by tolerances between 0.80 and 1.00, and for black colorants, between 1.00 and 1.20 in full tone surfaces [TU 2003b]. High values in the full tone density, without smear, yield high contrast. The problem when considering colour fidelity is that significant colour variations result from the approved tolerances between 0.80 and 1.00 units. Research into the colour variations of the Ifra [Ifra 2002] density-standard, has shown that for CMYK-colours printed by three and four colorants, a large variation of reproduced colour is implied, as well as when low area coverage or area coverage in the midtone range is reproduced [Wintzell 2002]. This implies that a colour printed within the standard, might become a variation of 16 different colours. This may cause a disagreement when an advertising customer who is not satisfied with the printed ad. The colorants in the ads are within the tolerance recommendation, proving that the newspaper company has printed a correct ad, but the customer visually gets quite a different ad compared to the original.

3.2 Problems and possibilities

Colour management is not new in the graphic arts industry; however, the tools are constantly being developed, although implemented a little more slowly. There is still an opinion among premedia and press operators that the ICC standard leads to an automatic increase of image quality, resulting in disappointment when this is not the case. The ICC standard is a powerful tool to attain an optimal quality, but the judgement of competent operators, skilled and experienced in a workflow that is consistent with high quality equipment and qualitative routines, is still of great importance. Essential for obtaining colour fidelity is also the preparatory work; evaluation and updates of the ICC profile(s) to be used, i.e. whether the profile accurately defines paper quality and white point, as well as employment of stable and consistent hardware. Due to the complexities involved, manufacturers of print media often provide specific guidelines to advertising customers, enabling them to set their document colour control attributes as required for the print workflow.
These guidelines are usually provided on the Internet. In many cases the prepress operators are not satisfied with the information given on the company web site; the information is found to often be incorrect, there is not enough of it, and in addition it is too hard to find. Internet web sites would be a simple way to provide helpful guidelines for advertising customers.

If the printed matter has met the requirements of prepress, a correct ICC profile is used, and correct measurements are made of density and/or grey balance, a proof should not be necessary for rapid printing process products such as newspapers. The press operator should be able to simply apply the measurement parameters. In case of an already existing hard proof, it is difficult for the press operator to know whether this hard proof is correctly done, together with the problems with visual reliability arising from spectral variances of the ambient environment. If the customer is present during printing, the adjustments usually differ to a higher extent, as do the waste of copies, unlike when only grey balance or density control methods are used. Some newspaper companies believe that incorrectness concerning printing of advertisements has decreased by reintroduced (hard copy) proofs.

Especially when display reproduction is essential, e.g. during image processing and soft proofing, even in well calibrated, well managed ICC workflows, problems with colour fidelity may occur because software based on different specifications may differ across markets, and between imaging component vendors. Deviation in software may even occur between programmes distributed from the same vendor, as older program versions may not support colour management or the freeware and full version may have different colour engines, resulting in divergently reproduced colour. The latter is shown in PDF files reproduced in Adobe Acrobat compared to Acrobat Reader, where the Reader-version will appear to be of higher contrast and of more saturated colours. Similarly, exchange of characterisation data is limited by restrictions in document and image formats. For example, common document and image formats do not support embedding of ICC profiles [McCarthy 2002].

For newsprint qualities, colorants printed with three or four colours are more likely to vary in density when printed. Especially when magenta is present, these variations are prominent. Red and blue hues are consequently more sensitive to density changes than green and yellow colours [Wintzell 2002].

3.2.1 Soft proof and hard proof

When considering colour fidelity, workflow and management of a stable and consistent system, the aim of the final product must be considered, especially as far as proofing method(s) and the control of the printing procedure are concerned.
The Prepress workflow that uses only soft proof claims to have a correspondence between proof and print of about 90-95%, though some colours are harder than others to reproduce correctly, related to differences of colour gamuts. It is easier to get similarity between proof and print for journal paper (and better) qualities than for newsprint qualities, naturally. At present, the poor properties of newsprint appearance cannot be reconstructed completely on any proof media. The colour quality of hard copies used to resemble newsprint would never be accepted in sheet fed printing production, but is considered as satisfactory proofs in web offset coldset printing.

Arguments against merely soft proofing have been that print problems related to halftoning, such as overprint and moiré, cannot be discovered. This might be possible to discover in the ripped version of the document, but not for sure. These are mistakes belonging to the starting phase, and they will disappear through knowledge of the workflow, essential for colour proofing. In workflows with a repetitive production process it is easier to get a successful dividend of soft proof as proofing media, as well as in workflows with a higher colour tolerance level. Investigated workflows fit in both these contexts, i.e. newspaper, journal and catalogue production, and medium to low quality advertisement prints.

In many cases hard proof is considered necessary, and one of the pronounced reasons is the customers’ demand for it. Such a case is mainly psychological, since the environment (at the customer’s) where the proof is judged, is unlikely to be standardised. Moreover, it is a source of income for the producer, because a high quality hard proof is costly (such proofs are not commonly used in investigated workflows). The use of soft proof in a prepress workflow instead of hard proof saves money by reduction of time consumed as well as of equipment and materials.

Displays used for proofing during printing, are not utilised much by today’s printing houses. Traditionally, high quality displays have been costly and have scattered light, but the LCD technology would probably be more appropriate, both with regards to characteristics and cost, especially for time-strained coldset offset printing, with minor time for corrections. Today, if proofs are used as a complement to grey balance control, it is a hard copy of varying colour divergence from the actual print. With visual control methods (common in press workflows) problems with colour fidelity will occur, if the ambient light is not standardised. In such a case an accurate display would probably deliver higher colour accuracy. Even more so with standardised surrounding illumination, along with software supporting colour management and routine calibration. The cost for high-end displays will soon be paid off by the reduced cost for hard copy materials.
Today, hard copies still serve as a control function, sent by an uncertain non-skilled advertiser as a complement to the digital ad. Then the premedia operator receiving the ad can form an opinion about the correctness of the digital file. This has one main drawback; automation is prevented, i.e. the procedure becomes time consuming. By using soft proof through web browsers a hard proof would not be necessary. Many newspapers already use this possibility. Their customers log in via a browser on the newspaper web site to check a composite version of their passed-for-press file. This serves as an acceptance that the passed-for-press file is correct and as a receipt for the customer that the ad looks like it is supposed to. Existing soft proof workflows do not (yet) utilise the possibility of correct colour reproduction for their remote proofing software. But with included accurate colour management, this could lead to reliable automation of the advertising workflow, and would reduce the need for any “just in case” hard copy proofs.

Hard copies are also accompanying digital proof by very concerned advertisers; an advertisement for, for example, a clothes-manufacturing company, to be printed in 70 different newspapers or magazines. The company might even bring a contract hard proof, which is often considered to be the most accurate proofing method, but it would not be of any use unless 70 different ones were sent, since all newspapers or magazines have their own printing parameters.

### 3.3 Conclusions on colour process workflows

In a given workflow, the desired colour depends on the calibration of the devices and can only be as good as the measurement process employed for the calibration and characterisation to maintain consistent colour appearance in the colour production over time. Neglect of correct standard parameters, such as well adjusted ambient light and ICC profiles, has no severe influence on the colour output in a workflow using coldset printing, but affects the possibility for maximum throughput and minimum operator interference, including time and material expenses. Improved efficiency and automation would also include reorganisation of existing methodology, to make more use of technically advanced facilities, (reliable equipment and routines), for colour management, such as displays and remote features.

Use of soft proof instead of hard proof throughout the printing workflow is fully possible, in-house, and as remote proofing; for customers, premedia operators and printers. Workflows producing higher colour tolerance levels, such as coldset printing products and repeatable printing production, like newspapers and journals, would gain assurance of a consistent and reliable colour reproduction flow and result in automation and flexibility of the colour media production.
Within premedia and print workflows, colour aims are based on experience with prepress and press capabilities. Reorganisation of methods and routines includes preparation. Before optimised results can be delivered, time and knowledge have to be allocated.
CHAPTER 4

LCD characteristics of relevance for proofing

This chapter presents fundamental and technical aspects in display technology regarding the use of displays for cross-media comparison and image reproduction, in case of colour fidelity. The analysis is based on examinations of measurements made on LCD and CRT displays, conducted by the author and compared to earlier researches from numerous reference papers and articles.

Displays technologies, including hardware and software, presently have failings concerning correct colour image reproduction. Much can be compensated for, however, and depending on demands of colour correctness, some displays show promising colour reproduction performance.

For a list of particular equipment and set-up used for the measurements discussed below, see Appendix: Equipment and set-up used for measurements.
4.1 Introduction

The main emphasis is on fundamental properties and colour management of LCDs, as qualities required to use the displays as high quality image reproduction devices in production workflows. Colour management systems do not always handle LCDs well, because LCD characteristics are significantly different from CRTs, for which colour management characteristics are well known. Hence, the CRT monitor is still most relied upon for high quality colour reproduction in media production workflows, despite the good quality of LCDs.

The performance of present high quality LCDs is compared to the properties of CRTs, portable LCDs, and to other work discussing LCDs. Their distinctions in the perspective of colour fidelity cog in prepress workflows are pointed out, especially concerning colour management aspects, such as calibration and characterisation. That is, both technical and perceptual issues regarding colour imaging and proofing of high-quality LCD, as well as restrictions connected to hardware and software is investigated with the purpose of providing recommendations for future colour management systems related to printing workflows.

4.2 Fundamental restrictions of hardware and software

To establish colour management systems, where displays play an important part, the relationship between the digital input values and output colours for display devices is essential. Previous researches by for example Kwak and MacDonald (2000) and Yoshida and Yamamoto (2002b) have demonstrated that two main characteristics have to be considered to predict LCD output colours according to the digital input. These are the electro-optical transfer functions and the non-constancy of channel chromaticity, i.e. the change of chromaticities in primary colours and achromatic colours depending on the drive signal level of each channel. Among perceptual characteristics that have to be understood are the changes of output colour depending on viewing angle. The latest wide-viewing angle technologies have adequate colour performance for most applications, yet far from ideal. Understanding of these issues will make LCDs gain acceptance for colour-intensive applications in the media industry, since these developments, when combined with the high pixel density, high local contrast ratio, and lack of distortion achievable with LCD technology, will lead to displays with an image quality that is superior to both CRT and print. As LCD image quality improves, some challenges remain prior to reaching explicit characterisation methods. For
the professional workflow operator, this means that the demands of colour management needed to reach an adequate final product, have to be adjusted to the LCD, i.e. to the hardware and software, as well as to the skills of the operators and users.

A colour management system including LCD, consists roughly of five parts: (1) fundamental components, such as a glass plate containing electrodes, thin film transistors and liquid displays, (2) optical components such as polarisers, colour filters and back lighting system, (3) source and gate driver Integrated Circuit (IC) [Yoshida and Yamamoto 2002b], (4) models and methods to control the hardware, (5) implementation of (1)-(4) in software. All these components influence the display colour management. For a more detailed description of LCD and CRT technology, see Appendix A: Display technology fundamentals.

4.2.1 Fundamental aspects of monitor quality

LCDs are becoming widely used for image reproduction in flat-panel notebooks, desktop computer displays and in projection displays. When the display is utilised for high quality colour reproduction, where consistent colour fidelity is of great importance, some fundamental technical demands have to be fulfilled. These demands have traditionally concerned CRT monitors, in which quite few manufacturers have specialised and they have been expensive. The same technical demands are applied for the LCD; not all displays are fitted for high colour quality reproduction. The problem with LCDs is that, while some trends are common to all LCDs, presently, there are no standard characteristics, such as those of CRTs. When the LCD technology matures this situation will change [Wright et al. 2000].

LCD devices have received significant technical credits during recent years at the same time as their initial cost has decreased, resulting in proliferation, mostly due to the high brightness, high contrast, high sharpness, virtually no geometric image distortion, compactness and low power consumption [Silverstein and Fiske 1993]. However, in terms of colour capability and for image reproduction where the colour quality is essential, LCD devices have not yet been able to outbid the CRT devices, mostly due to the reputation of CRT for being more accurate, for having larger colour gamut and for offering practically no colour variation in the viewing angle [Silverstein and Fiske 1993]. These CRT qualifications, together with the variations of performance, the relatively few years of evaluation and the (former) high purchase price, have impeded the competitiveness of LCDs.

At present, three types of monitors are technically feasible or in use for quality image reproduction: CRT monitors, TFTLCD desktop displays and TFTLCD portable computers. The chromaticity gamut of a high-quality LCD is almost the
same as that of a CRT, but it is somewhat larger for the LCD in the blue and green areas. In the luminance axis the LCD can be great deal larger. If a display possesses higher luminance, its gamut appears larger. This may happen if the colour reproduction of a CRT and a portable LCD is compared. Even if the particular CRT display offers a larger chromatic gamut than LCD displays, the advantages of higher luminance makes the LCD displays appear as if it had a larger perceptual gamut [Marcu et al. 2002a]. This is an important aspect of colour perception related to displays, which has already been observed by many users and made them switch from CRTs to LCDs.

![Diagram](https://example.com/diagram.png)

**Figure 27**. Chromatic gamut for different display technologies. (x and y are defined in Chapter 2: Theoretical background.)

For LCDs, a desktop display almost always possesses both higher luminance and chrominance than a portable computer. As seen in Figure 27, the display of the portable computer represents approximately 70% of the chrominance of the LCD desktop display. Thus, it is important for an operator/user to be aware of the technical qualifications expected from the display and its ability to reproduce colours, both as far as display specifications and workflow quality demands are concerned.

4.2.1.1 **Component aspects compared for LCD and CRT**

It is interesting to compare LCDs with issues related to CRTs to point out the characteristics that sets the transmissive LCD apart from the traditional CRT self-luminous device concerning colour rendering. Such an analysis is critical for the assessment of the LCD’s potential for high-performance colour imaging applications. CRT and LCD displays do not have the same technical and perceptual characteristics and on account of that, software and utilisation processes are not always linearly interchangeable between these displays.
4.2.1.1 Exclusive problems related only to LCD or CRT monitors

Exclusive problems for CRT displays, used for colour rendition, are related to the viewing ambient contras the colour temperature of the monitor and other aspects related to the comparison of emissive display images with images printed on paper [Wright et al. 1998]. Due to the high reflectivity of phosphor materials, changes in the viewing environment influence the reproduced colours, especially dark colours of CRT, and affect the image quality. Another main drawback is that the colours of a CRT drift over time, due to changes in the analogue and high voltage electronics, and to aging of phosphorous at different rates [Cappels 1996].

The problems of LCD performance are structural ones; the shape of the electro-optical transfer functions, the non-constancy of channel chromaticity, channel interactions and perceptually; the changes of output colour depending on viewing angle [Silverstein and Fiske 1993], [Marucu et al. 2002a], [Fairchild and Wyble 1998], [Kwak and MacDonald 2000]. These issues will not be discussed further here but they will be touched on in the below section Source and gate driver issues.

4.2.1.2 Comparison of characteristics of LCD and CRT

The colour stability of LCDs, Figure 28, measured peak primaries, is potentially better than that of CRT monitors, Figure 29, since the spectral characteristics of colour filters and LCs are stable compared to the CRT phosphor beams. To a large extent this arises from the digital drive environment of LCDs, which is inherently more stable than that of analogue drives. If the LCD monitor uses an analogue signal path to preserve CRT compatibility, a limiting factor arises because the digital signals for LCDs only need to be converted to analogue ones at the output of the driver chip on the glass, located close to the edge of the array. If backlight phosphors are used as backlight in the LCD, they exhibit similar characteristics as the ones used in CRTs, e.g. the same aging properties, which depend on the amount of luminance used over time. [Wright et al. 1998]

![Diagram](image)

**Figure 28.** The stability of colours reproduced on a LCD. The figure shows δE-variations (δE, see Chapter 2: Theoretical background) for repeatable measurements during one minute, for each of the four sample colours. The violet bar (hindmost) shows the mean variation from the previous measurement of each colour and the blue bar (foremost) shows the mean variation from the first measurement of each colour. The variations are below 1 δE for all colours, with red and green showing greatest variances.
One way to improve the colour gamut of LCDs is to replace present cold-cathode fluorescent lamps (CCFL) in the backlight with light emitting diodes (LEDs) [Wright et al. 1998]. LEDs emit an even narrower band of wavelengths compared to phosphorous, which maximises the emission of narrow regions of the spectrum, hence increases colour-gamut volume and efficiency. Recent developments have led to the development of green and blue LEDs with chromaticities close to the corners of the spectral locus [Wright et al. 1998], which are in part due to higher peak radiance in all three channels for LCDs compared to CRT displays.

![Graph showing ΔE variations for repeatable measurements](image)

**Figure 29.** The stability of a colour reproduced on a CRT display. The figure shows ΔE- variations for repeatable measurements during one minute, for each of the four sample colours. The violet bar (‘indmost) shows the mean variation from the previous measurement of each colour and the blue bar (foremost) shows the mean variation from the first measurement of each colour. The variations are below 1 ΔE for all colours but white, which is very disturbing, since proper display of white is essential for colour-critical work.

Both CRT and LCD displays require time to reach steady state from a cold start. Warm-up of phosphor tubes requires significant time to reach a stable output. A couple of hours usually have to be spent before colour-imaging work can be performed. The backlight type in LCDs depends on manufacturer, and hence, warm-up times differ. Manufacturers specify about an hour of warm-up time. Figures 30 and 31 show tristimulus values of white (w) and grey (gr (128 128 128)) for LCD and Figure 32 during CRT monitor warm-up. The output does not fluctuate much during a 3-hour period, but reaches steady state after approximately 2 hours for LCDs as well as for the CRT monitor. The magnitude of fluctuation depends on display manufacturer.
Figure 30 and 31. Warm-up characteristics of high-quality LCDs (Eizo left and Apple right). The warm up characteristics differs depending on manufacturer.

Figure 32. Warm-up characteristics of a high-quality CRT (Barco). Both CRT and LCDs values fluctuate slightly during warm-up and need approximately two hours of warm up to reproduce a stable output.

Compared to CRTs that produce colours by cathode-ray beams meeting a phosphor screen that emits light, the primary colours on a LCD are accomplished by thin-film colour absorption filters [Silverstein and Fiske 1993], one for each colour accompanied by external backlight. The selection of dyes and pigments, which are compatible with LC materials and the LCD manufacturing process, is limited, and this defines the degrees of freedom for tailoring the spectral transmission of thin-film colour filters.

The thickness and/or concentration of colour filters have an effect on the efficiency of light throughput of the LCD. The LC cell gap is a critical parameter for tuning the colour performance, luminance and contrast ratio of a colour LCD. The cell gap may be selected such that the LCD contrast ratio, colour gamut and colour saturation are maximised or adjusted to another important quality, such as weight or power supply. [Silverstein and Fiske 1993].
The peak white of LCDs is about twice as high (230-250 cd/m²) as that of a CRT. When processing images it is not always desirable to have such a high luminance, and some LCDs have hardware adjustable brightness. Nevertheless, the contrast ratio (white compared to black level) is also more than twice on a LCD (300:1-400:1), indicating a darker black level both for full screen measurements and when the target was reduced in size. Given the nature of the LCD, it is expected that this contrast would hold even for very small targets [Gibson et al. 2000b]. In comparison, the CRT contrast is slightly more reduced because of further decrease of the target size [Gibson et al. 2000b].

Better black level on an LCD can be obtained by firstly placing a negative birefringence compensation film after the liquid crystal cell to compensate a greater extinction level. Secondly, thick colour filters are used to maintain high crystal saturation levels in the primary colour sub-pixels, minimising the impact of any stray leakage from adjacent pixels [Gibson and Fairchild 2000a].

![Spectral distribution of black (0, 0, 0) and white (255, 255, 255) from an LCD. Increased energy emission can be seen around 480 and 780 nm.](image)

**Figure 33.** Spectral distribution of black (0, 0, 0) and white (255, 255, 255) from an LCD. Increased energy emission can be seen around 480 and 780 nm.

The normalised spectral power distribution of black for the measured LCD in Figure 33 has a similar spectral distribution as white, but with more energy (relatively seen) emitted around 480 and 780 nm. This is a result of leakage of energy, yielding a black point of non-zero black radiance opposite to a properly set-up CRT.
The difference in performance of LCDs is shown in Figure 34, where the normalised spectral power distribution of apparent (displayed) black is shown for two high-quality LCDs, with very different leakage characteristics, similar to displays from the same manufacturer, shown in Figure 35. An initial problem with CRTs, though, is that they often differ from a proper set-up, e.g. a standard set-up described in Chapter 2: Theoretical background, meaning these monitors also converge as the input levels are reduced and that they illuminate light at the apparent black level. Both LCDs examined had a darker black level than the measured CRT.
Spatial independence refers to the impact (or lack thereof) of a colour, displayed on one area of the monitor, on another colour. A monitor with poor spatial independence cannot produce reliable colour stimuli, since the colours displayed on another area of the screen influence the colorimetry of a test stimulus. [Fairchild and Wyble 1993]

Colour differences ($\Delta E$), measured for two LCDs shown in Table 3, were largest when the background colour had high chromaticity and high lightness, e.g. white and yellow, and when the stimulus was a darker colour. Most affected was black stimulus with a colour difference higher than one, for all backgrounds except dark blue (0 0 128). The result is similar to these measurements presented by Kwak, and MacDonald (2001) but differs from the ones presented by Fairchild and Wyble (1998) and Gibson et al. (2000a). Each pixel in an active-matrix LCD is physically distinct from its neighbours and good spatial independence should be expected, compared to a CRT where a single scanning electron beam is used to address each pixel of a given colour. CRT therefore often suffers from poor spatial independence [Gibson et al. 2000a]. The resulting colour differences for dark colour on light backgrounds are disturbing. Such differences may result from cross talk from neighbouring pixels and/or flare from the screen and reflections from the walls, in spite of an almost totally dark environment.

Table 3. Color differences ($\Delta E$) where 11 colour stimuli were measured on 11 different backgrounds made up of the same set of colours.

<table>
<thead>
<tr>
<th>($\Delta E$) background</th>
<th>sample ($\Delta E$)</th>
<th>white</th>
<th>yellow</th>
<th>magenta</th>
<th>cyan</th>
<th>red</th>
<th>green</th>
<th>blue</th>
<th>dark red</th>
<th>dark green</th>
<th>dark blue</th>
<th>black</th>
</tr>
</thead>
<tbody>
<tr>
<td>(255,255,255) white</td>
<td>0.671</td>
<td>0.230</td>
<td>0.330</td>
<td>0.232</td>
<td>0.287</td>
<td>0.287</td>
<td>0.076</td>
<td>0.267</td>
<td>0.187</td>
<td>0.460</td>
<td>0.732</td>
<td></td>
</tr>
<tr>
<td>(255,255,0) yellow</td>
<td>1.329</td>
<td>0</td>
<td>0.673</td>
<td>0.999</td>
<td>0.706</td>
<td>0.656</td>
<td>2.250</td>
<td>0.829</td>
<td>0.800</td>
<td>0.713</td>
<td>0.320</td>
<td></td>
</tr>
<tr>
<td>(255,0,255) magenta</td>
<td>0.401</td>
<td>0</td>
<td>0.478</td>
<td>0</td>
<td>0.422</td>
<td>0.208</td>
<td>0.425</td>
<td>0.187</td>
<td>0.130</td>
<td>0.226</td>
<td>0.190</td>
<td>1.463</td>
</tr>
<tr>
<td>(255,255,255) cyan</td>
<td>0.390</td>
<td>0.319</td>
<td>0.379</td>
<td>0</td>
<td>0.655</td>
<td>0.403</td>
<td>0.437</td>
<td>0.212</td>
<td>0.470</td>
<td>0.618</td>
<td>3.416</td>
<td></td>
</tr>
<tr>
<td>(255,0,0) red</td>
<td>1.929</td>
<td>0.706</td>
<td>0.576</td>
<td>1.239</td>
<td>0</td>
<td>0.712</td>
<td>1.064</td>
<td>0.610</td>
<td>1.213</td>
<td>0.560</td>
<td>0.596</td>
<td></td>
</tr>
<tr>
<td>(255,0,0) green</td>
<td>1.151</td>
<td>0.481</td>
<td>0.723</td>
<td>0.515</td>
<td>0.796</td>
<td>0</td>
<td>0.546</td>
<td>0.659</td>
<td>0.675</td>
<td>0.616</td>
<td>0.931</td>
<td></td>
</tr>
<tr>
<td>(255,0,255) blue</td>
<td>1.324</td>
<td>1.251</td>
<td>0.491</td>
<td>1.451</td>
<td>0.463</td>
<td>1.277</td>
<td>0</td>
<td>0.155</td>
<td>0.360</td>
<td>0.081</td>
<td>0.172</td>
<td></td>
</tr>
<tr>
<td>(255,0,255,0) dark red</td>
<td>2.269</td>
<td>1.168</td>
<td>2.142</td>
<td>2.327</td>
<td>0.793</td>
<td>1.244</td>
<td>1.822</td>
<td>0</td>
<td>0.234</td>
<td>0.158</td>
<td>0.079</td>
<td></td>
</tr>
<tr>
<td>(255,0,0,255) dark green</td>
<td>1.389</td>
<td>0.907</td>
<td>1.141</td>
<td>0.800</td>
<td>0.842</td>
<td>0.308</td>
<td>0.741</td>
<td>0.363</td>
<td>0</td>
<td>0.312</td>
<td>0.346</td>
<td></td>
</tr>
<tr>
<td>(255,0,0,255,0) dark blue</td>
<td>2.552</td>
<td>2.773</td>
<td>0.967</td>
<td>2.655</td>
<td>1.007</td>
<td>2.637</td>
<td>0.241</td>
<td>0.314</td>
<td>0.724</td>
<td>0.339</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>(0,0,0,0,0) black</td>
<td>2.479</td>
<td>4.167</td>
<td>4.469</td>
<td>3.339</td>
<td>3.831</td>
<td>4.441</td>
<td>2.906</td>
<td>1.027</td>
<td>1.197</td>
<td>0.807</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

The ability of a monitor to display an equal colour gamut uniformly over the entire screen surface varies as seen in Figures 36 and 37, where colour samples (peak primaries and secondary colours) were measured in the four corners of the screen, from a normal viewing distance of 0.5 m, and compared to (reference)
measurements in the centre of the screen. For one of the displays the mean \( \Delta E \) was approximately 3, which is better or equal to a CRT, with greatest variation in the blue-yellow (b) axis, Figure 36. The other LCD had more than twice as high a mean deviation, and with much greater variation in luminance (L), Figure 37.

![Figure 36 and 37. The ability of two LCD panels of different brand to uniformly display colours. Depending on the LCD model the divergence of CIELAB values is different according to the two figures. For example the divergence of the reproduction in the yellow-blue chromaticity axis (\( \Delta b \) - topmost bars in Figure 36) is greatest for the model seen in Figure 36, compared to the model in Figure 37, which has generally greater divergences in all Lab-axes.](image)

**4.2.1.2 Limitations of portable (LCD) computers**

Professional colour rendering on portable computers is accompanied by several limitations. Colour quality and the ability to control the basic structure are some of the important aspects explaining why the use of portable computers is less suitable than desktop LCD for colour reproduction. As the portable computer holds other appealing characteristics, such as light weight, it should be used as a complement to, but not as, a desktop high quality LCD.

Limitations in the colour rendering ability of portable computers:

- For TN-mode LCDs, there is a wide range of behaviour, primarily related to designs optimised for notebook applications, where colour rendering is not the primary concern. Generally, there is a chrominance shift with level for the grey state, due to different transmission characteristics of the primaries [Wright et al. 1998]. The rapid shift can begin to occur on levels as high as mid tones (128) [Okano 1998]. The faster the chromaticity converges toward the black point, the harder it is to receive an accurate rendering of dark colours. However, differences in dim colours are difficult to perceive, and this makes the colours less rich in contrast. It is worth noting that even for properly adjusted CRTs, and
recently also for some high-quality desktop LCDs, the chromaticity of primaries shift very little before the level falls below 20 of 255 [Cazes 1998], with very little chrominance shift of the grey state.

♦ The dependence on viewing angle for TN panels is due to asymmetry of the panel states with cells perpendicular and parallel to the panel surface [Marcu et al. 2002a]. Leaking light passes through the panel and causes asymmetric variation for the optical properties of the TN panels in both horizontal and vertical viewing angles, significantly limiting the usage of the panel for critical colour work.

♦ Besides greater colour variations depending on viewing angle than for desktop displays, another issue that minimises acceptable colour management on a portable display, is the fact that it is very hard to receive repeatable lid angle once the computer is moved. This minimises the reproduction of perceptually consistent colours.

♦ Most 8-bits per pixel LCD screens in present notebook computers use 6-bit driven panels and the least significant 2 bits are produced by time-frame modulation. The grey levels produced by time-frame modulation are not evenly distributed by luminance. The luminance step resulting from switching on the first frame is different from the luminance step obtained by switching on the 2\textsuperscript{nd}, 3\textsuperscript{rd} or 4\textsuperscript{th} frame in sequence. This results in non-uniform grey levels. This behaviour in conjunction with gamma correction of asymmetric RGB channels may lead to colour banding corresponding to the less significant bits. [Marcu and Chen 2002b]

♦ The colour gamut of the LCDs is determined by the spectral power distribution of the backlight, matched by the absorption characteristics of the panel's colour filter [Oh-e et al. 1995]. In most cases, there is a trade-off between the brightness and the gamut of a display. For many notebook displays, the colour gamut has been intentionally reduced by broadening the spectral transmission through the colour filters.

♦ In general, a transmissive LCD has a luminous efficiency of about 5-6\%, demanding a powerful backlight source to drive these panels [Marcu et al. 2002a]. To create a display with higher luminance without changing the power supply, thinner filters are needed, corresponding to less saturated chromaticities, and hence a smaller colour gamut. For portable computers, the power available to the panel is limited, and therefore a relatively high luminance can be achieved at the price of a smaller gamut [Marcu et al. 2002a]. On desktop displays the weight is of no concern, so the backlight source(s) can be more powerful and the
colour filters can be thicker. This creates a much larger gamut and a high luminance.

Portable computers exhibit larger technical and perceptual divergences than desktop LCDs, and therefore they are harder to calibrate and characterise, in order to improve colour reproduction.

4.2.2 Optical components

Depending on the desired colour quality, different aspects of the LCD performance have to be considered. As with high quality CRT monitors, high quality LCDs perform quite well by default. Disregarding the colour management issues in the ICC-structure, the colour variation induced by changes of viewing angle is the most important drawback of the current LCD technique [Marcu et al. 2002a]. Improvements have been made to the LCD structure by several approaches of LC-modes such as In Plane Switching (IPS), Dual Domain (DD) or Multi Domain Vertical Alignment (MVA) replacing previously predominant TN-mode panels, which show large colour shift variations. (LC-modes are described in more detail in Appendix A: Display technology fundamentals.)

The narrow acceptable viewing angle causes performance problems at deviations in both horizontal and vertical angle. The amount of colour shift for the same angle depends on the structure mode of the liquid LC cells of the display. However, dramatic improvements in viewing angle have been achieved with IPS cells [Oh-e et al. 1995] and vertically-aligned LC cell modes [Takeda et al. 1998], [Lien et al. 1998] in contrast to the liquid crystal cells of the TN-mode, and there is a continued development of compensation films for all modes [Sergan and Kelly 1998], [Saitoh et al. 1998], [Yuan et al. 1998]. This is important for large-area desktop displays, where the subtended angle from corner-to-corner for a single user can be large and it is then more suited for colour rendering work than portable computers.

4.2.2.1 Perceptual issues regarding the viewing angle

Both luminance and chromaticity shift over the viewing cone. Furthermore, the magnitude of the shift in colour and the divergence are different for different LC modes, as well as the colour variations depending on viewing angle off axis (not perpendicular) from the panel. Variations in colour reproduction for different viewing angles for LCDs are related to the leaking light through the LC-material, further discussed in the coming section treating black correction. If the panel exhibits larger colour variations (after black correction), for example in the middle tone region of the grey level on-axis, this is also most likely going to affect the
reproduction on off-axis angle. The variation according to viewing angle appears both in horizontal and vertical angles. The colour differences according to viewing angle for various liquid crystal modes, including displays of twisted-nematic compensation film (TN+CF), twisted-nematic single and dual domain IPS (SD-IPS and DD-IPS) and MVA modes have been investigated by Wright et al. (2000). The results showed that the average colour shift from the on-axis is much lower for the DD-IPS and MVA modes than for the other modes. It was also shown that the magnitude of colour shifts strongly depends on display manufacturer: there was a large difference in the colour characteristics of the two SD-IPS displays, tested by Wright et al. (2000), which were from different manufacturers. The colour variations depend on the leaking light. While the grey level was reduced, the colour rendition generally shows an increasingly large variation with viewing angle. For TN and TN+CF modes, midtones and dark greys showed phenomena related to reversal of luminance level [Tanaka et al. 1994], [Hunt 1995]. Level reversal is a situation in which a portion of the slope of the tone reproduction curve reverses sign, that is, a change in luminance versus a change in grey level changes sign. This corresponds to a reverse of contrast. Reverse of contrast dramatically reduces the image quality in TN-mode panels, but is absent for IPS and MVA modes [Wright et al. 2000]. Even though the luminance characteristics are improved for IPS and MVA modes, without black correction and improvement of the black state, colour variations with viewing angle is about the same as for TN modes. The colour quality of the dark states is one of the factors limiting the colour performance of the wide-view TFTLCD technology [Wright et al. 2000].

The dependence of the luminance on the horizontal viewing angle was also investigated in this study, ranging from on-axis and ± 50°, of measured peak primaries and grey (128, 128, 128). The results showed that luminance reduces drastically for colours with high luminance, such as white and green, when the viewing angle is increased, as shown in Figure 38. For blue colour the differences in luminance is below 4 ΔE for an angle of 30°. The blue has the highest variations in chromaticity, but under 20° the colour difference is almost acceptable for all colours, Figure 39.

![Figure 38. Luminance variations for different viewing cones. Strongest decrease in luminance for colour samples with highest brightness. Blue is least affected.](image-url)
Viewed off-axis in a dark room at certain viewing angles, the black state of many LC modes appears yellowish viewed from one side or purplish viewed from the other, not black. The variations in green-red and yellow-blue axis is about the same for the various modes, averaged over incident angles (0<50°).

![Graph showing chroma variations for different viewing angles. Blue is most affected from on-axis deviations.](image)

**Figure 39.** Chroma variations for different viewing angles. Blue is most affected from on-axis deviations.

### 4.2.2.2 The influence of ambient light

Because displays emit light the appearance of colours can either be related or unrelated depending upon viewing ambience and the detailed colours rendered on the display [Hunt 1995], [Fairchild 1998a]. For most viewing environments the observer is partially adapted to the display and partially to the ambient illumination. For CRTs and prints viewed under various illumination conditions this partial adaptation effect has been studied by Katho (1995) and Berns and Choh (1995). For LCDs, which are brighter than CRT monitors, this adaptation to the display should be stronger, but the changes in chromaticity and brightness with viewing angle introduce additional complications, presented in Wright et al. (2000).

Many LCDs show a poor black level due to leakage of light, especially when they are observed in a dark room or at an angle not close to the axis of the screen surface. However, in typical viewing environment (1000-5000 cd/m²) the contrast ratio of LCDs is approximately twice as high as that of CRTs, due to differences in screen reflectivity and peak brightness. Flare influencing the LCD screen, may appear negligible due to the diffuse antiglare film, which has superior light absorption performance than the front glass of a CRT. The effectiveness of the antiglare film may vary depending on type of LCD. Desktop LCDs tend to better
reduce flare than notebook computers. Moreover, the LCD device distributes light
by LC cells, whose operating principles differ from those of CRT. In spite of
surface reflection, resulting in reduced colour performance e.g. contrast ratio, the
colour reproduction on LCDs viewed under ambient light is just slightly
influenced by flare, hence, in addition to the higher brightness level, the viewer is
more adapted to the white point of the LCD display than to the surroundings.

For CRT monitors the influence of surface reflection is considerable [CIE 1996].
However, under dark viewing conditions, CRTs have dimmer dark states, and the
contrast ratio of CRTs can be very large. This contrast can be utilised to better
render images, containing detail in dark areas of the image [Wright et al. 1998].
The opposite could be true for LCDs viewed in dark environments, if the LCD has
a large amount of leakage light. In such a case, a poor contrast ratio requires an
improved dark state. By increasing the backlight intensity, the white state
luminance can be increased. This will not improve the contrast ratio in dark
ambient conditions, but if the brightness of the apparent colour saturation peak
becomes better and so does its contrast in a bright ambience. Peak brightness is
important for rendering image highlights [Wright et al. 1998].

To avoid image artefacts due to additional TFT photo leakage [Johnson 1995],
improved black matrix structures are needed in the array. The black state can be
improved by cell structures that do not contain spacer balls, with better cell gap
uniformity, and improved compensation films [Wright et al. 1998]. For TN-mode
cells, the spacer balls leak light in the dark state.

However, high-quality LCDs give an excellent contrast under dim (CRT standard
compatible) viewing conditions even prior to black correction.

Surface reflection of the display does not depend on the digital input level and
therefore, in the perspective of colorimetry [Yoshida and Yamamoto 2002b] it
may be handled in a manner equivalent to the above stated leakage of light.

### 4.2.3 Source and gate driver issues

#### 4.2.3.1 Calibration problems

Essential for a successful performance of a colour management procedure is the
ability of the imaging-device to reproduce data in a repeatable way. For a display
the calibration is staged by setting up the white point according to a reference
value, the contrast and brightness.
Wise from experience with CRT displays and the users’ ability to make adjustments themselves, scarcely compatible with a standard, the display manufacturers have reduced the possibility for making adjustments in the hardware. The possibility of hardware calibration of a CRT has given the indication that the display is accurate for colour management. Since the LCD monitors are made through a different technique, and since they have not yet been seriously used in colour workflows, the possibility to calibrate an LCD correctly is not well determined. However, at present, there is at least one LCD brand that can be hardware calibrated, and software possibilities are developed continuously along with spectrophotometers and calibrators adapted for the LC-technique. Still, the high-quality LCDs examined, showed uncertain calibration results. Since the LCD display technology still is quite recent in work related to colour, standard adjustments do not yet exist. Therefore, in the absence of such standards, CRT standards are transferred to LCD applications.

4.2.3.1.1 White point temperature
The chromaticities do not vary with changes in the set-up of a display, caused by adjustments of the gun amplifier’s gain (contrast) and offset (brightness) or of video look-up tables. However, the maximum luminance of each primary is quite dependent on set-up. This concept is used to change the white point of a display – that is, the chromaticities of the white produced by equal monitor tristimulus values [Berns 2000]. The correlated colour temperature (CCT) depicts the white point of a display. This temperature should vary insignificantly according to the digital input values. However, even high-quality LCDs with a reference white set to, for instance, 5000K, gets enlarged CCT around the black state. Temperatures around 10000K are common for the black level, even though a few LCDs have a modest enlargement of 2000K from the white point, whereas others, mostly notebook LCDs, get enlargement of the CCT already for middle grey with a black point CCT of approximately 30000K [Okano 1999]. For high-quality LCDs this phenomenon is mainly a severe concern with regards to the influence of the output of the digital input levels between 0-50. This enlargement is due to limitations of the channel structures, e.g. due to leakage of light through the LC-material, which will be discussed further under Black correction in the next section.

Thus, an uncorrected LCD can be described as a display whose white-balance hardly is achieved, since the colour coordinates of the white point are measured as the sum of the light from all primary colours plus the leakage light [Yoshida and Yamamoto 2002b]. The coordinates of the white point of an uncorrected display drift towards the coordinates of the channel whose characteristics deviate most, resulting in shifts in the output colour. Previous investigations by Marcu et al. (2002a), Fairchild and Wyble (1998) and Kwak and MacDonald (2000) have shown that the blue channel is most affected, resulting in blue tinted output
reproduction and, correction methods are based mainly on improvements of the blue shift reduction. For high-quality LCDs with less enlargement in CCT (e.g. from 6500K to 8000K) and/or with the main enlargement on the small range of input digital levels of 0-50, the deviation of the blue channel is slightly more affected at low digital input levels than the other channels. This is illustrated in Figure 40.

![Figure 40. Deviation of primary chromaticities (0-255). The deviation for blue is slightly higher than for the other channels.](image)

The compensation of the default white point to a reference (target) white point can be done by subtracting the leakage light and by 1D LUTs modifying the balance between the maximum values of the RGB channels to achieve the chromaticity of the reference white point [Marcu et al. 2002a], discussed further in the section Black correction and Electro-optical transfer function.

By subtracting the leakage light from the chromaticities, the CCT of the display receives approximately equal digital input levels, adapted to the CCT of the white point. For the lowest digital input levels (i.e. 0-20, with main focus on 0-5), the temperature becomes slightly less than the average CCT of the display, approximately by minus 500K. By adjusting the LUTs of the channels, the desired CCT of the white point can be obtained, as shown in Figures 41 and 42.

![Figure 41. CCT after black correction of grey (0-255). The chromaticities diverge very little, inducing a stable white point temperature, however, far from the black locus. (u and v are defined in Chapter 2: Theoretical background).](image)
These aspects should be integrated in the LCD calibration software. Present LCD calibration software products generate ambivalent results of this task. This introduces one of the main problems with LCD colour management, which will be mentioned again in this text; namely the variations of the fundamental characteristics due to design. The colour management software is not designed to account for various characteristics of current LCDs, e.g. high quality LCDs have a very modest effect of the chromaticities from the digital input level, but other LCDs are severely influenced by leakage of light, especially originating from the blue channel. The possibility of hardware calibration gives a potentially more accurate result than plain software calibration. At present there are very few LCD models that offer this possibility.

When the user calibrates the display, employing manufactured software, the desired white point (e.g. D50) stays at the default (e.g. D65). It should also be noted that the white-point chromaticity of LCDs often differs significantly from the nominal default (in the full range of digital input levels). For instance, an Apple Cinema Display, calibrated by Eye-one software for D50, yields an approximate CCT of 6700K. A few LCD manufacturers have adjusted the default CCTs of their displays to the media industry by choosing the default temperatures D50 and D65, which facilitates white point compensation. A panel with the default white point closer to the reference (target) white point, keeps the compensation to a minimum. A panel with a D65 default white point should be more easily compensated for D50 than for a temperature of e.g. 9300K [Marcu et al. 2002a].

Many LCD manufacturers have reduced the possibility to manually adjust the gain and offset of the display. Since an uncorrected LCD has more than twice the brightness of a CRT monitor (250 cd/m² compared with 120 cd/m²), the calibration to the (CRT) ISO standard level of 80 cd/m² reduces the luminance of the LCD display significantly. Drop in luminance may occur involuntarily while calibrating displays with only one backlight source, e.g. notebook computers. When moving the default white point, positioned far from the black body locus, to a target white point on or near by the black locus the luminance of the display may be significantly reduced, caused by the change of balance between the maximum
RGB-components required to get the desired chromaticity of the target white point [Marcu et al. 2002a]. In this case the adjustment of the white point will only reduce the luminance of the panel.

4.2.3.2 Characterisation issues

4.2.3.2.1 What characterisation means
The calibration and characterisation procedures are essential parts when integrating colour-imaging devices into a colour management process. The characterisation result depends on the calibrated state, and defines the relationship between the signal space of the device and the colours generated by the device, specified in terms of the CIE system [Johnson 1995]. Thus, for an LCD it defines the relationship between the voltage quantised, such as the data input to the display and the colours displayed on the screen. The characterisation may be defined as a mathematical model based on a set of equations or a definition of discrete points that constitute a look-up table [Kwak and MacDonald 2001]. The calibration and characterising stages are included in the process that the user of the display accomplishes while making an ICC profile for the monitor.

4.2.3.2.2 What the ICC profile does
The specification for colour management, which is employed in the present ICC profile standard, describes colour compensation from the gain-offset-gamma (GOG) model [Berns 1996] for characterising CRT displays by a two-stage process. Firstly, three 1D-LUT’s are used to transform the incoming digital counts into linear scalars. Secondly, the linear scalars are multiplied by a 3x3 matrix [Gibson and Fairchild 2000a]. Thus, the estimated signal is a scaled version of the full strength primaries. This model is built to function successfully if applied to well-calibrated high quality CRTs, situated in a dim environment, since it is modelled for devices that satisfy the proportionality and the additivity law [Yoshida and Yamamoto 2002a].

4.2.3.2.3 Problems related to the characterisation process
As mentioned, one of the essential problems of LCDs in colour management systems is that it is still a new technique and fundamental characteristics vary depending on manufacturer. There are as yet no standard methods elaborated for calibration and characterisation, and there are no user standards. Therefore CRT standards are currently being used in the LCD interface until something better turns up. This is not always propitious, since the two panels are based on different technical structures and characteristics. For reasons described below, the present standard ICC profile characterisation procedure could not directly be transferred to an LCD display, caused by the present inconsistency and not yet optimised
performance of some LCD characteristics (further noticeable in non high-quality displays).

The following items may cause problems for high fidelity colour reproduction on LCDs, relating to essential problems in the design and structure inherent in current LCD:

- Leakage light due to limitations of the characteristics of the LC-material, and non-proportionality characteristics of the chromaticity coordinates.
- Difference in shape of the electro-optical transfer function.
- Lack of additivity due to channel interaction (cross talk) [Yoshida and Yamamoto 2002a, 2002b].

These problems are essential for the colour management of LCDs and need to be taken into account, since they all relate to structure characteristics and therefore most likely differ in magnitude, depending on panel type and model. Thus, these problems should be solved specifically in the framework of the colour management [Yoshida and Yamamoto 2002a]. The conventional ICC profile cannot describe the above mentioned items and therefore, the present ICC specifications do not do the LCD justice.

4.2.3.2.3.1 Channel interaction and additivity

Additivity for an LCD is the black corrected sum of equal levels of the luminance value Y or all the three tristimulus values of the chromatic values and should equal that of the achromatic values at the same level. However, the additivity for the examined LCDs is not preserved along the three colorimetric dimensions or the luminance, except at the highest digital input levels (240-255 deviates less than 2%). A degree of additivity less than 2% is sufficient to justify the use of a 3x3 primary matrix transform [Fairchild and Wyble 1998b]. Lack of additivity is most evident at the lowest digital input levels with slight improvement as the levels increases. Additivity is necessary to justify a 3x3 primary transform matrix.

There is a lack of additivity if neighbouring electrodes control closely related neighbouring colours and results in unwanted variations of luminance and chromaticity. This channel interaction is called cross talk and can be divided into two types: (1) optical cross talk, on LCDs due to insufficient response of the colour filter, such cross talk also occurs occasionally for CRT monitors, and (2) cross talk due to capacitive coupling between electrodes [Yoshida and Yamamoto 2002a]. Optical cross talk occurs when each channel is slightly contaminated by another channel; the blue channel is overlapping the green channel, for example. This kind of cross talk can be removed by a 3 x 3 linear matrix, applied to signals that are proportional to the optical intensity [Yoshida and Yamamoto 2002a].
Cross talk caused by capacitive coupling talk only appears upon two adjacent sub-pixels.

There is a parasitic capacitor between a source line and a sub-pixel electrode next to a source line. Therefore the transparency of the sub-pixel must be changed according to the change of the voltage applied to next sub-pixel. For example cross talk at the blue channel $B_o$ can be expressed as:

$$B_o = \psi(\text{Red, Green, Blue}) + \phi(\text{Red, Green, Blue})$$

(10)

where $\psi$ refers to optical cross talk and $\phi$ to cross talk due to capacitive coupling [Yoshida and Yamamoto 2002a].

An example of capacitive coupling is given by the spectral power distribution of the blue and the green channels, where the blue digital input level is fixed at 255 and the green input level is changed from 0 to 255. In this example, shown in Figure 43 the brightness of the blue primary for full-saturated cyan ($G=255$, blue line) is about 7% brighter than for blue ($G=0$, brown line), indicating a cross talk of 7% has appeared [Yoshida and Yamamoto 2002b]. Thus, a uniform performance cannot be expected for the entire colour range. Cross talk due to capacitive coupling should be handled as an essential subject of the colour reproduction, since the problem depends on the structure of the LCD [Yoshida and Yamamoto 2002a].

Figure 43. Blue is fixed at the digital input level of 255 ($G=0$ - farthest down line between 500 nm and 430 nm) and green is changed from 0 to 255 ($G=255$ - topmost line between 500 nm and 430 nm), indicating cross talk by capacitive coupling [Yoshida and Yamamoto 2002a].
4.2.3.3 Black correction - displacement of primary colour coordinates

For all LCDs the chromaticities of the RGB channels vary according to the digital level of the input and the changes in magnitude of the replacement of the primary colour coordinates is different for different kinds of LC-panels and differ depending on colour channel. Jointly for all panels, however, is that the closer the input level approaches zero the more rapidly the primary coordinates approach the coordinate of black. That is, the lower the input digital levels are, the smaller the colour gamuts become. Moreover, previous researches have shown that the gamuts mainly shift towards the blue region [Marcu et al. 2002a], [Okano 1999] [Yoshida and Yamamoto 2002a]. These physical replacements are due to leakage light, which is always added to the rendered colour, even for black colour, considered to be caused by a small amount of energy that 'leaks' through the LC cells, i.e. the changes in spectral transmission of the LC cell according to the voltage applied, and hence, according to the grey level [Silverstein and Fiske 1993].

Physical displacement of the primary colours due to changes in the distribution of spectral radiance of each primary: The transparency of the LC and the rotation characteristics of the light axis show variable wavelength characteristics depending on the voltage applied [Yoshida and Yamamoto 2002a]. In the spectral radiance distribution graph of the backlight, Figure 33, humps can be observed for all the primaries. Especially around the wavelengths of 430 to 500 nm, corresponding to blue and green, and at 700 to 780, corresponding to red, the shape of the spectral radiance does not change linearly with other parts of the graphs, according to the change of input digital values, that is, according to the change of chromaticity.

![Figure 44. Normalised spectral distribution for blue chromaticity between 0-255, which are not black corrected.](image)
The level of alteration in the spectral power distribution (i.e. the amount of leaking light) according to the digital input level differs depends on LCD manufacturer. However, most spectral power distributions of LC-displays do not change linearly in the beginning and in the end of the visual spectra, and some displays change all over the spectra, Figure 34. The altitude of changes is most noticeable for low levels (0-50) for high-quality LCDs, as shown in Figures 44 and 45, but for some LCDs these changes occur at as high levels as middle level (128). Similar behaviour is recorded for all channels.

![Graph showing spectral distribution](image)

**Figure 45.** Normalised spectral distribution for blue chromaticity between 60-255, which are not black corrected. In comparison with Figure 44, this shows that the physical change of the chromaticity coordinates is greatest between (approximately) 0 and 50.

The physical change in the primary chromaticity coordinates is non-proportional. If the chromaticities of the primaries were constant the chromaticities should vary along a straight line from maximum level of R, G and B to the black point, which they do not according to Figure 40, and after a black correction the chromaticities from each channel should fall on the same points [Kwak and MacDonald 2000].

Figure 46 shows the primary chromaticities after a black correction. It reveals that blue primary does not always exhibit the largest variation: for this particular LCD the highest variation is at red (might not be noticeable in the figure due to non-perceptuality). The non-proportionality after black correction is very small, which induces small hue angle variations.
A change of hue is visible in TN-mode displays, noticeable as a peak in the chromaticity locus of the blue primary, Figure 47. This can be observed in relation to the migration of the chromaticities with the input driving voltage [Silverstein and Fiske 1993] corresponding to a peak below level 255. This is a consequence of a cell gap thickness, optimised for green pixel operation and minimal power, in the extension the characteristics of the transmission voltage of the three primaries will not be exactly the same [Tsukada 1996].

The more the input digital level decreases, the more the intensity of leakage light affects the rendered colour. By substituting leakage light, the black value of the chromaticities can be corrected effectively [Fairchild and Wyble 1998], Figure 46. Usually, some displacement along the levels still remains, mainly in low and/or mid tone grey input levels. However, for some high-quality LCDs the black correction is successful for all levels, except for 1-2 % divergence for 0-20 digital input levels.
Variations in the appearance of the grey level due to additivity problems as a result of cross talk: After a black correction, the hue shift of the primaries is mainly consistent with capacitive cross talk in the array [Wright et al. 1998].

4.2.3.3.1 Conclusions on black correction
The above mentioned phenomena (bold text) concerning the displacement of the colour coordinates of the primaries and the reference white cannot be solved by a colorimetric approach [Yoshida and Yamamoto 2002a], since it is a fundamental phenomenon based on characteristics of the raw LC-material that can only be effectively treated in step with the development of LC-material. LCDs do not apply to the proportionality law as long as these problems remain. However, the problems can be sufficiently compensated by: Adjusting the electro-optical functions to minimise displacement of the reference white (grey levels) [Okano 1999]. Definition of a 3x3 matrix for the conversion of primaries by means of the least mean square error method [Tamura et al. 2001b].

4.2.3.4 Electro-optical transfer function
The electro-optical transfer function describes the relationship between the signal driving a given display channel and the luminance produced by that channel, also known as tone characteristics [Kwak and MacDonald 2000]. This function is often a GOG portion of the traditional CRT-characterisation model [Fairchild and Wyble 1998]. The electro-optical transfer responses of most display devices are not linear. The fundamental electro-optical response of LC material has an S-shaped characteristic. The LCD is inherently a binary device that switches from an OFF state to an ON state following an S-shaped curve, implying a failure of the GOG model [Fairchild and Wyble 1998b], [Monovic 1998] for LC-based displays. However, many manufacturers choose to mimic [Marcu et al. 2002a], [Yoshida and Yamamoto 2002b] the digital drive circuitry for a general-purpose CRT, i.e. producing a transfer function that obeys a power law variation of a target gamma, Figure 48, since many applications are constructed to presume such monitor properties. For LCDs exhibited by means of a source driver, the IC is attached upon the glass plate directly [Yoshida and Yamamoto 2002a]. A great inconvenience for characterisation of LCDs is that default transfer functions (gain control) of LCD panels can result in various shapes [Marcu 2001], different from the power law function, depending on the design of the driver IC.

The gamma characteristics of an LCD basically depend on the design of source driver IC. In general the driver IC contains a D to A converter circuit and the digital input level is directly converted to analogue voltage applied to the LC panel because the average picture level does not affect the analogue voltage and does not contain unstable elements like a high-voltage power supply of CRT. Accordingly gamma variations do not occur in LCDs. [Yoshida and Yamamoto 2002b]
Gamma correction can be done by a power law inversion based on a single gamma value with respect to the function describing the target gamma or point by point in a LUT-based correction. For gamma correction of LCDs high precision compensation of LUTs is preferable, rather than single gamma power law compensation, which is most often the case in CRT gamma correction. For example, an error in gamma compensation of 2% may result in as much as 5 grey level differences between the desired output and the real output. This difference is perceptually noticeable on the screen [Marcu and Chen 2002b], [Yoshida and Yamamoto 2002b].

When the default transfer function differs from the target transfer function, a correction function for each component of the RGB channel is stored in 1D LUT of the video card and is accessed by each colour component of each displayed RGB pixel. The amount of gamma compensation depends on the deviation between default and target gamma response. In most cases TN-mode LCDs require a greater compensation than IPS technology based LCDs [Marcu and Chen 2002b].

![Graph showing the relationship between brightness (luminance) and gradation (digital counts) for grey and the sum of red, green and blue, for an LCD. The curves have a slight deviation, which means that the combined (r+g+b) grey is brighter than plain grey and there is a deviation of additivity.](image)

**Figure 48.** The gamma values (the relationship between brightness (luminance) and gradation (digital counts)) shown for grey and the sum of red, green and blue, for an LCD. The curves have a slight deviation, which means that the combined (r+g+b) grey is brighter than plain grey and there is a deviation of additivity.

### 4.2.4 Characterisation methods

Yet, there is no standard characterisation method for LCDs, although model proposals have been made by Gibson and Fairchild (2000a), Kwak and MacDonald (2001), Tamura et al. (2001b) and Yoshida and Yamamoto (2000). Work in this area is an interesting part in the future use of LCDs in critical colour reproduction.
4.2.5 Quality of colour management software

[Sharma and Fleming 2003] have examined how present ICC profiling and colour management software handles LCD in terms of gamma and white point values. The result showed that all the eight products could create the requested gamma value (1.8), but none could produce a white point of less than 1 ΔE from the requested white point (D50). However, three of the products were less than 2 ΔE from the requested white point, which was considered very good and two products produced a ΔE less than 3, which was considered to be likely to produce good results.

This proves that present colour management software handles LCD reasonably well.

4.3 Conclusions on display measurements

In many ways LCDs are superior to CRT monitors in terms of colour imaging. However, high-quality monitors, both CRTs and LCDs, often perform very well by default and this is sufficient in many applications. The demands are high, however, when the monitor is to accomplish certain requirements, such as those set by standard values. This is where the LCD, expected to fulfil a duty as a colour fidelity device in media production workflows, comes across obstacles:

**Calibration:** in spite of the manufacturers' claim, the LCD is hard to calibrate correctly; both in terms of correct (desired) white point and black point, whose temperature often increases when the input level approaches the black point level.

**Characterisation:** the characterisation criteria are mainly the convergence of the primary chromaticities at lower digital input levels and the non-proportionality characteristics of the primaries, the differently shaped electro-optical curve and the lack of additivity. These criteria, related to the fundamental structure of the LCD, make the LCDs hard to characterise in a satisfactory way, even by the general methods used in LCD ICC profiling software.

These characteristics, related to fundamental aspects of the performance of monitors, are the reason why there is as yet no characterisation method that works correctly. Since CRT monitors have characteristics, which are different from those of LCD, solutions and software intended for CRTs are not linearly applicable on LCDs and do not yield the same results. However, some current ICC software [Sharma and Fleming 2003] handles LCD characterisation reasonably well yielding satisfactory results.
4.3  CONCLUSIONS ON DISPLAY MEASUREMENTS

Perceptually, it is mainly the viewing angle that may cause problems in colour reproduction. The level of chromaticity and luminance varies with the viewing angle, depending on primary colour. At present, some high-quality LCDs give reasonably good results until a viewing angle of 30°.

Apart from the problems related to colour reproduction of the LCD mentioned above, this work has shown that, at present there are LCDs with very good colour rendering, converging very little even at low digital input levels (comparable to CRT monitors), and that the rendering of blue and midtone colours has improved.

However, the examined displays diverged in some important aspects (temperature, additivity, uniformity etc) from the claims asserted by the display manufacturers by yielding less accurate results.
CHAPTER 5

Soft proofing - degree of accuracy

A perceptual experiment of how skilled users perceived printed images compared to soft copy images proofed on LCD and CRT displays, is presented in this chapter. It establishes how well perceptually present colour management software handles different display technologies, in relation to observers skilled in graphic arts. Currently displays match prints reasonably well in controlled conditions.
5.1 Images reproduction on displays

The ability to accomplish requested consistent colour fidelity over time could be considered as the aim for media (prepress and press related) companies. This goal is boosted by the utilisation of colour management systems: the use of appropriate hardware, software, and methodology to control and adjust colour in an imaging system [Giorgianni and Madden 1998]. A colour management system does not necessarily imply standardised device independent colour encoding as the best solution to achieve colour fidelity. A closed-loop system may be more efficient and of higher quality by particular definitions for materials and devices. However, recently the traditional methods of reproducing colours have been augmented with digitalised methods, entailing customers with higher demands of quality, rate and flexibility, make necessary versatile and remote image processing.

Due to this development, the ability to match colour images displayed on monitors to the images produced when the same digital file is rendered by a printing system is of increasing importance in the graphic arts industry.

There are three types of matching for images and graphics: spectral (invariant), colorimetric (conditional) and colour appearance (conditional with different viewing and illuminating conditions). The first two apply when matching colours in similar media and/or when the conditions are identical. The third type of matching, colour appearance matching, applies to the use of dissimilar media viewed under different conditions. The vast majority of colour matches are conditional, which implies that the reproduction is not a duplicate, i.e. the world is not made up of three emitting beams or four printing inks, but a representation of the object that has been produced. There are two cases where spectral matches can be achieved. The first is the quite recent interest in matching the spectral properties of the original objects, notably artwork [Berns et al. 1999]. This requires imaging techniques of numerous channels or planes of data corresponding to each wavelength within the visible spectrum, resulting in spectral images rather than the usual trichromatic (rgb or cmy) images created using conventional and digital imaging. The second is colour proofing, which simulates the (conventional) printed product. The colours of the colour-proofing device are engineered to match the spectral properties of the printed product as closely as possible. The proof is just to verify various aspects of the printing process and to provide a colour standard agreed upon between the customer and printer.

The third type of matching mentioned in the beginning of this paragraph, called colour appearance matching, applies when viewing conditions differ, e.g. when a monitor with uncorrected white point (CCT between 4000-10000K) is compared to a print, under fluorescent illumination of 4000K, both spectrum and amount of
illuminantion differ between the media. Then a model of colour appearance predicts colour names for stimuli viewed under various conditions, illuminations and viewing [Berns 2000]. For more detail see Chapter 2: Theoretical background. Colour appearance models are useful when acceptable colour matches are demanded.

To obtain a successful match between soft and hard copy, a number of issues have to be taken into consideration. Given that this match is metameric, described in Chapter 2: Theoretical background, each medium using different colorants and substrates, a single condition has to be defined. The advantages of having an invariant colour standard are numerous. Even though standardised adjustments (Chapter 2: Theoretical background), issued by authorised organisations, e.g. CIE, ICC, ISO, NPES, are employed along with high-quality devices, it is not uncomplicated to obtain a true match because of the limitations imposed by the accuracy of the colour management system. The system throughput is dependent on manufacturer, technology and conditions of the hard and software used, e.g. the monitors, printers, presses, ICC-profiles, as well as environmental conditions and standardisation of equipment.

5.1.1 Perceptual experiment

To measure the agreement of the various parts of a colour management system, a perceptual experiment between soft and hard copy matches of different media devices was carried out. The aim of the experiment was threefold: to evaluate the level of matching, to discuss the impact of different colour reproduction characteristics, such as displays, printing techniques, papers, colour image content and profiles, and to base it on the preferences of observers. This includes:

- the level of ability of a monitor device to correctly match a hard copy print,
- the differences in reproduction between LCD and CRT displays,
- the different impact on matching ability depending on paper quality (coated and newsprint)
- the different impact on matching ability depending on printing method (offset, digital)
- the impact of software (ICC profiling program, image processing program)
- the impact of image content (details versus areas, memory colours, GUI versus photographs)
- the preferences of observers versus instrument measuring.

The experiment was intended to determine the general level of soft proofing, the expected perceptual resemblance between a display and a print. The main interest was to study the ability of LCDs to replace the CRT monitor for soft proofing.
Naturally different premises generate different levels of resemblance. A perfect match between displays and print is not expected, as discussed above. However, with developments in all areas (hardware and software technologies, methodology) of colour image production, the resemblance and utilisation is becoming more sophisticated.

5.1.1.1 Experimental methods

Six ISO and Standard High Precision Pictures (SHIPP) standard images with varying content were printed as references by two printing presses on two different paper qualities. Two desktop monitors a CRT and a LCD reproduced the soft copy images. The equipment was set-up in a room, specially made for image comparisons, following the standards of ISO TC130 WD 12646.5. 13 subjects skilled in graphic arts participated in the experiment.

5.1.1.1.1 Test images

Six pictorial images were used in this experiment. They were chosen to represent as wide a viewpoint of significant attributes for subjective evaluation as possible. The images were selected from the JIS XYZ/Standard Colour Image Data (SCID) and Standard High Precision Pictures (SHIPP) XYZ/SCID collections of high-resolution standard pictures, standard colour image data given by ISO/JIS - SCID [Sakamoto and Urabe 1997]. They are shown in Figure 49.

![Figure 49](image_url)

The six pictorial images used in the experiments, described above: Flower, Fishing tools, Harbour, Girl, Bottles and Wool. (Shown here in low resolution). These are standard images and can be find at www.iso.org.

The first two images, denoted as “Flowers” and “Fishing tools” provide both textured and smooth areas, the images are more and less saturated, and contain blue and brown tone reproduction for the observer to examine.

The third image denoted “Harbour” includes, as the title suggest, an outdoor scene with a great deal of fine details and structures as well as a blue sky suitable to check device registration accuracy and tone jumps.

The fourth image “Girl” is a close-up portrait suitable for the assessment of skin tone and green area reproduction.

The fifth image denoted “Bottles” is suited for the evaluation of tone reproduction of greys as well as lustrous appearance of metallic objects.
5.1 · IMAGE REPRODUCTION ON DISPLAYS

The last image denoted “Wool” includes highly saturated coloured products and has a large colour gamut suitable for evaluation of colour reproduction in general.

The six selected stimuli images were printed with three different set-ups, using three different printing press techniques and two different papers, giving a total of 18 images to be used in the experiment.

One pair of the images, denoted “Digital”, was printed on Silverblade 130g matte coated paper on a Xeikon DCP 50D (CMYK) digital printing press at a resolution of 150 lpi. The other pair of images denoted “Offset”, were printed on Silverblade 130g matte coated paper on a Solna 425 Offset Press (KCMY) at a resolution of 170 lpi. The third pair of images denoted as “Newspaper” were printed on a Koenig & Bauer offset press (CMYK) on 45 g matte newspaper paper at a resolution of 85 lpi.

The soft and hard copy images were of a size of 20x15 cm and had an extra 5 mm white border and were presented surrounded by a uniform grey background with 20% of the luminance of the reference white (paper white and monitor white). The grey background, used for the hard copies, was made of cardboard and had the same physical size as the CRT and LCD monitors.

5.1.1.1.2 Configuration and viewing environment

The experiment was conducted in a specialised room designed for cross-media image comparisons. This room is designed with neutral paint and curtains to control the state of adaptation and minimise flare and reflectance from monitors and light sources. The light sources are assembled above a grey table, i.e. a viewing table, specialised for image comparisons. The experiment follows the guidelines of the ISO TC130 WD 12646.5 The ambient illumination of the room consisted of high frequency fluorescent tubes configured with CIE illuminant D50 to control the correlated colour temperature and the luminance level.

5.1.1.1.3 Soft copy characteristics

The monitors were calibrated to a temperature of D50. The luminance level of the CRT monitor was set at high level, approximately 100 cd/m² and the LCD luminance level was varied between high level, approximately 220 cd/m² referred to as L_{high} and at approximately 40% of the maximum luminance level, 100 cd/m² (referred to as L_{low}). The first experiment was performed using a Radius CRT display, controlled by a Macintosh G3, to allow a reference as a device that has been used for colour reproduction in graphic arts industry. The experiment was then repeated on a TFT-LCD Apple Studio Display controlled by a Macintosh Cube. The CRT was of the size 17” and the LCD of 15” to accomplish equal viewing size. The contrast ratio and colour still depend on viewing angle and uniformity. This was not an issue in this test, since the experiments were
conducted perpendicular to the monitor and the image was displayed centred on the monitor.

5.1.1.1.4 Soft copy characterisation
The performance of the monitors has been checked in previous experiments (more information can be received from the author), and was deemed adequate. (The characterisation of the CRT was made by a GOG-model (further described in Chapter 4: *What the ICC profile does*) and the characterisation of the LCD was made by a LUT-model [Fairchild and Wyble 1998b]. The characterisation performance for the CRT and LCD was 0.26 (1.07) mean (max) ΔE and 1.03 (1.72) ΔE, respectively and based on 27 sample steps of each channel.

5.1.1.1.5 Hard copy characterisation
The printing presses were adjusted to their optimal settings. Characterisation of the Xeikon digital press and the Solna offset press was (after making films and plates for the offset press) made by printing 430 colour patches at each press. The ICC-profiles were made by tetrahedral interpolating technique. In order to make sure that the gamut of the selected images was within the gamut of the printing presses, the images were transferred from the Lab space to the CMYK space of the printers using the ICC-profiles. The CMYK values were then converted back by the reverse ICC-profile. The images printed on newsprint were printed at one of the largest newspaper companies in Sweden. For these images an ICC-profile provided by the newspaper company was used. Performance of the press characterisation was for the Digital press 1.06 (4.09) mean (max) ΔE and the Solna Offset press 0.72 (2.37) ΔE.

5.1.1.1.6 Observer criterion and psychophysical methods
The threshold method was category scaling [Engeldrum 2000]. This method seems most appropriate when the correspondence or non-correspondence between the images is of interest. Before the test started the subjects had time to adapt to the viewing conditions of the room for some minutes. The subjects were then asked to judge how well the soft copy image resembled the hard copy image. The image quality was assigned a five-category qualitative scale. This method relies on the subjective judgement of the observer, but it is suitable in this experiment because it is the way proofing of images is done. The qualitative scale was defined from 1 to 5, where 1 defines *no matching resemblance*, 2-4 define increasing levels of resemblance and 5 defines *total matching resemblance*, between the test images. In the presentation of the results this scale is expressed in percentage, where 5 is hundred percent. There were thirteen subjects, aged 23-50 with normal colour vision and professionals in graphic arts, ten of the observers work with colour reproduction of soft and/or hard copy colour image reproduction.
The correlation between the subjects’ judgements, shown as mean and standard deviation, was for the CRT 0.70 and 0.07, and for the LCD 0.64 and 0.13, respectively. One deviant subject caused the lower correlation for the LCD. (If the data of the subject were removed, the correlation would be the same as for the CRT). The performance of this method was deemed adequate.

Simultaneous binocular matching technique was used [Braun and Fairchild 1997], Figure 50. The test images were first shown on the CRT and compared with the hard copies. The experiment was then repeated on the LCD. The subject was allowed to move the hardcopy, which was placed in front of a cardboard placed on an easel, vertically alongside with the monitor, if preferred. The images were displayed in the centre of the display in random order. Besides the task of categorising the images on the qualitative scale, the subjects were asked to comment on the reason if they disapproved the correspondence of the matches. No time restriction was placed on the observer and each experiment matching took approximately 25 minutes.

![Image of experimental set-up](image)

**Figure 50.** Experimental set-up: The monitors were positioned on the table, horizontally from each other. The two viewing areas consisted of one monitor displaying the soft copy and an easel where the hard copy was placed. The area was shielded to avoid distracting influences from the surroundings by walls made of grey paper.

### 5.2 Results and discussion

Generally, images reproduced on a CRT give better correspondence with the hard copy images, than a LCD according to the subjects. However, if the luminance of the LCD is reduced to a level equal with the CRT monitor, approximately 100 cd/m², the correspondence for coated paper quality increases. The opposite is true for the lower paper quality. The print technique chosen has no noticeable influence of the matching resemblances.

When matching is performed with coated paper qualities exclusively, matching resemblance for CRTs is approximately 80%, Figure 51. For LCDs, with maximum luminance, the resemblance for coated papers is between 65-70%. 

When the luminance level is reduced on the LCD, the matching resemblance increases to approximately 75%. For images printed on coated papers in a digital press, the decrease in display luminance means an increase in the matching resemblance of 10%.

![Graph showing matching resemblance of monitors and paper qualities](image)

**Figure 51.** The ability of monitors to match different paper qualities and printing techniques.

Coated paper qualities printed with a digital printing method produced the highest matching resemblances, approximately 80%, with similar performances for CRT and LCD\(_\text{low}\), Figure 51. Images printed by offset resembled a few percentages less than images printed by digital press, but for LCDs with higher luminance, the tables are turned. With lowered luminance on the LCD, the colour correspondence between hard and soft copies tends to increase for images printed on coated paper, especially for images printed by digital printing. However, for images printed on newsprint the situation is the reverse; the resemblance between hard and soft copies tends to be greater, by approximately 5%, if the luminance of the LCD is set to full power, Figure 51. The matching resemblance for images printed on newsprint is approximately 40% on the CRT and LCD\(_\text{high}\), the results slightly more diverging for the displays than the match between the coated paper qualities, Figure 51. It was expected, however, that images printed on newsprint would yield the lowest matching level. This is caused by the inability of hardware and software technologies to resemble low quality prints, above all the resolution and luminance.

The matching conception divergence of the subjects was less on the newsprint quality than for the other paper qualities. Most likely; in comparison with the images printed on coated paper, the newsprint images appeared as of really inferior quality, generating a uniform low rating. If the experiment had been
conducted simply on images printed on newsprint, the results would probably have diverged to a higher extent.

Coated paper showed approximately equal matching resemblance, as shown in Figure 51. Digital printing methods had higher matching resemblance than the images printed in offset, both on the CRT and the LCD (LCD_low), in spite of the higher resolution of the offset printing method. A reason for this could be the ability of display technology to blur the sharpness of prints, to some extent concurrent with the inability of the profile software to correctly calculate differences in resolution, lightness and chroma. However, coated paper qualities yield satisfactorily resembling matching regardless of printing method.

As for image content, all images received similar values; though the “wool”-image got the highest value of matching resemblance and the “girl”-image the lowest, suggesting that acceptability of images is to some extent content dependent [Song and Luo 2001], e.g. skin tones. The only exception, concerning the monitor reproduction, was the “bottle”-image that obtained higher resemblance values on the LCD_high than the LCD_low, Figure 52, which could be caused by perceptually better grey levels at high luminance.

![Figure 52](image)

**Figure 52.** The correspondence of image content in relation to the image reproduction on different monitors and set-up.

There is no clear indication that medium contrast images were regarded as specifically more bluish, referring to the LCD’s tendencies to display bluish reproduction at lower code value, discussed in Chapter 4. However, both CRT and LCD monitors are considered to reproduce images that appear “colder” than the same hard copies, according to the subjects. Concerning LCDs, to some extent this can be related to monitor temperature. The Apple LCD used in the experiment
seemed to have a tendency to strive for the default temperature of 6500K, discussed further in Chapter 4: Source and gate driver issues. As well as being "colder", the LCD has a tendency to produce darker soft copy images, compared to the same printed images. When the display luminance is reduced, this tendency decreases. Proper account must be taken of the fact that the light from a nearly dark state grey levels contains contributions from three additional dark sub pixels of the primaries. To achieve good results it is necessary to reduce the allowed dynamic range of the luminance. Alternatively, automatic colour correction can be obtained by changing the pixel data within the display drive electronics. In some cases the chromaticity shift from the white point can become significant at a pixel luminance of about 20% of the maximum, but in others at a luminance as low as about 1%. [Wright et al. 2000] In reproduced images it is important to maintain achromatic greys.

The general conception of the subjects, in the comparison between soft and hard copy images, was that the colours of the displayed images were purer and crisper than the hard copies, yielding superior sharpness of the soft copy images. Also the chroma was increased in the soft copies compared to the hard copies, as well as the brightness in the images displayed on the LCD_high. To summarise, the impression of the experimental comparison of matching resemblance between hard copy and soft copy images, the soft copy images feel too good compared to hard copies. Since the colourfulness of the display increases with luminance [Gibson et al. 2000b], a reduction of the LCD luminance will resulted in higher resemblance to a printed image.

5.3 Conclusion of colour reproduction on displays

Displays have much higher contrast ratios with a larger number of luminance levels than do prints. Under some conditions, e.g. when proofing newsprint images, this is clearly discernable. CRT monitors are still the display devices that achieve the highest matching correspondence between soft and hard copy images. However, the TFT LCD is not far behind and offers displays with an image quality that is superior to CRT in many ways. The colour quality of present LCDs is sufficient for most colour applications, especially if the luminance is reduced. As electronic commerce increases with decreased use of paper prints, increased demands will be placed on the colour quality of displays. To gain full benefit from the high image quality achievable with both CRT and LCD, improved colour characterisation and specification is needed, especially when low quality paper, such as newsprint, is being proofed.
Summary and conclusions

By three methods we learn wisdom: First, by reflection, which is the noblest; second, by imitation, which is the easiest; and third, by experience, which is the bitterest.

- Confucius (around 551-479 B.C.)

This thesis investigates some aspects of techniques for management of print production processes of low quality paper products. Specifically, mechanisms and methods concerning the use of soft proofing as the control of colour is investigated as well as other colour control factors. Furthermore, LCD and CRT displays are studied fundamentally and perceptually, with regard to colour reproduction. This chapter summarises the contributions put forward and attempts to draw conclusions from the results obtained.
6.1 Summary of research contributions

Here a summary of the result and the contribution of this work are presented. More detailed accounts are found in the respective chapters as indicated.

6.1.1 Evaluation and presentation of the colour process

In Chapter 3 three different print production processes are investigated and analysed through case studies of real-time processes at companies producing products on low quality papers; newspapers, journals and advertisements. Chapter 3 provides an overview of these processes in respect to the handling and control of the colour data.

Even though the processes investigated produce different products the results show that the main approach of handling and control of colour could be generalised. Colour management is not new in graphic arts, although it is constantly developed. It takes time and money to keep up with the technological progress and time and money are not always available. However, it still seems to be an opinion among process operators and managers that colour management tools themselves will perform miracles. Within premedia and print workflows, consistent colour fidelity is based on the experience with the capabilities of the colour management systems and the equipment. This might be an obvious reflection, but there is a surprising lack of standard procedures and control equipment or knowledge of correct utilisation of these.

However, the lack of above mentioned factors in the delineated workflows is not significant and has no severe influence on the colour output in such workflows, but affects the possibility for maximum throughput and minimum operator interference, as well as time and material costs. Some of the colour-related bottlenecks are presented below.

6.1.2 Bottleneck detection and efficiency strategies

Further investigation and analysis is carried out in Chapter 3 of the processes addressed and concerns specific aspects and factors regarding the colour management. The use of standard methods, colour management systems, colour control methods and equipment is presented and discussed, with regard to the colour quality on the way from customer to printing. There are colour data transfer bottlenecks in the automation, due to inadequacies imposed by man and/or machine. This means that manual involvement may be required or the colour information will possibly be severely changed. Efficiency strategies are presented.
Bottlenecks

1. Incorrect colour attributes: Many colour problems are caused by the advertising customers through the ad materials.
2. Inaccurate ICC profiles: The profile does not define the paper quality and white point. It is not uncommon in the described workflows that one ICC profile is used for many different paper qualities. And/or the profile is not redefined for a long time.
3. Uncalibrated and uncharacterised equipment: the colour fidelity can only be as good as the measurement process employed in the calibration and characterisation.
4. Non-standardised ambient illumination: Colour controls in print production are largely dependent on visual judgements. With non-standardised illuminants these judgements will be inconsistent.
5. Discrepancies between software: Can cause problems for consistent colour fidelity; older programme versions might not support colour management, freeware and full version may have different colour engines. Furthermore, exchange of characterisation data is limited by restrictions in document and image formats.
6. Variation of printed colour despite being within a standard: Printed colour can vary greatly even if the colour is printed within a standard. This can cause problems if the customer is not satisfied. The colorants in the ads are within the tolerance recommendation, proving that the newspaper company has printed a correct ad, but the customer visually gets quite a different ad compared to the original.

Efficiency strategies

1. Guidelines made available on the Internet for customers to set their document colour attributes as required for the print workflow. Surprisingly often these guidelines and methods are not optimally utilised by the companies. Customer-induced colour inadequacies can also be reduced by offering of support to customers by employees assigned for this purpose.
2. Obtain necessary knowledge in profile colour management; create routine procedures for the use of profiles and updates.
3. Create routine procedures for calibration and characterisation of equipment, preferably assigned to one person responsible for calibration and characterisation in parts or in hole.
4. Create routine procedures etc, as in item 3.
5. Learn by knowledge and experience or modernise equipment.
6. Be aware of the problem. Present a printed colour guide e.g. Färgguiden [TU 2003c] to the customer when the ad space in the paper is ordered. Then the customer will be aware of the reproduced colour quality of low paper qualities.
The strategies presented above might seem obvious, but surprisingly enough they are often neglected. These methods are quite easily implemented, but will increase automation and the colour consistency. Another way to increase colour fidelity, but that takes further effort to implement, is the use of soft proofing discussed in the next section.

### 6.1.3 Use of proofing

Particular interest is focused on the dependence of hard copy proofs in the print production processes in Chapter 3. The solutions presented favour the use of soft proofing, particularly employing flat panel displays.

Traditionally, hard copy proofs are considered to be of higher accuracy than soft proofs. However, the aim of the final product must be considered as well as the production process and the colour quality attainable, when choosing the method(s) of colour control. With respect to proofing, this means the choice of proofing method(s). Hard proofs are accurate if halftoning and ink of the final printing can be simulated. Such hard proofs are often costly, thus suitable for expensive print products. Hard proofs are also relevant as hard copy outputs but when colour fidelity is not an issue. However, in prepress hard copy proofs often function as a physical verification of the accuracy of the digital colour. In these cases hard proofs are mainly a psychological safety and a sign that the operator does not trust the colour management procedure or does not trust the equipment in the company’s prepress workflow. Such problems are connected to factors mentioned in the sections discussed earlier; the lack or shortcomings regarding knowledge and routine procedures concerning colour management. Hard copies are also often accompanying the digital file sent from the customer to the media company. In many cases this is due to the customer not trusting the content of the file to be correct, the media company requiring a copy because they do not trust the content of the file, or the customer being very concerned about the accuracy, wanting a hard proof as an assurance that the company print correctly. In rapid production workflows, as often the production processes of low quality papers, hard proofs have one main drawback; automation is prevented. By using soft proofing through web browsers the hard copies accompanying the digital files would not be necessary. Through the browser the customer can check the passed-for-press ad file and approve it or not for printing. This serves as an acceptance that the file is correct and as a receipt, hence reducing the need for any “just in case” hard copy proof.

Accurate colour soft proofing, e.g. where the display functions as a well calibrated and characterised tool for colour prediction, is as yet not much used in graphic arts production. Arguments against merely soft proofing concerns problems related to
halftoning and colour accuracy, factors seen as less reliable on a display than on a hard copy. Other important reasons are probably the rather high cost of high-quality CRT displays, that until recently have been the only display technology sufficient for accurate colour work, as well as colour inconsistency related to ambient illumination versus CRT display fundamentals. However, along with the development and declining prices of high-quality LCDs, which are (and will continue to be with further development of colour related issues which is discussed in Chapter 4) more suitable for the print production environment than CRT, further use of displays as a means of control of colour accuracy would be beneficial for colour consistency and process automation. This is especially true if the soft proof is used throughout the whole process, i.e. in prepress as well as in press, in-house and remotely. Workflows which would particularly benefit would be those producing products of higher colour variation tolerance levels such and repeatable printing productions, such as newspapers and magazines. Naturally new methods require a starting phase, but with knowledge and experience of the general problems that arise e.g. halftoning related problems, soft proofing will be more reliable than hard proofs in such process workflows.

Display technologies, among other technologies in graphic arts, still have insufficiencies when it comes to colour rendering. By knowledge of these inadequacies it is possible to make compensations. The fundamentals of display technologies are discussed below:

### 6.1.4 Evaluation of technical display characteristics

Displays suited for high-quality colour work have been evaluated in Chapter 4. Fundamental characteristics influencing the colour reproduction are presented for such displays in general and LCDs in particular.

In many ways desktop LCDs are superior to CRT monitors in terms of colour imaging. Higher colour consistency, contrast, crispness, brightness and less tendency of reflectivity. Other advantages are related to ergonomics and working environment aspects. Still they are not much used in graphic arts, partly due to prejudices and unawareness of the colour reproduction capability and partly due to new rather expensive device technology.

The lingering problems of the performance of LCDs are structural ones; the shape of the electro-optical transfer functions, the non-constancy of channel chromaticity, channel interactions and perceptual problems: the changes of output colour depending on viewing angle.
The structural problems affect calibration and characterisation. In spite of the manufacturers’ claims, the LCD is hard to get correctly calibrated; both in terms of correct (desired) white point and black point, as the temperature often increases when the input level approaches the black point level. The development of satisfactory working algorithms for characterisation and ICC profiles is made difficult by the convergence of the primary chromaticities at lower digital input levels, the non-proportional characteristics of the primaries, the differently shaped electro-optical curves and the lack of additivity (the magnitudes vary depending on LCD manufacturer).

Perceptually, it is mainly the viewing angle that may cause problems in colour reproduction. The level of chromaticity and luminance varies with the viewing angle, depending on primary colour. At present, some high-quality LCDs give reasonably good results for viewing angles of up to 30°.

These characteristics, related to fundamental aspects of the performance of monitors, are the reason why it is as yet not possible to fully utilise colour reproduction on LCDs. At present, colour management manufacturers and colour management system operators often use solutions and software intended for CRTs, which are not linearly applicable on LCDs and do not yield the same results. However, most current ICC software handles LCD characterisation reasonably well yielding satisfactory results.

Colour rendering on portable LCDs is connected with several limitations, and such displays are not suitable for colour work where high accuracy is needed. This is further discussed in Chapter 4.

Apart from the problems related to colour reproduction of the LCD mentioned above, this work has shown that, at present there are LCDs with very good colour fidelity, converging very little even at low digital input levels (comparable to CRT monitors), and that the rendering of blue and midtone colours has improved. However, the results show that the LCD characteristics often diverge from the manufacturers’ (optimistic) claims and that further development is needed before LCD become optimal for colour-critical work.

Perceptual aspects of the co-operation of display hardware and colour management software through a colour management system are presented in the following section.
6.1.5 Evaluation of perceptual display characteristics

Chapter 5 presented an experiment conducted to determine the level of correspondence that could be achieved through cross-media comparison between prints and displays, i.e. by soft proofing. The experiment determined the ability of hardware and software to cooperate through a colour management system. The level of correspondence was determined by observers, skilled in graphic arts.

Apart from the fundamental differences between prints and displays, which make complete correspondence impossible, it was of interest in the experiments presented in Chapter 5 to determine the ability of an LCD to reproduce colour images compared to that of a CRT display, with respect to human perception. As hard copy test material, coated and newsprint papers were used, printed on offset and digital presses. The results showed that for images on a coated paper quality the matching correspondence between hard and soft copy images was approximately equally high for the LCD and the CRT display, if the luminance level of the LCD was decreased to the level of the CRT, that is, to approximately 100 cd/m². In the matching correspondence between the newsprint quality and the displays the inability of the hardware and software to reproduce the lower paper quality characteristics is clearly discernable. Matches made with newsprint correspond at somewhat higher levels with the CRT than the LCD. However, in this case the LCD with increased luminance (approximately twice the CRT) achieves higher matching correspondence than the one with decreased luminance.

Proofs have a general inadequacy, presented and discussed in Chapter 3, in that the physical properties of low quality paper quality are harder to imitate than higher paper qualities. The colour quality of the hard copies used to resemble newsprint would never be accepted in a sheetfed printing production, but is considered satisfactory in proofs for low paper quality workflows. The results of the cross-media comparison, evaluated in Chapter 4, indicate that newsprint soft copies correspond only half as much as soft copies matched with higher paper qualities.

As for image content and proofing there was no indication that image content would affect the matching results in particular.

To gain full benefit from the high image quality achievable with both CRT and LCD, improved colour characterisation and specification is needed, especially when low quality paper, such as newsprint, is being proofed. At present the poor properties of newsprint appearance cannot be reconstructed completely on any proofing media.
6.2 Conclusions

In conjunction with the increasing digitalisation and automation of the graphic arts production workflow, there are increasing demands on colour management systems, methodology and devices, and not least on the users, who need to be able to reproduce and transfer colour data in a correct and stable way. The increasing digitalisation is not exclusively positive, but it puts demands on the increasing number of users who create their own originals to be printed. Those demands include knowledge of layout and colour software and calibration of hardware. Increasing digitalisation creates a need for high quality equipment, well established routines, which follow prevalent standards, and for qualified operators, since premedia and printing is increasingly done at geographical distance. It also means that companies working with colour premedia and printing workflows can, if taking advantage of the new technology, increase the control, consistency and stability of the material to be printed.

Taking advantage of new technology includes knowledge of the limitations of technical devices and systems. It also requires the right surroundings and adjustments in order to receive optimal reproduction conditions. “Right” surroundings and adjustments involve in most cases the use of standards, initiated for the media and graphic arts industry. Incorrect use of equipment will in most cases be noticeable both in the automation and stability of the production workflow as well as in the quality of the final product and number of necessary reprints. In some production workflows, especially where tolerance levels of colour variation are higher, lack of system adjustments might not be fatal for the final colour reproduction, but they will affect the automation of the production workflow (and the quality of the final product).

With the increasing digitalisation of graphic arts production, use of displays will be more and more important in the premedia and printing workflow, for image processing and in-house and remote proofing. At present LCDs are rarely used for essential colour reproduction work. The cost of LCDs has decreased during recent years, but uncertainty concerning the colour quality and stability of image reproduction is still a matter of consideration and causes hesitation in using thin displays in the graphic arts industry. However, LCDs are in many respects better than CRTs for colour reproduction, but it is a different technology that in some aspects requires different procedures and adjustments.

IT IS RARE THAT A COLOUR REPRODUCTION ACTUALLY MATCHES AN ORIGINAL OBJECT. FORTUNATELY, THE ORIGINAL OBJECT IS JUST AS RARELY AVAILABLE FOR COMPARISON.
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Appendix A

A.1 Display technology fundamentals

A.1.1 Basic colour fundamentals of CRT and LCD

Images seen on a colour display are built up as a grid of numbers known as pixels. There are three sets of numbers corresponding to red, green and blue display channels. The digital information is stored in a frame buffer. The numbers (digital counts) are usually expressed between 0 (no luminescence or light) and 255 (full luminescence or light) (i.e. \(2^8-1\) for a 8-bits channel system: 24 bits images), and are first redefined through a look-up table [Berns 2000].

A.1.1.1 CRT

For Cathode Ray Tube (CRT) displays, Figure A.1, the RGB numbers are converted to a video signal that varies in intensity in each of three (red, green, blue) electron beams inside the CRT. Before the video signals become input to the display tube, they are greatly amplified. Each amplified signal controls a grid inside the CRT that repels one of the three electron beams. If the beam is completely repelled, black results; if the grid does not repel the electron beam at all, the full primary colour results. The modulated electron beams are accelerated towards the front of the tube, where phosphors are coated onto the inside surface of the screen. As the electron beam strikes a phosphor, luminescent excitation and emission occur, resulting in the coloured light that we see, Figure A.2. [Berns 2000]

![Figure A.1. CRT monitor.](image1)

![Figure A.2. The modulated electron beams are accelerated towards the front of the tube, where phosphors are coated onto the inside surface of the screen, strikes a phosphor and emission occur.](image2)
A.1.1.2 LCD

The most common liquid crystal displays (LCDs) in use today rely on picture elements, or pixels, formed by liquid crystal (LC) cells that change the polarisation direction of light from the backlight passing through them in response to an electrical voltage. The active matrix driving method is used to produce a liquid-crystal image with such cells. In active-matrix LCDs (AMLCDs), a switching device and a storage capacitor are integrated at the each cross point of the electrodes, to drive the pixels. There are many kinds of AMLCDs. Most use transistors made of deposited thin films, which are therefore called thin-film transistors (TFTs). These films can be made of different materials.

The TFT LCD display basically contains two glass plates (one TFT and colour filter), polarisers, LCs and a backlight (consisting of one or more lamps), Figure A.3. More detailed the TFT array substrate contains the TFTs, storage capacitors, pixel electrodes, and interconnect wiring. The colour filter contains the black matrix and resin film containing three primary colour - red, green, and blue - dyes or pigments. The two glass substrates are assembled with a sealant, the gap between them is maintained by spacers, and LC material is injected into the gap between the substrates. Two sheets of polariser film are attached to the outer faces of the sandwich formed by the glass substrates. A set of bonding pads is fabricated on each end of the gate and data-signal bus-lines to attach LCD Driver IC (LDI) chips. [Avdeals 2003].

The TFT glass plate has as many TFTs as the number of pixels displayed. In a 15-inch monitor, this adds up to 1,024 times 768 times 3 equalling 2,359,296 sub pixels, each driven individually. Transistors or diodes are placed at each pixel, Figure A.4. The transistors, by generating its own individual voltage, which can vary widely, causes the liquid crystals in each sub pixel to move to a particular angle. The angle determines the quantity of light that passes through the sub pixel, which, in turn, determines the reproduction on the panel. The crystals’ actual purpose is to deflect light so that it can pass a polarised filter before striking the display. If the crystals are arranged in the same direction as the filter, the light will pass through. On the other hand, if they are arranged perpendicular to the filter, the panel will remain black.

![Figure A.3. and A.4. LCD technology architecture.](image-url)
Essentially, three different liquid-crystal technologies are used in TFTLCD monitors: TN + film, IPS and MVA, presented in the following sections. However, whatever technology is used, all LCDs obey the same fundamental principle.

A.1.2 TN technology

A couple of years ago the predominant LC cell configuration for high performance colour LCDs was twisted nematic technology (TN) [Silverstein and Fiske 1993]. Today this technique can be found in notebook computers due to the advantages of TN-mode design for such LC-displays. (This includes variations of TN-mode, such as twisted-nematic compensation film (TN+CF), twisted-nematic single and dual domain (TN+SD, TN+DD)).

Figure A.5. 'On': voltage is applied and the LC molecules align themselves in the direction of the electric field.

In the TN cell an entrance polariser linearly polarises entering light, and then the axis of polarisation is optically rotated by the LC layer. Depending on the optical characteristics desired, the twist angle varies, but typical rotation (twist) angles of TN LCDs are 90° or 180° [Scheffer and Nehrling 1990]. After optical rotation by the LC layer, the polarisation state of the light, exiting the LC layer, is analysed by the exit polariser or “analyser”, Figure A.5. There are two principle configurations of cell entrances and exit polarisers. One is LCDs that utilise crossed polarisers (normally-white mode) where off voltage results in a white or coloured pixel (which is composed by RGB filters) and on voltage, gives a black pixel. The other configuration is LCDs consisting of parallel polarisers (normally-black mode), which yield colours in the opposite way. [Silverstein and Fiske 1993]

Since TN-mode exhibit limitations for colour reproduction due to optimisations for other aspects, developments have been made.

A.1.3 IPS technology

Present high-quality desktop LCDs typically use the “In Plane Switching” (IPS) technology, which provides much better optical colour performance than previous designs. In IPS technology the rubbing alignment on both surfaces of the panels is parallel. This forces the LC molecules to align in one direction only, parallel to the rubbing alignment, Figure A.6. There is no twisted alignment of the molecules in the passive state of the IPS technology. The electrodes are placed on a single side of the panel and they can produce an electric field parallel to the panel surface, when voltage is applied. [Marcu et al. 2002a] When no electronic field is applied between the electrodes, the polarised light passes unchanged through the panel but
is impeded at the second polariser, resulting in opaqueness. When polarised light is applied, one of the components of the polarisation vector changes its polarisation with 180°, which is equivalent of a rotation of the polarised light with 90°, allowing the light to pass through the second polariser. In this state the panel is transparent. [Marcu et al 2002a]

![Figure A.6](image_url)

**Figure A.6.** If voltage is applied, the molecules align themselves parallel to the substrate.

### A.1.4 IPS technology compared to TN technology

In IPS-mode the LC-molecules are always oriented parallel to the surfaces of the panel (active, passive or intermediary position) yielding improved consistency in the optical performance with viewing angle. Therefore, IPS technology has a significant advantage over the TN technology in colour quality. However, both electrodes are on the same plane and the cell aperture is reduced. Hence, the efficiency of the panel is less than of the TN-mode panel and to achieve the same luminance the IPS technology would require significantly more power to drive the backlight(s). Also, the time response, switching the LCs from one alignment direction to another, is slower for IPS panels than for TN panels. [Marcu et al 2002a]

### A.1.5 Dual Domain technology

An improvement of colour performance for both TN and IPS panels can be achieved by a structure where each pixel RGB cell can be divided into two regions, dual domain technology, using a different alignment of the LC cells, Figure A.7. Dual domain can be achieved if the rubbing alignment has two directions on a single side for each RGB cell, giving the LC cell two regions (domains), with opposite twist. This structure provides improved symmetric optical response because whatever is lost during the twist in one domain of the LC cell, is compensated by the twist in the opposite direction in the other half of the cell. [Marcu et al. 2002a] A further improvement of this technology is Multi Domain Vertical Alignment (MVA).
Figure A.7. The sub pixel is divided into several regions in which the crystals are free to move, independently of their neighbours, in opposite directions.
A.2 Equipment and set up used for measurements

Particular equipment and set-up used for the measurements discussed in Chapter 4 are as follows:

Displays:
CRT Barco Calibrator Lire, 20”, 1844x1300 – www.barco.com
LCD Apple, 17”, 1280x1024 – www.apple.com
LCD Eizo CG21, 21”, 1600x1200 – www.eizo.com
Highest colour mode was used (32-bit)

Computers:
Power Mac G4 - 400 Mhz / IMChache /128SDRAM/20 G hard disk / VGA, OS 9.0.4
Power Mac G4 - double i,25Ghz processors/2MB SRAM/512 MB processor/ OS X 10.2.6

Software:
Graphic Converter PPC v 4.7.1, Graphic Converter v 4.4 Budel, PhotoShop 7, 11 1.1, ColorNavigator, BarcoCalibrator

Measuring Instruments:
Photo Research SpectroScan 750 – www.saven.se
Colorimeter Eye-One Colorimeter – Gretag Macbeth

All measurements were made in a dark room on 400x400 square colour samples placed in the centre of the screen, with the remainder of the screen set to black. The measurements were made perpendicular to the screen if not otherwise mentioned at a distance of approximately 0.5 m between the spectroradiometer and the monitor.

All the displays were calibrated to a temperature of D50, with gamma set to 1.8 and luminance to 80 cd/m² using the calibration software. Maximum resolution and full colour (16.7 million colours) mode were used for all displays.

All colorimetric coordinates were determined using the CIE 1931 Standard colorimetric observer of 2°.