

The Development of Multi-Channel Inkjet Printing
Methodologies for Fine Art Applications

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Abstract

This thesis contributes to the defence of the practitioner perspective as a means of undertaking problems addressed predominantly in the field of colour science. Whilst artists have been exploring the use of colour for centuries through their personal practice and education, the rise of industrialised printing processes has generated a shift in focus away from these creative pursuits and into the computational field of colour research. It is argued here that the disposition and knowledge generated by creative practice has significant value to offer developing technologies. While creative practice has limited influence in the development of colour printing, practitioners and users of technology actively engage with the process in ways that extend beyond its intended uses in order to overcome recognised shortcomings. Here consideration is given to this creative engagement as motivation to develop bespoke printing parameters that demonstrate the effects of colour mixing through methods alternative to standard workflows. The research is undertaken incorporating both qualitative and quantitative analysis, collecting data from visual assessments and by examining spectral measurements taken from printed output. Action research is employed to directly assess and act upon the constant developments in the art and science disciplines related to inkjet printing, observing and engaging with current methods and techniques employed by practitioners and developers. This method of research has strongly informed the empirical testing that has formed this thesis's contribution to fine art inkjet printing practice. The research follows a practitioner led approach to designing and testing alternative printing methods and is aimed at expanding the number of discernible colours an inkjet printer can reproduce. The application of this methodology is evidenced through demonstrative prints and a reproduction study undertaken at the National Gallery, London. The experimentation undertaken in partnership with the National Gallery has proven the ability to increase accuracy between colour measured from the original target and reproduction, beyond the capabilities of current inkjet printing workflows.

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Contents

Abstract.....	II
Acknowledgements	III
Contents.....	IV
List of Figures	VIII
List of Tables.....	XIII

Chapter 1. Introduction to Research and Methodological Approach

1.1. Chapter Overview	1
1.2. Definition of Research Area	2
1.2.1. Historical Influences on Colour Inkjet Printing	2
1.2.2. Summary of Digital Colour Managed Inkjet Printing Workflow	4
1.2.3. Introduction to the Limitations in Obtaining Colour Accuracy in an ICC Colour Managed Workflow	5
1.3. Statement of Research Aim and Objectives.....	7
1.4. The Context for My Undertaking of this Research	8
1.4.1. Background of the Centre for Fine Print Research and My Position Within It	8
1.4.2. Role Within CP7.0 Project	9
1.4.3. Working with the National Gallery, London	10
1.4.4. My Personal Disposition	11
1.5. Strategy for Investigation and Methodological Approaches	11
1.5.1. Overview of Strategy.....	11
1.5.2. Introduction to Scientific Inquiry through an Art's Perspective	12
1.5.3. Methods for Undertaking the Research.....	14
1.6. Overview of the Following Chapters.....	18

Chapter 2. Historical Baseline & Contemporary Context

2.1. Chapter Overview	20
2.2. Early Inquiry into the Understanding and Organisation of Colour	21
2.2.1. The Evolution of Colour Order Systems (for colour mixing)	22
2.2.2. How the Scientific Understanding of Colour Evolved (Colour Theory)	24
2.3. Modern Colour Measurement and Representation	26
2.3.1. Spectral Reflectance Acquisition	27
2.3.2. Colourimetry Standards and the Commission Internationale de l'Éclairage (CIE).....	29
2.4. Colour Difference Formulae	34

2.4.1. CIE Colour Difference Formulas	34
2.4.2. Calculation of Spectral Reflectance Differences using Root Mean Square (RMS) Errors.....	36
2.5. Chapter Summary	38
Chapter 3. The Current State of, and Practices in, Digital Printing	
3.1. Chapter Overview	39
3.2. Advancing Scientific Research in Inkjet Printing.....	39
3.2.1. The Limited Gamut of Paper.....	40
3.2.2. Extending Colour Gamut Boundaries with CMYK+ Inkjet Printing	42
3.2.3. Minimising Metamerism through Spectral Printing Workflows	45
3.2.4. Response to Advancing Colour Computation	49
3.3. Contemporary Context of Printing from an Arts Practitioner Perspective	51
3.3.1. Implementation of Digital Printing in Arts Practice.....	51
3.3.2. Adverse Effects of Prescribed Print Dialogues.....	52
3.3.3. Contemporary Art Practitioners Addressing These Limitations	53
Chapter 4. Development of Test Procedures	
4.1. Rationale for Chapter.....	58
4.2. Chapter Overview	59
4.3. Equipment & Consumables Specification.....	61
4.3.1. Imaging Software	61
4.3.2. Multi-Channel Inkjet Printers	62
4.3.3. Raster Image Processor (RIP) Software.....	64
4.3.4. Paper Selection	65
4.3.5. Measuring Devices.....	66
4.4. Development and Refinement of Direct Channel & Multiple Pass Printing Methods Using Colour Charts	68
4.4.1. Preliminary Evaluation Using a Colour Bar Chart.....	68
4.4.2. Further Investigation of Colour Order Effects Using the Colour Circle Chart	73
4.4.3. Generation of a Custom Ink Limit Chart	90
4.4.4. Standardising the Colourant Sequence	93
4.4.5. Unification of Findings into Culminating Maximum Variable "MAX" Colour Chart	95
4.5. Conclusion.....	107
Chapter 5. Application in Colour Reproduction: Secondment Work with the National Gallery, London	
5.1. Rationale for Addressing Colour Reproduction	110

5.2. Chapter Overview.....	111
5.3. Design of Experiment Parameters for Colour Matching.....	113
5.3.1. Measurement of Target Painting for Reference Colour	113
5.3.2 Collection of Data from Inkjet Printed Colour Charts	116
5.3.3. Comparison of Reference and Inkjet Printed Colours.....	118
5.4. Early Exploration of Colour Matching for Reproduction.....	118
5.4.1. Sampling of Dark Colourant Combinations Excluding Black	119
5.4.2. Sampling of Colourant Combinations Including Black	123
5.5. Advanced Testing Parameters for Colour Matching.....	129
5.5.1. Enhancing the Inkjet Printed Output with Varnish Coatings	130
5.5.2. Colour Match Testing Using Coated Colour Charts	134
5.6 Appraisal of Experimental Outcomes	142
Chapter 6. Demonstration of Findings through Creative Practice	
6.1. Rationale for Chapter.....	144
6.2. Chapter Overview	144
6.3. Early Exploration of Special Effects in Print	145
6.4. Development of a Standardised Design Template	150
6.5. Creation of Original Prints Implementing a Custom Design Template and Direct Channel / Multiple Pass Print Methods	153
6.6. Comparative Evaluation of Direct Channel / Multiple Pass Prints and Colour Managed Print Reproductions	161
6.7. Appraisal of Impact of the Printed Designs on Demonstrating Research Outcomes.....	165
Chapter 7. Conclusion	
7.1. Chapter Overview	167
7.2. Meeting Research Objectives	167
7.2.1. Identification of Limitations in Inkjet Printing Colour Management	167
7.2.2. Impact of Contemporary Digital Print Practitioners on Developed Methodology.....	168
7.2.3. Development of Direct Channel and Multiple Pass Printing Methods	168
7.2.4. Testing Print Method's Ability to Reproduce Colour from an Old Master Painting	169
7.2.5. Demonstrating Increased Colour Control in Fine Art Design and Print Applications	169
7.3. Appraisal of Findings	170
7.4. Impact of Research	170
7.5. Contribution to Knowledge.....	171

7.6. Areas for Further Research	171
7.7. Concluding Remarks	172
Bibliography.....	173
Appendix A. Glossary of Key Terms	
A.1. Terms Defined	182
Appendix B. Comparison of Canon iPF8400 and HP z3200 Printer Capabilities	
B.1. Transferability of Print Methods from the Canon to HP Printer	185
B.2. Comparison of Printable Hue and Chroma Range Using the Dark Colour Sample Set.....	186
Appendix C. Specification for Test Chart Compositions	
C.1. Design of the Colour Bar Chart (as appears in 4.4.1)	192
C.2. Design of the Three Layer / Six Colourant Colour Circle Chart (as appears in 4.4.2)	193
C.3. Design of the Ink Limit Chart (as appears in 4.4.3)	195
C.4. Design of a Permutation Test Chart (as appears in 4.4.4)	200
C.5. Design of the Maximum Variable "MAX" Colour Chart (as appears in 4.4.5)	202
C.6. Design of the Dark Colour Test Chart (as appears in 5.4.1).....	208
C.7. Design of the Colourful Blacks Test Chart (as appears in 5.4.2).....	210
C.8. Design of the Varnish Coating Tests (as appears in 5.5.1).....	212
Appendix D. Supplemental Colour Data for Select Experimental Outcomes	
D.1. Colour Data for the Colour Circle Chart.....	214
D.2. Graphed Colour Reproduction Experimental Results	224

List of Figures

Figure 1.1. Venn diagram illustrating the distinct areas of my research.....	8
Figure 1.2. Diagram showing the cyclical nature of action research.....	15
Figure 1.3. Illustration of A.D. de Groot's Empirical Cycle	17
Figure 2.1. Illustration of G.J. Chamberlin and D.G. Chamberlin's probable sensitivity curves for human vision	26
Figure 2.2. Illustration depicting Maxwell's Colour Triangle.....	30
Figure 2.3. Illustration depicting the CIE Spectrum Locus.....	30
Figure 2.4. Illustration depicting the XYZ coordinates drawn to encompass the spectrum locus and the transition into a readable scale	31
Figure 2.5. Illustration depicting the CIELAB Colour Space.....	33
Figure 3.1. Illustration of Ostromoukhov's 7 colour, 6 subgamut division.....	43
Figure 3.2. Illustration of Boll's 7 colour, 6 subgamut division.....	44
Figure 3.3. Illustration of Mahy and Verbeek's 6 colour, 3 subgamut division.....	45
Figure 4.1. Microscopic image capture of printed yellow outputs using colour management and direct channel capabilities	65
Figure 4.2. Scan of the Colour Bar Chart.....	70
Figure 4.3. Scanned section of the Colour Bar Chart with diagrams showing colourant orders.....	71
Figure 4.4. Enlarged section of the scanned Colour Bar Chart showing all colour created with black as the base layer.....	72
Figure 4.5. Scan of page one of the Colour Circle Chart.....	75
Figure 4.6. Scan of page two of the Colour Circle Chart.....	76
Figure 4.7. Scanned colour patches and spectral reflectance curves for each ink colourant printed as one, two, and three layers.....	78
Figure 4.8. Scanned colour patches and spectral reflectance curves comparing the colour generated by printing layers of green and darkening the green by printing percentages of black.....	79
Figure 4.9. Measurements of ink colourants printed as one, two, and three layers plotted on the Lab a* b* axes	81
Figure 4.10. Measurements of the -MG-, GGM, and MGG printed patches plotted on the Lab a* b* axes	83
Figure 4.11. Measurements of all two colourant combination variations plotted on the Lab a* b* axes	85
Figure 4.12. Measurements of all three colourant combination variations plotted on the Lab a* b* axes	86
Figure 4.13. Illustration of all DC/MP colour patch measurements from the Colour Circle Chart plotted in Lab colour space alongside a wire frame representing the comparative colour profile's gamut.....	88

Figure 4.14. Distribution of calculated dE2000 between measured DC/MP print patches of the Colour Circle Chart and the colour profile's gamut.....	88
Figure 4.15. Scan of Custom Ink Limit Chart printed using the direct channel, single pass (DC/SP) method.....	91
Figure 4.16. Scan of Custom Ink Limit Chart printed using direct channel, multiple pass (DC/MP) printing methods.....	92
Figure 4.17. Scanned samples from the colourant permutations test	94
Figure 4.18. Scanned print output from YBRMCG colourant sequence step wedge test with gradated transitions, and with 0 to 100% coverage gradation.....	94
Figure 4.19. Scanned print output from YBRMCG colourant sequence hexagon test	95
Figure 4.20. Scan of the MAX Colour Chart printed using DC/SP methods.....	98
Figure 4.21. Scan of the MAX Colour Chart printed using DC/MP printing methods	98
Figure 4.22. Selection of BMCG combination patches demonstrating the increased range of colour Lightness values achieved with DC/MP printing	99
Figure 4.23. Scanned colour patches and spectral reflectance curves comparing the colour generated by printing combinations of yellow and green with both DC/SP and DC/MP methods	100
Figure 4.24. Scanned colour patches and spectral reflectance curves comparing the colour generated by printing MCG colourant combinations with both DC/SP and DC/MP methods	101
Figure 4.25. Measurements of the DC/MP and DC/SP printed patches from the MAX Colour Chart	102
Figure 4.26. Illustration of all DC/MP colour patch measurements from the MAX Colour Chart plotted in Lab colour space alongside a wire frame representing the comparative colour profile's gamut.....	103
Figure 4.27. Distribution of calculated dE2000 between measured DC/MP print patches of the MAX Colour Chart and the colour profile's gamut	104
Figure 4.28. Distribution of reduced patch set's calculated dE2000 differences with comparison to the MAX Colour Chart's original 2,840 patches	107
Figure 5.1. Michelangelo Merisi da Caravaggio, <i>The Supper at Emmaus</i> , 1601, Oil and tempera on canvas, 141 x 196.2 cm, National Gallery London, NG172. (© The National Gallery, London)	114
Figure 5.2. Nineteen white dots indicating the location each colour measurement was taken from Michelangelo Merisi da Caravaggio, <i>The Supper at Emmaus</i> , 1601, Oil and tempera on canvas, 141 x 196.2 cm, National Gallery London, NG172. (© The National Gallery, London)	116
Figure 5.3. Scan of the six page Dark Colour Sampling Chart.....	120
Figure 5.4. Solid colour patches representing the nineteen painting reference colours and the colour matching results from the Dark Colour Sampling Chart	121
Figure 5.5. Spectral reflectance curves (SRCs) of painting reference sample 14, plotted alongside the lowest RMS results from the DC/MP printed Dark Colour Sampling Chart.....	122

Figure 5.6. SRCs of painting reference samples 2, 8, and 17, plotted alongside the lowest RMS results from the DC/MP printed Dark Colour Sampling Chart	123
Figure 5.7. Scan of the three page Colourful Blacks Sampling Chart	125
Figure 5.8. Solid colour patches representing the nineteen painting reference colours (top row) and the colour matching results from the Colourful Blacks Sampling Chart (bottom row)	126
Figure 5.9. SRCs of painting reference samples 2, 8, and 17, plotted alongside the lowest RMS results from the DC/MP printed Dark Colour and Colourful Blacks Sampling Charts	126
Figure 5.10. Plotted SRCs of the varnish coating trials using one, two, and three layers of black ink printed on Somerset Satin Enhanced paper.....	133
Figure 5.11. Plotted SRCs of the varnish coating trials using one, two, and three layers of black ink printed on Somerset Velvet Enhanced paper	134
Figure 5.12. SRCs of painting reference samples 2, 8, and 17, plotted alongside the lowest RMS results from the DC/MP printed Dark Colour, Colourful Blacks, and all varnish coated Sampling Charts	137
Figure 5.13. Solid colour patches representing the nineteen painting reference colours (top row) and the colour matching results from the coated colour sampling charts (bottom row)	138
Figure 5.14. SRCs of painting reference samples 2, 8, and 17, plotted alongside the lowest RMS results from the varnish coated DC/MP printed Sampling Charts and the SRCs of the colour managed reproductions.....	141
Figure 5.15. SRCs of painting reference sample 15, plotted alongside the lowest RMS results from the varnish coated DC/MP printed Sampling Charts and the SRCs of the colour managed reproductions	142
Figure 6.1. Screen capture of image file for the ‘gnome’ design	147
Figure 6.2. Two photographs of the ‘gnome’ print, each illuminated from a different angle	147
Figure 6.3. Two layers of the “Pay Close Attention” print file	148
Figure 6.4. Photograph of the “Pay Close Attention” print showing the bronzing effect and its appearance change as a result of illumination angle	149
Figure 6.5. Screen captures of the CMYK and RGB values compared to the custom Lab values used in template document	151
Figure 6.6. Screen capture of design template document	152
Figure 6.7. Screen capture of design template document	152
Figure 6.8. Screen capture of the blending mode settings	153
Figure 6.9. Screen capture of wave design file	154
Figure 6.10. Screen capture of wheat design file.....	155
Figure 6.11. Photograph of the Canon iPF8000 printer in action.....	156
Figure 6.12. Individual layers of wave design	156
Figure 6.13. Individual layers of wheat design	157

Figure 6.14. Scan of wave design print	158
Figure 6.15. Scan of wheat design print.....	159
Figure 6.16. Scan of printed colour swatches for each of the seven ink colourants....	161
Figure 6.17. Detail of wave print scans showing the topmost portion of wave pattern	162
Figure 6.18. Detail of the wave print scans showing the bottom portion of the design	163
Figure 6.19. Scan of wheat design printed as a colour managed reproduction.....	164
Figure 6.20. Two photographs of the DC/MP 'wheat' print, each illuminated from a different angle	165
Figure B.1. Scanned samples from the colourant Permutations Test printed with the HP z3200.....	186
Figure B.2. Illustration of the Dark Colour Sampling Chart's colour gamut from the Canon iPF8400 printer.....	186
Figure B.3. Illustration of the Dark Colour Sampling Chart's colour gamut from the HP z3200 printer.....	186
Figure B.4. Median hues from the HP and Canon printed Dark Colour Sampling Chart indicating at the corresponding hue angle on an illustrated hue circle	188
Figure B.5. Scanned DC/MP printed Dark Colour Sampling Chart, rows 1-52 from the Canon iPF8400	189
Figure B.6. Scanned DC/MP printed Dark Colour Sampling Chart, rows 1-52 from the HP z3200	189
Figure B.7. Scanned DC/MP printed Dark Colour Sampling Chart, rows 53-104 from the Canon iPF8400	190
Figure B.8. Scanned DC/MP printed Dark Colour Sampling Chart, rows 53-104 from the HP z3200	190
Figure B.9. Scanned DC/MP printed Dark Colour Sampling Chart, rows 105-136 from the Canon iPF8400	191
Figure B.10. Scanned DC/MP printed Dark Colour Sampling Chart, rows 105-136 from the HP z3200	191
Figure C.1. Illustration of the Colour Bar Chart's layered design	192
Figure C2. Cross section diagrams of the example colour combinations and sequences from the Circle Colour Chart	194
Figure C.3. Illustration of the two page Colour Circle Chart's layered design	195
Figure C.4. Illustration of colourant layer sequence, adding one new colourant at a time to increase the total ink coverage	195
Figure C.5. Illustration of colourant layer sequence, using equal amounts of two colourants to increase the total ink coverage for each 200% interval, up to 600% TAC	196
Figure C.6. Illustration of the colourant layer sequence for the set of nine rows using different colourant permutations.....	197

Figure C.7. Illustration of the final three rows of the custom ink limit chart	198
Figure C.8. Illustration of the seven print layers making up the DC/MP Custom Ink Limit Chart.....	199
Figure C.9. Illustration of the print layers for the Six Colourant Permutation test	200
Figure C.10. Illustration of the print layers and screen capture of the layered print file from YBRMCG colourant sequence step wedge test.....	201
Figure C.11. Illustration of the print layers and screen capture of the layered print file from YBRMCG colourant sequence step wedge test with gradated transitions.....	201
Figure C.12. Illustration of the print layers and screen capture of the layered print file from YBRMCG colourant sequence test with 0 to 100% coverage gradation	201
Figure C.13. Illustration of the print layers for the YBRMCG colourant sequence hexagon test	202
Figure C.14. Illustration of triangulated five colourant subgroup containing two colourant pairs and black.....	203
Figure C.15. Illustration of first three layer modifications deriving from the BRMGK colourant combination	204
Figure C.16. Illustration of layer modifications 4 thru 7, derived from the BRMGK colourant combination	205
Figure C.17. Illustration of the five-colourant patch layers resulting from command four, modifying the YYYG colourant combination.....	207
Figure C.18. Illustration of the MAX Colour Chart's layered design.....	208
Figure C.19. Illustration of the colourant layer sequence for the set of nine rows of the Dark Colour Sampling Chart.....	209
Figure C.20. Illustration of the Dark Colour Sampling Chart's layered design for page 1	210
Figure C.21. Illustration of the colourant layer sequence for the set of nine rows of the Colourful Black Sampling Chart	211
Figure C.22. Illustration of the colourant layer sequence for rows 221 and 222 of the Colourful Blacks Sampling Chart	212
Figure C.23. Illustration of the Colourful Blacks Sampling Chart's layered design for the first 26 rows.....	212
Figure C.24. Illustration of the colourant layer sequence for the varnish coating tests.....	213

List of Tables

Table 4.1. Calculated colour differences between one and two, two and three, and one and three layers of each CMYRGB ink colourant.....	80
Table 4.2. Calculated hue differences between layer orderings for all CMYRGB colourant pairs.....	82
Table 4.3. Minimum, average, and maximum dE2000 values for patches containing combinations where any single colourant reaches 100%, 150% - 200%, or 250% - 300% total area coverage.....	105
Table 5.1. Calculated RMS errors for the Dark Colour Chart's best match results	121
Table 5.2. Calculated RMS errors for the Dark Colour and Colourful Blacks Sampling Charts' best match results.....	127
Table 5.3. Calculated RMS and dE2000 errors for the coated colour charts' results..	137
Table 5.4. Calculated RMS and dE2000 errors for the coated colour charts' results, compared with ICC colour managed (CM) reproductions of each painting reference.....	140
Table B.1. Colour data collected from the Canon iPF8400 printed Dark Colour Sampling Chart	187
Table B.2. Colour data collected from the HP z3200 printed Dark Colour Sampling Char	187

1

Introduction to Research and Methodological Approach

1.1. Chapter Overview

Chapter 1 introduces the context and methodologies to the research presented in this thesis. This begins by identifying the parameters of current applications in the area of multi-channel¹ (CMYK+) inkjet colour printing that this research investigates, followed by a statement of my research's aim and objectives. The defined area of research is heavily influenced by the circumstances in which my opportunity to undertake this PhD study was made available. Specifically this was the EU Marie Curie funded project titled "Colour Printing 7.0: Next Generation Multi-Channel Printing," which funded my research at the Centre for Fine Print Research, at the University of the West of England, Bristol (UWE). Overviews of these contributing influences are presented in section 1.4. This chapter also covers the methodological approaches to the undertaking of this research. The chapter concludes with an overview of the following chapters, providing a summary of where each

¹ Multi-Channel is an industry term given to any printing device containing more than the standard set of CMYK inks. Alternative terms "high fidelity" and "multicolourant" have also been previously used. For clarity, all such systems will be referred to as CMYK+ from this point forward.

research objective is addressed and which methods of approach were implemented.

1.2. Definition of Research Area

My research addresses the advancement of colour inkjet printing technology for the production of new art prints and the reproduction of Old Master paintings. In conducting this research it has been recognised that a comprehensive understanding of colour printing, from traditional analogue practices, through to the recent advancements of computational digital colour communication is essential for the re-evaluation of current technologies. The identification of the connections between traditional and digital has been the foundation of the research presented in this thesis.

1.2.1. Historical Influences on Colour Inkjet Printing

In early colour printing inks were pre-mixed using a combination of colourants² to produce the desired colour for a print application. These ink colourants were not predefined, but were reliant on the colour palette mixed by the artist or printmaker. An early example is in the production of colour prints in woodblock printing, where pictorial elements could be separated by colour through the hand carving of multiple blocks. By sequentially printing each block in register, making multiple impressions on a single sheet of paper, the colour image was created by the subsequent layering of ink colourants. With the advent of lithography in the late 18th century, new techniques for manipulating colour and tonality variations emerged. While the woodblock printers created colour and tonal variations through inking the block with gradated colourant mixtures, Western lithography's rendition of colour was the product of uniform, single colourant inking over the stippled patterns on multiple stones to create a perceived blend of multiple

² The term colourant, as defined in the Oxford Dictionary, is the dye, pigments, or other substance that colours something. In this thesis the term is used to differentiate the substance from the colour it produces when printed.

colourants when viewed from a suitable distance (Benson, 2008, pp. 62-64,70).

Periodic advancements in colour reproduction also directly informed modern print practices and colour primaries for printing. In the mid 18th century engraver Jacob Christoph Le Blon, credited as the inventor of four colour printing (Kuehni, 2003, p. 51), began to investigate standardising the number of colour plates required in the mezzotint printmaking process. However, despite Le Blon's initial intentions to create full colour prints from separations limited to blue, red, and yellow, in practise his works required the use of additional, image specific, colours. These included browns and blacks printed as additional colourant separations, and white paint used for finishing (Hults, 1996, pp. 314,466).

Halftoning techniques were developed from stippling techniques in early lithographic printing to break up the continuous tone of an image into a structured dot pattern for printing. This prevents semi opaque printing inks, which cannot all sit on top of each other in a discernable way, to not obstruct underlying colourants. Hans E.J. Neugebauer, a German imaging scientist, presented in 1937 a model to predict printed colour in the three-colourant relief printing process. In his model he considered not only the three primary ink colourants, but also the colour achieved by the superimposition that occurred in the halftone printing process.³ By giving consideration to this superimposition, Neugebauer was able to predict the gamut of printable colours using colorimetric tristimulus values, and accurately represent the chromatic boundary as a hexagonal shape (Viggiano, 2005). In 1948 Arthur C. Hardy and F.L. Wurzburg, Jr. were able to expand Neugebauer's equations to include black so the four colour printing process could be modelled and

³ The eight colours that result from the printed colourant mixtures, and the unprinted paper, are termed the Neugebauer Primaries. Specifically, Neugebauer describes these colours as the *white* of the paper, *yellow*, *purple*, and *blue-green*, as a result of printing each same named ink on the paper, *red*, resulting from the superimposition of purple over yellow, *green*, resulting from the superimposition of blue-green over yellow, *blue*, from the superimposition of blue-green over purple, and *black* formed by the overprinting of all three inks (Wyble and Kraushaar, 2005).

managed. Hardy and Wurzburg further specified that their equations could be expanded further to accommodate alternative colourants and larger ink sets, concluding the opportunity existed for an “entirely new printing process” (Hardy and Wurzburg, 1948).

1.2.2. Summary of Digital Colour Managed Inkjet Printing Workflow

The cyan, magenta, yellow, and black colourants, which became known as process colours, were later adapted into inkjet printing technologies. Then, to address the constraints of the colour gamut, printer manufacturers have modified these inks’ recipes and expanded to CMYK+ systems that include a larger number of ink colourants. However, this resulted in hue variations between manufactures’ inks, and the printed output is therefore inconsistent from one printing device to the next. This variance is further exaggerated by the print industry’s utilisation of different technology and patterning for applying ink to paper.⁴ The result of printing two same-named colourants using different ink jetting and halftone methods results in the colourants not optically blending into the same perceived colour.

Recognising a need to correct for machine variance, and improve upon colour communication between devices on a broader level, the International Colour Consortium (ICC) was established by a group of imaging and printing companies in 1993 (*Introduction to the ICC profile format*, n.d.). Their aim was to provide an independent platform that could correctly communicate colour from one device to the next, resulting in the formation of the ICC colour profile. This ICC specification provides a meaningful translation of colour information from one device to another.⁵ In relation to colour inkjet

⁴ Two major factors attribute to the way ink is physically jetted onto paper. One is the hardware, with the two primary technologies of piezography and bubble jet, employing electrical current and heat, respectively. The second factor is halftoning, a computational tool for breaking a continuous tone image down into a predefined pattern or structure, directing the dispersion of inkjet dots on the printing media/substrate.

⁵ An ICC profile is ideally created for every possible printer and paper combination. The first step to generating a profile is printing a standardised colour patch chart from a characterised device on a chosen media. This chart is then measured, and the colour data recorded to form a look up table in the form of an ICC profile.

printing, the translation comes in the form of a look up table, mapping the colour in the source image file to the colourant space of a printer.⁶

It is often the case that a portion of colours do not print as expected, even when following an ICC colour managed workflow. When all predefined specifications are followed and the machine is operating properly, the remaining explanation is that the colours in question extend beyond the capabilities of the printer-ink-paper combination. The source colours that extend beyond the printer's colour gamut simply cannot be accurately reproduced. Instead each will have to be represented by an alternative, in gamut colour. This is an integral aspect to the whole of the gamut mapping process, as there are various methods for mapping the out of gamut colours, the selection of which is dependent on either preference or application. These methods, known as rendering intents, were devised by the ICC. One of the most common rendering intents involves faithfully reproducing the in gamut colours while remapping, or clipping, the out of gamut colours to the closest in gamut colour available. An alternative is perceptually based, preserving the relationships between colours and tones (ICC, 2001). More detail on the rendering intents that specifically relate to my research will be presented in Chapter 5 (5.5.2).

The ICC profile is an integral aspect of what I will refer to as an ICC colour managed workflow. In the context of this thesis, this workflow is representative of the common industry recommendation for inkjet printing, including characterisation and process control. The specifics of this will be expanded upon as appropriate in the following chapters.

1.2.3. Introduction to the Limitations in Obtaining Colour Accuracy in an ICC Colour Managed Workflow

The limitations to the printer's colour gamut restrict the ability to replicate a vast number of colours that can be achieved with printmaking and paint

⁶ The colourant space represents the entire range of colours that can be produced by the set of inks. More specifically, it is dependent on the entire printing system including the printer hardware and software, the inkset, and the substrate, and is often referred to as the printer's *colour gamut*.

colourants. And despite the options in rendering intents, the reproduction of out of gamut colour immediately becomes a trade off between colour accuracy and maintaining the relationships between adjacent colours. Many problematic colours are predominantly seen in the darker, yet still chromatic colour regions of the gamut. Furthermore, dark colours tend to be printed by mixing the chromatic ink colourants with high proportions of black ink. The black then dominates the printed colour, leading to a smaller perceivable gamut of printed dark colour. Here distinctions between hues with perceivable differences in blackness tend to be lost in print.

J. Reid Clonts Haslup, Renzo Shamey, and David Hinks have demonstrated the threshold at which observers can still perceive hue difference. Here observers with normal colour vision were consistently able to perceive hue differences at 20% lightness levels (Haslup et al., 2013), which is below the darkest colour attainable using an ICC colour managed workflow with certain inkjet printer and paper combinations.⁷ These results are supported by the prior findings of Stephen Westland, Vien Cheung, and Owen Lozman's psychophysical experimentation on perceived blackness. Here the results indicated that only colour samples below the same 20% threshold could be considered "black" by the majority of observers, indicating perceivable colour hues above this threshold (Westland et al., 2006).

The inability to reproduce perceivable differences between dark colours poses a problem in fine art printing applications, including the reproduction of Old Master paintings. The problem lies in aiming to achieve an accurate colorimetric replication of the colours found in the darker painted regions, and in the generation of new printed works with similar chromatic concerns. My research aims to address this shortfall through the objectives presented in the following section.

⁷ The study undertaken by Haslup, Shamey, and Hinks used Munsell Colour Samples with L* values between 19.3 and 20.75 (Haslup et al., 2013). The comparison of these values to inkjet printing was made against the lowest L* values achieved with the Canon iPF8400 printer and Somerset Velvet Enhanced paper. This is the printer and paper combination used in the research presented in Chapter 4 of this thesis.

1.3. Statement of Research Aim and Objectives

My research deviates from ICC managed print workflows, and challenges scientifically informed notions integrated into fine art and commercial practices. The research references both traditional and contemporary printmaking approaches in the development of alternative methodologies for the fine art printing market, which includes the generation of digitally generated fine art prints as well as the reproduction of colours from existing artworks. More specifically, it focuses on how the chosen combination and physical application of inks are employed to create colour, and how these processes can be altered to generate colours previously unattainable using the same inkjet printer. The aim of this research is to develop a printing methodology that expands the number of discernable colours within the inkjet printer's achievable gamut when compared to standard inkjet printing workflows.

The following objectives are outlined to address my research aim from multiple angles within the art and science disciplines:

- Explore the current limitations in inkjet printing that relate to colour management, including colour separations and ink restrictions.
- Survey contemporary digital print practices with focus on user centred approaches to digital technology in the creation of artist prints.
- Develop a printing methodology utilising user defined colourant selections and a layering process not found in current standard inkjet printing workflows to expand the range of printable colours.
- Test the developed print method's ability to improve the reproduction of colours from an Old Master painting.
- Demonstrate increased colour control in the design and printing of digitally generated artworks using the developed methodology.

1.4. The Context for My Undertaking of this Research

This research spans three distinct areas; inkjet technologies, colour science, and creative practice. As illustrated in the Venn diagram in Figure 1.1, the primary research carried out at the CFPR combined inkjet technology with artist-led methods of practice, in an environment where working closely with practicing artists and industry allowed for an approach directly oriented towards end-user application. The EU funded project “Colour Printing 7.0: Next Generation Multi-Channel Printing” (CP7.0) facilitated my examination of current industry standards and methods, as well as scientific research undertaken into inkjet technologies and colour reproduction. My secondment at the National Gallery (NG), London, aimed to inform my research by gaining practical and technical understanding of the Old Master painted works in the Gallery’s Collection. The secondment further provided an opportunity to apply the methodologies developed over the course of this research in a series of colour reproduction experiments. The multidisciplinary nature of my training and the diversity in supervision is further exemplified in the sections below.

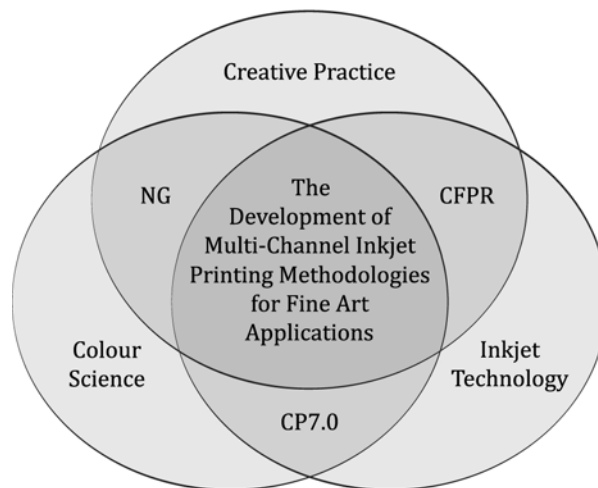


Figure 1.1. Venn diagram illustrating the distinct areas of my research.

1.4.1. Background of the Centre for Fine Print Research and My Position Within It

My research has been primarily undertaken at the Centre for Fine Print Research (CFPR) at UWE. The CFPR combines traditional and digital

technologies to investigate methods relating to the output of fine quality printed artefacts. The environment of the CFPR relies upon multidisciplinary approaches to research, where practitioners and industry work in concert to advance print technologies.

Particular previous work undertaken at the CFPR has been seminal to setting the foundation for further developments evidenced by my research. From 2003 to 2007 an Arts and Humanities Research Council (AHRC) funded project, in collaboration with Hewlett Packard, was undertaken at the CFPR in order to develop “methodologies for the integration of fine art practice and wide format digital printing” (Hoskins et al., 2008). As part of this investigation experimentation with printing multiple layers of black ink was conducted with the aim of expanding the tonal range of an inkjet printer for producing artists’ prints (Parraman et al., 2005). Additional exploration included the investigation of bespoke colour palettes, alternative to CMYK, for artists (Parraman, 2010).

1.4.2. Role Within CP7.0 Project

This research was funded through the EU Marie Curie International Training Network, on a project titled “Colour Printing 7.0: Next Generation Multichannel Printing” (CP7.0).⁸ This project brought together both early stage and experienced researchers to participate in peer training and collaboration on research relating to CMYK+ colour printing sciences. The CP7.0 project facilitated study on a range of topics including modelling, gamut mapping and prediction, analysis of ink and paper interactions, and halftoning for CMYK+ printing. The expertise of the participants in this project was diverse. The CP7.0 project group comprised eleven academic and industrial partners across five European countries. The majority of the research in this project was undertaken in the scientific disciplines, which has allowed my research, while grounded in practice, to be examined and challenged by the scientific community.

⁸ Marie Curie Initial Training Networks (ITN) CP7.0 N-290154. (www.cp70.org)

My research has been framed by the CP7.0 project and influenced by its collaborative elements. Involvement in the project has afforded me the opportunity to travel and collaborate with researchers at both academic and industrial laboratories throughout Europe. There I gained advanced knowledge into the current state of colour printing sciences through presentations, workshops, industry tours, and lecture based courses contained within training events and special sessions.

1.4.3. Working with the National Gallery, London

In addition to my primary placement at UWE and other CP7.0 training obligations, I undertook a secondment at the National Gallery, London. Overall I spent approximately thirty days at the Gallery over the course of my doctoral studies. Individual trips ranged in length from two days to two weeks, depending on the project undertaken at the time. Here I was able to work under the supervision of Joseph Padfield, Conservation Scientist in the Scientific Department. Building on the knowledge gained through research conducted at UWE, work at the National Gallery involved testing and implementing my methodologies in a colour reproduction experiment using an Old Master painting from the Gallery's Collection. This work is described in Chapter 5.

The National Gallery offered an immersive environment in which to gain knowledge and understanding of the considerations required of colour reproduction of Old Master paintings. This ranged from the need for quantifiable precision in colour matching, to subjectively reproducing the look and feel of original works, with the goal of consumer satisfaction, which varied from one department to another.⁹ While at the National Gallery I interacted within the Scientific Department and collaborated with the Photographic Department and the National Gallery Company, a private organization responsible for commercial aspects of the Gallery and its collection, including the print on demand service.

⁹ The topic of differing intents depending on the department at the national gallery is discussed further in Chapter 5.

1.4.4. My Personal Disposition

My research is strongly rooted in the creative industries and undertaken from a practitioner's perspective. Through my photographic background in both input and output applications, I have been able to acquire advanced knowledge of various hardware and software applications. This knowledge was further enhanced by over five years of working in a number of fine art print studios and commercial environments with diverse client needs. However, it is the study of the scientific disciplines relating to colour imaging and printing, both during and preceding my doctoral studies, that have contributed significantly to my multidisciplinary outlook. These studies have enhanced my understanding of the methods used in digital colour printing research and development, most specifically in regards to the computational procedures integrated in the printing systems. The experiences have allowed me to approach this research from a unique perspective, drawing from the methodologies undertaken by creative practitioners and merging them with procedural methods informed by the colour and printing science disciplines.

1.5. Strategy for Investigation and Methodological Approaches

1.5.1. Overview of Strategy

My research covers multiple aspects of digital printing disciplines in the formation of this thesis. A significant portion of the research has involved my own practice in generating printed output as well as an assessment of contemporary art practitioners' requirements through visual survey and conversation with practitioner colleagues. This has allowed for the early identification of the capabilities and limitations within digital colour printing. I have considered methods by which inkjet print technologies can be better informed by reflecting on the study of colour from an arts perspective, such as how paint is mixed and applied, or how pigments are superimposed as layers onto a substrate in screen printing and lithographic processes. The practical aspects of the research explore the capabilities of a range of hardware and software in relation to developing a novel print methodology

for the creation of original works, as well as achieving improvements in the process of art production and reproduction. A key aspect to this work is that it's equally informed by the colour and printing sciences, which is a direct result of my position within the CP7.0 project, collaborations at the National Gallery, and periphery associations in the imaging and printing fields. By also undertaking empirical research, and applying computational analysis to the data collected, I have taken a multidisciplinary approach to this work. The following sections of this thesis provide a rationale for the employment of approaching empirical research through an art's perspective and describe the methods in which the multidisciplinary approach is undertaken.

1.5.2. Introduction to Scientific Inquiry through an Art's Perspective

Through my research I argue for the importance of the creative and applied perspectives within the scientific disciplines, which aims to lessen categorical divides between the critical thinking processes associated with arts practice and the systematic methods present in scientific studies. Sir Christopher Frayling, an educator in art and design, most notably at the Royal College of Art (RCA), addresses such an end to the divide between the arts and sciences. Reflecting upon the stereotypical depiction of scientists he considers their portrayal as contributing to the world's knowledge through "Eureka!" moments whenever new discoveries are made. However, as he continues, he addresses the reality of the situation as "conjectures, but many of them are unconscious and they tend to be changed or modified without any explicit discussion, and they tend to involve a significant measure of subjectivity" (Frayling, 1993, p. 3). As Frayling addresses the stereotypical viewpoint given to the scientist, he argues that they should be portrayed more realistically. Likewise, I think awareness should be given to the scientist's subjectivity on their research. It should be considered that certain assumptions are made through the research process, whether it be solutions not validated through experimental rigour, data blindly carried forward from reference material, or tacit knowledge mistakenly taken for granted as an unfailing solution.

In the same manner that the science disciplines should be aware of the level of subjectivity in their research, the research undertaken by artists and practitioners should also be credited for the level of objectivity that is involved in a highly subjective discipline. This calls into consideration Frayling's seminal distinction between research for art, research into art, and research through art. Research for art describes study of process and material only as necessitated by the making of an artefact, where the art object is the final culmination of all work undertaken. Research into art has a clear and concise definition, as it incorporates literature and technological surveys to lay the conceptual and technical framework of the research. Research through art has the broadest definition of the three, as it encompasses material research, developmental work, and research methods. (Frayling, 1993)

My research involves two of these aspects: research into art and research through art. While the research into art activity can be recognised by my literature and visual surveys, research through art relates more directly to my contribution to knowledge as identified in this thesis. This includes my developed printing methodologies and the subsequent visible and quantifiable improvements to the CMYK+ inkjet printing processes. This approach to research is upheld by Bruce Archer, a predecessor of Frayling at the RCA, in his criteria that practitioner activity must be "a systematic enquiry whose goal is communicable knowledge" in order to be considered research (Archer, 1995). This requires the research to be methodologically sound, clearly documented, and repeatable. By this definition the research presented in this thesis, which has been developed through my perspective as a practitioner, qualifies as research due to its adherence to the systematic approach and contribution to the development of the creative solutions for the digital printing of art pieces.

1.5.3. Methods for Undertaking the Research

Action Research

Action research, borrowed from the social sciences, provides a framework that can be easily modified for the manner in which my research has been undertaken. Katheryn Herr and Gary L. Anderson describe such research as “inherently interdisciplinary and seldom fits neatly into the norms of a particular discipline or field” (Herr and Anderson, 2005, p. 2). In this way it lends itself to the multidisciplinary approach to my research, which combines the gathering of source material and dialogue from both the science and arts disciplines. My particular approach correlates with Ortrun Zuber-Skerritt’s definition of emancipatory action research as

“it aims not only at the technical and practical improvement and the practitioners’ better understanding, [...] but also at changing the system itself or those conditions which impede desired improvement in the system/organisation” (Zuber-Skerritt, 1996, p. 5).

I have employed this method to structure my involvement in the CP7.0 project. With a cumulative goal of advancing research in the field of colour printing, the project members had clearly defined ambitions to pursue through knowledge exchange and collaboration.

My research follows Rory O’Brien’s adaptation of Gerald I. Susmans’ Action Research Model (O’Brien, 2001). This cyclical model begins with the identification of a problem and follows through action planning, execution of the plan, evaluation of results, identifying the outcomes, and repeating the process by re-evaluating the problem and devising a new plan (Figure 1.2). This model is followed through exchanges with colleagues within the CFPR and through the extended network of CP7.0 partners. Action research is extremely prevalent at the CFPR, even if not directly credited by those undertaking the work. Open discussions regarding ideas and approaches to problems have directly contributed to the development of this research, for example, in the implementation of the mathematical calculations used in the analysis presented in Chapter 5.

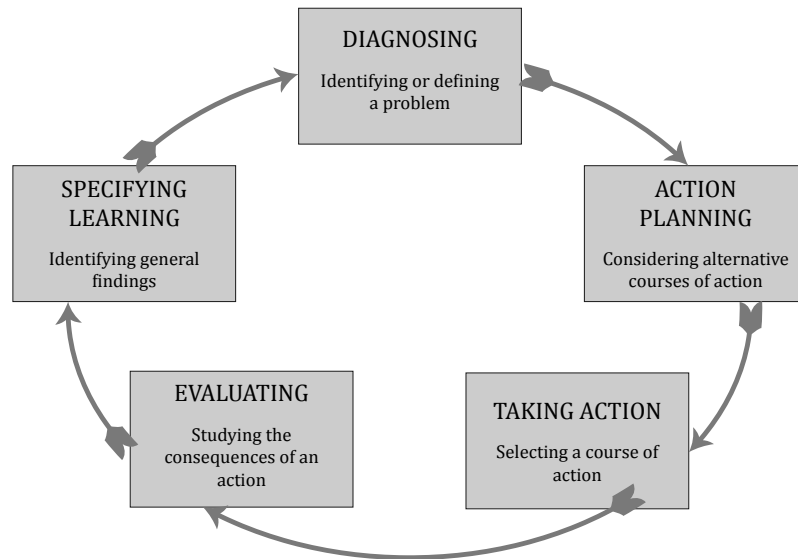


Figure 1.2. Diagram showing the cyclical nature of action research. Redrawn from “Detailed Action Research Model” by O’Brien and reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

The training events organised as part of the CP7.0 project were integral to many of the stages in this action research model from identifying problems and potential solutions, to evaluating and interpreting results of work carried out independently between events. Jim McKernan argued for action research meriting scientific validity by recounting Stephen Corey’s stipulation that “critical perspective can be validated and verified only through practical discourse among those forming the critical community of researchers” (McKernan, 1988). Through the CP7.0 training events I was able to gain this critical perspective, which in turn informed not only the design and execution of my experimental studies, but also ensured its value to the rapidly advancing colour printing science and technology fields.

Mixed Method Research Following an Empirical Model

As this research takes a multidisciplinary approach for the investigation of the boundaries between art application, technological uses, and scientific developments, multiple research methods were required. Utilising both qualitative analysis and computational methods for evaluation, I have found it necessary to employ pure mixed methods research, as defined by R. Burke Johnson, Anthony J. Onwuegbuzie, and Lisa A. Turner, where neither the

qualitative nor quantitative method is dominant, but are interwoven throughout the course of one study (Johnson et al., 2007). Also defined as triangulation, this method of research is recognized for use “not only to examine the same phenomenon from multiple perspectives but also to enrich our understanding by allowing for new or deeper dimensions to emerge” (Jick, 1979). This method allows my research to incorporate qualitative and quantitative analysis interchangeably, as deemed appropriate by the strength and limitations of each to balance and reinforce the other. This is particularly important in working within the art and design context, where qualitative assessments are essential for evaluating the quality of printed output, but simultaneously rely upon the quantitative analysis to uphold the validity of the research in a predominantly scientific field.

While action research defines my engagement with the CP7.0 group, the CFPR, and the National Gallery, the action stage, which involved a series of print tests, followed an empirical model. The foundation of this research was built upon assessing the capabilities of current fine art inkjet printers through the observation of printed output, while experimenting with the drivers and raster image processing (RIP) software that control the printer. These tests were designed to identify the strengths and weaknesses of current printers, print drivers, and RIPs, as well as developing novel applications to push them beyond current limitations. In the progression of my research numerous test charts have been designed and used to test evolving hypotheses. The evolution of these test charts has followed an empirical model where a preliminary hypothesis was generated, based on surveys of literature and printed matter, challenging the possible outcome of a particular printing parameter. At each stage observation and assessment of the experimental outcomes were evaluated and inductions were made which led to the generation of a new hypothesis. This model, illustrated in Figure 1.3, follows the empirical cycle designed by A.D. de Groot, in which observations form a hypothesis based on empirical facts, followed by deducing a testing procedure, performing the experiment, and evaluating the

results (Guimaraes, p. 29). The analysis of developed test charts allowed for both qualitative and quantitative analyses through visual and mathematical colour evaluations.

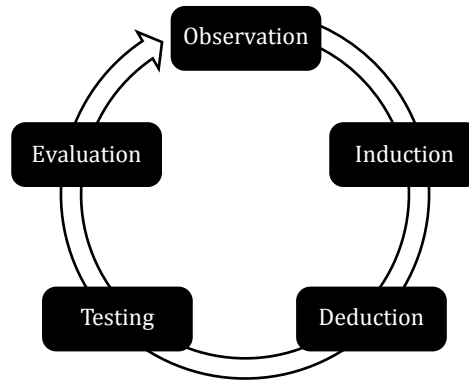


Figure 1.3. Illustration of A.D. de Groot's Empirical Cycle. Redrawn from "A visual representation of A.D. de Groot's empirical cycle" by TesseUndDaan, used under CC BY 3.0.

This method for developing and refining the early colour work has directly informed the later aspect of my research undertaken at UWE and the National Gallery, London. This portion of the research, presented in Chapters 5 and 6, aims to investigate the potential benefits of incorporating the developed alternative printing techniques into future production and reproduction workflows, expanding the available gamut of darker colours and improving the overall colour accuracy of inkjet printing. In Chapter 5 I specifically address the known problem at the National Gallery that colour distinctions in the dark regions of Old Master paintings are difficult to reproduce, particularly where edges are not clearly defined. When using current inkjet print workflows, these colour distinctions cannot be made in printed reproductions despite their perceivable appearance in the original. In Chapter 6 I evidence the improvement of colour production in inkjet printing by applying my developed print methodology to the creation of new printed works.

1.6. Overview of the Following Chapters

I present in Chapter 2 the historical baseline for this research, beginning with the organisation of colour, and leading into how it is described, mixed, and measured today. By reflecting on the range of colour modelling theories and various qualitative and quantitative explanations for them, I am able to provide the context for the developed methodologies described in my research. In Chapter 3 I discuss the concepts and practices that provided the point of departure for my developed print methods, which are introduced in the subsequent chapter. This begins with an evaluation of established parameters in inkjet printing workflows, covering the critical aspects that contribute to determining colourant combinations and the application of inks onto paper. This is followed by an overview of the working methods of current arts practitioners that have informed my research through their alternative uses of colour inkjet printing. It then assesses alternative practices undertaken by active practitioners in the digital photography and graphic arts disciplines, illustrating how arts practice can inform the development of new print methods and technologies.

The primary empirical studies conducted for expanding the achievable colour gamut using a CMYK+ inkjet printer are presented in Chapter 4. The chapter begins by providing rationalisation for the equipment and materials used in the research. This is followed by a recounting of the series of specially made colour charts aimed at developing a print methodology to expand the achievable colour gamut using developed alternative printing methods. The incorporated variables of each test chart are evaluated and modified to improve the outcomes for the subsequent chart.

Details of the colour reproduction experimentation, informed by my secondment to the National Gallery, London, is presented in Chapter 5. This chapter summarises how, by gaining an understanding of current practices within numerous departments at the National Gallery and National Gallery Company, I was able to identify a correlation between my developed print methods and their need for improved colour reproduction. The associated

demonstrations by, and discussions with, staff members informed my empirical tests on improving the colour accuracy of the dark colours found in the Gallery's Collection through the use of my developed inkjet printing methods. I continue the focus on applications for the developed print methodologies in Chapter 6. In this chapter, which is informed by dialogue with members of the CP7.0 project, I present my printing method's contribution to print quality through qualitative assessments. This is done through the implementation of the developed printing methods into a creative workflow, highlighting the ability to maintain colour distinctions and edge detail beyond the ability of the usual colour managed, single pass printing workflow. Furthermore, it brings attention back to the secondary print effects discussed in Chapter 4 and provides examples of how these effects can be integrated into a purposeful special effect in the creation of new works.

In Chapter 7 I conclude all the elements of this research. This conclusion contains an overview of why I have explored my research question, the historical context surrounding the variant elements of the research, and the experimentation undertaken to test my hypotheses. I then use this summary to state my contribution to knowledge, along with avenues of further research that developed from this thesis. The appendices include supporting material to various aspects of this research including a glossary of terms, comparative information regarding variant inkjet printers, a further explanation of the design and testing of colour charts, and supplemental colour data in Appendices A, B, C and D respectively.

2

Historical Baseline & Contemporary Context

2.1. Chapter Overview

In this chapter I provide background and fundamental understanding of the rationale for, and metrics used in, the later parts of this research. The ideas and perspectives presented in this research are informed by the extensive study of colour from the past two centuries. This chapter looks at the motivation for, and advancement of, structuring and quantifying colour from both the artistic and scientific perspectives, beginning with a summarised account of the development of colour ordering systems. This theme of investigating ways to structurally, systematically, and comprehensively represent colour will remain present in this thesis through the later chapters, where the development of colour charts aims to continually re-examine methods for subsampling specific regions of colour. The descriptions on how the understanding of colour, transformed from studies of light and the mixture of paint pigments to quantifiable metrics, then leads to a declaration of the measurement and colour comparison techniques utilised in this research.

2.2. Early Inquiry into the Understanding and Organisation of Colour

Colour is a complex phenomenon. It's this complexity that has led to colour's extensive study by both artists and scientists who have sought to describe, structurally arrange, and predict it. The study of colour dates back to antiquity with artists and theoreticians alike seeking to better understand the phenomenon. Of the ancient Greek philosophers, Aristotle's interpretation was the most influential. He proposed that colour was the property of an object, which reacted to light on a linear scale from white to black - an understanding that held true for two thousand years (Ball et al., 2013, p. 71, Benson, 2000, p. 18). It was not until 1666 that Sir Isaac Newton discounted Aristotle's ideas through his discovery that white light was created through the mixture of all colours, which he termed the colour spectrum (Hunt and Pointer, 2011, pp. 1-2).

Newton's publication of *Opticks* in 1704 brought mixed reactions among an arts audience when he presented his diagram of a colour circle, which comprised of seven identified primary colours distributed around a circle. This was presented alongside a rationale for the structure of the circle and a description of additive colour mixing (Kuehni, 2003, pp. 43-45). Johann Wolfgang von Goethe strongly opposed Newton's theory, believing it unsubstantiated, and developed his own symmetrical colour wheel comprising of only six colours evenly placed around the circle (Goethe, 1840, p. lii). Goethe's work on colour, specifically the development of his colour circle addressing subtractive colour mixing and the use of complementary colours, was especially influential with practicing artists, such as Philipp Otto Runge's paintings of colour circles and spheres (Kuehni, 2008, pp. 84-85).

As these colour theories, and their associated colour circles and colour mixing principles, underpin all developments in modern colour studies for both the arts and sciences, I am providing a brief review of the systems and notations that directly relate to my research topic.

2.2.1. The Evolution of Colour Order Systems (for colour mixing)

The history of colour theory and colour ordering systems has been well investigated and documented by many contemporary researchers, and it is improbable to open any textbook relating to either the art or science of colour and not be presented with an overview of this history. Rolf G Kuehni, recipient of the Inter-Society Color Council's prestigious Godlove Award for his outstanding contribution to the field of colour, has produced substantive writings on the topic of early colour theory, and more significantly, organised colour spaces and solids that informed both theory and practice. In the introduction to his book *Color Space and Its Divisions: Color Order from Antiquity to the Present*, Kuehni states that:

"Generally, a color space and the related color solid may be defined as an economic systematic description of subjective color experiences, and as such it is not subject to engineering precision. It is indicative of our visual strategies vis-à-vis the world" (Kuehni, 2003, p. 3).

This statement highlights the important fact that no one representation of colour can be accepted as an all encompassing whole without error. Yet the complexity of representing even a subsection of a colour system is a problem artists have been trying to resolve in practice from as early as 1708 with the first painting of a colour circle. Goethe speculated that the artist, known only by his initials C.B., needed to mix multiple pigments in order to represent a true red, indicating that no single pigment was available (Kuehni, 2003, p. 47).

Further developments in the representation of colour relationships were made over time, with intermittent benchmark contributions by artists such as Moses Harris. In 1766 Harris produced *The Natural System of Colours*, which included a 'prismatic' colour circle in which he explored the possibility of producing all colours from the three primaries of red, yellow, and blue. The arrangement presented complementary colours opposite one another on the circle and further included tonal adjustments of each hue. He further illustrated and described a 'compound' colour circle, portraying the

intermediary colours between the primaries. Because of the comprehensiveness of his book's description of these hand coloured circles, Harris has been recognised for his advanced colour knowledge (Schmid, 1948).

Between 1808 and 1809 Runge further expanded on the idea of a colour circle mixed from yellow, red, and blue, by devising the first colour sphere with the addition of black and white as opposite poles (Ball et al., 2013, p. 74). Runge's colourant selection corresponds directly with the theory of Goethe, with whom he conversed. Goethe made specific mention of the necessary symmetry of a colour wheel, where the colours placed opposite one another evoke an afterimage of each other (Goethe, 1840, p. 20). Unaware of Runge's work in Germany, Albert Henry Munsell, an artist and educator in Boston, also began working on his own colour sphere by painting directly onto a spherical globe (Munsell, 1905, p. 18). In his 1905 publication *A Color Notation*, Munsell discusses mixing balanced colours and painting them on opposite sides of the globe. Munsell was able to create perfect complements, and, when spun, the globe produced the appearance of neutral grey bands ranging in value from white at the top pole to and black at the bottom.

Munsell described the arrangement of colours on his sphere using terminology he defined for his *Color Notation*, qualifying colours by hue, value, and chroma.¹ On the globe colour hues were wrapped around the perimeter and the value ran between the two poles along a neutral axis from white to black. But perhaps the most significant term Munsell introduces was the term chroma. When balancing the hue and value of colours around his globe, Munsell noted that the colours around the equator would be the most chromatic, similar to Runge's illustrations. However, he recognised that in order to create perfect complements, the painted colour he mixed could only

¹ By Munsell's definition "HUE is the name of a color," "VALUE is the light of a color" and "CHROMA is the strength of a color" Munsell (1905).

be as chromatic as the least chromatic pigment he was using. Therefore, a colour ordered system containing all possible variations of hue, value, and chroma could not be confined to a sphere, but would instead take on an irregular shape with some hues extending out with a higher chroma than others.

Although Munsell's *Color Notation* is perhaps the most widely known, studied, and accepted text among both artists and scientists (Nickerson, 1940, Landa and Fairchild, 2005), it is far from the only system developed. The Natural Colour System (NCS), designed in Sweden in 1952, was developed following the opponent colour theory of Ewald Hering² (Hard et al., 1996). The NCS Notation incorporates only yellow, red, blue, and green, and qualifies all colour variations by hue and nuance while Munsell subjectively chose to identify five principle hues based on the correlation to musical notation. Additional systems include the German DIN, established in the late 1970s, and the Hungarian Coloroid system, developed between 1962 and 1980. The DIN colour solid is formed by a cone shape transitioning between the four main primaries of yellow, red, blue, and green, which wrap around the cylindrical top where colour saturation increases from a neutral centre outward, with the highest chroma along the outer edge. The darkness axis then tapers from the lightest point at the outer edge of chroma, down to the point of the cone where black is located. The Coloroid system structures the colour solid much in the same way as Munsell, but uses the terminology hue, luminosity, and saturation to denote the three axes, as it represents a perceptual colour space, as opposed to surface colour. Like the Munsell system, the Coloroid colour space aims to maintain perceptual uniformity.

2.2.2. How the Scientific Understanding of Colour Evolved (Colour Theory)

The perception of colour is a subjective interaction between light, object, and observer. In Newton's seminal text, *Opticks*, he presents the theory that all

² Hering's colour theory is described in the following section of this chapter (2.2.2).

colour is contained in white light, and by focusing it through a prism the light particles refract, displaying the colour spectrum. It is then the properties of the object that absorb portions of the spectrum and only the non absorbed light is reflected and transmitted to the observer, in what Newton referred to as a colour-making process (Newton, 1704). Thus he concluded the perceived colour is the result of the portion of the light particles reaching the eye, making the perceived colour dependent on the source of light, and conditional to the eye of the observer. Newton's theory was later amended to account for Thomas Young's discovery that light was emitted as rays, and not particles.

In the 19th century Thomas Young, and later Hermann von Helmholtz brought forth and refined the theory of trichromatic colour vision (Ohta and Robertson, 2005, pp. 39-41). Trichromatic theory identifies three types of photoreceptors present within the eye, each with different peak sensitivities along the visible portion of the electromagnetic spectrum. Assuming normal colour vision, the sensitivities of the three photoreceptors are near the long, medium, and short wavelengths, as illustrated in Figure 2.1 (Chamberlin and Chamberlin, 1980, p. 6). Helmholtz differentiated between the use of the red and blue primary colours identified in work of Young and painters like Le Blon when he classified the terms additive and subtractive colour mixing in 1852 (Kuehni, 2003, pp. 59,72). Additive colour mixing, as seen in the work of Young and Helmholtz, was defined as colour mixing by use of red, green, and blue light. Le Blon's mixing the primary colourants blue, red, and yellow using dyes or pigments was defined as subtractive colour mixing.

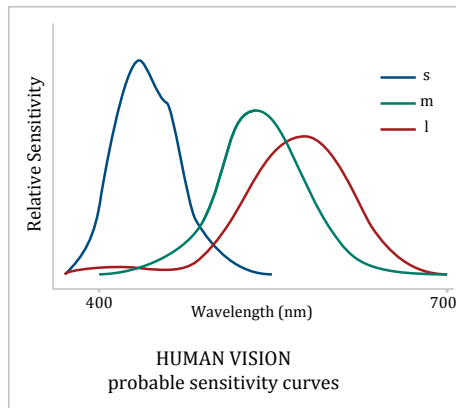


Figure 2.1. Illustration of G.J. Chamberlin and D.G. Chamberlin's probable sensitivity curves for human vision. Redrawn from figure 1.2 in *Colour: Its Measurement, Computation and Application* (1980, p. 6). Reproduced with permission from John Wiley & Sons, Inc. Further reproduction prohibited without permission.

A later oppositional, yet still scientifically valid, theory of colour vision was opponent-colours theory, first presented by Hering in 1878 (Ohta and Robertson, 2005, pp. 41-42). Hering theorised that the three photoreceptors of the eye were yellow-blue, green-red, and white-black sensitive. Therefore any colour could be a combination of any three opponent colours, such as a bluish green, but never contain opposing colours, such as perceiving a yellowish blue. This concept of opponent colours was not new. Goethe pre-empted Hering in his *Theory of Colours* in discussing the after-image of coloured objects, where “the colours diametrically opposed to each other [on the colour circle] are those which reciprocally evoke each other in the eye” (Goethe, 1840, p. 21). While new research is further clarifying these colour vision theories, these primary concepts alone have directly informed the principle understanding of vision in relation to the colour observer.

2.3. Modern Colour Measurement and Representation

There are two approaches to measuring colour. The first is by the use of a colour referencing system. It was the previous lack of such a system that prompted Munsell to construct his *Color Notation*, providing an alphanumeric structure to a range of printed hues at varying levels of value and chroma. In the subsequent publication of the *Munsell Book of Colour* (1929) a series of painted samples were presented, each marked with the

notation that identified its position in the book, and relation to all other colours. With the advent of this referencing system, colour could be accurately communicated between parties without the exchange of a physical hardcopy. These systems are particularly advantageous to understanding colour relationships, as the colour samples can be viewed both as part of the total colour structure, and also rearranged to make additional visual comparisons. The colour reference method is still in use today, with a number of colour order structures available, including the NCS, DIN and Coloroid (discussed in section 2.2.1), and the Pantone and RAL systems that, while not arranged to make colour relationships like the others, still provide a colour sample and use an alphanumeric referencing system.

While the colour ordered systems have their advantages, without a mathematical description of these colour relationships the colours that lay in-between samples, or beyond the represented gamut, fail to be described, or even compared from one system to the next. Furthermore, they fail to account for observer variability. Therefore it is imperative to have secondary, mathematical methods for acquiring and computing colour information. In *Colour: It's Measurement, Computation and Application*, G.J. and D.G. Chamberlin provide an essential caveat to measuring colour:

“One cannot, strictly speaking, measure colour instrumentally, because it is a subjective sensation. What can be done is to describe colour in idealized and standardized terms, using numbers which can be correlated with visual images” (Chamberlin and Chamberlin, 1980, p. 21)

2.3.1. Spectral Reflectance Acquisition

The colour information presented in this thesis has been measured using spectroradiometry and spectrophotometry devices. These types of devices record the spectral power distribution by measuring the amount of radiation from the sample, or more specifically for the spectrophotometer, comparing the radiant power of the illuminating source against the reflection of the sample (Hunt and Pointer, 2011, pp. 108-110). A series of measurements are

taken at set intervals over the visible portion of the spectrum, recording the spectral power distribution of the samples, which can then be plotted to provide a spectral reflectance curve as a representation of the colour.

Measurements taken with a spectrophotometer are contact measurements, with the device placed directly on the sample from which the spectral data is required. These devices include both an integrated controlled illuminant and fixed measurement geometry. Before a series of measurements are taken the device requires calibration to ensure consistency and repeatability. Then, as a sample is measured, it is illuminated from a 90° angle, and the measurement taken using a detector located at 45° to the light source.³ Since the spectral power of the illuminant is known, it is discounted from the final spectral reflectance data that is output by the device. This ensures consistency between each colour sample that is measured, allowing for quantifiable precision when using the colour data in analysis.

Spectroradiometers differ from spectrophotometers in that these devices do not come into contact with the sample, and do not have an illuminating light source integrated into the device. Therefore the angles between the illuminant, sample, and device can be inconsistent if the sample, or device and light source require repositioning between measurements, thus requiring care to be taken to ensure consistency.⁴ Similar to a spectrophotometer, the device is paired with a calibration tile, from which a measurement of the light source can be recorded and later discounted from the sample measurement.

Although the colour data recorded by these two devices is able to give a quantifiable description of the colour, it cannot describe what the colour's

³ There are four CIE recommended illumination and viewing geometries for colour measurement devices. The example given here is specific to the instrumentation utilised in this research.

⁴ In the case of my research, as will be described in Chapter 5, consistency in positioning a spectroradiometer and light bank in front of a painting on display in the National Gallery, London was unattainable. Therefore it is recognized that the measurements taken were not standardized and repeatable, leading them to be referred to as sample reference colour measured from the paint, and not described as the exact colour present in the painting itself.

appearance would be. Before the colour's appearance could be determined, consideration would have to be given to the viewing conditions and the observer. Contributions to this have been put forth by the Commission Internationale de l'Eclairage (International Commission on Illumination).

2.3.2. Colourimetry Standards and the Commission Internationale de l'Eclairage (CIE)

The Commission Internationale de l'Eclairage (CIE) is an independent organization that defines standards and terminology for topics relating to illumination. In 1931 the CIE's technical committee made significant contributions to the field of colourimetry, establishing a quantifiable description of human colour perception by defining the CIE 1931 RGB and XYZ colour spaces. These colour spaces provided a mathematical correlation between the physical properties of colour and the human visual system through developed colour matching functions (Hunt and Pointer, 2011, pp. 33-35). This work stemmed from James Clerk Maxwell's adaptation of Thomas Young's red, green, and blue primaries into a colour triangle in 1861 (Chamberlin and Chamberlin, 1980, p. 51). Here the pure red, green, and blue primaries were placed at each of the vertices, which faded out toward the adjacent primaries. Following the principles of additive colour mixing, the combination of the three primaries mix to white in the centre.⁵ Present within the boundary of the triangle is every combination of the three primaries, at all possible proportions, thus representing every possible attainable hue (Figure 2.2). It was found that the red, green, and blue points of Maxwell's triangle could be replaced by spectral colours at 700, 546.1, and 435.8 nanometre wavelengths, respectively, forming the CIE RGB colour space (Smith and Guild, 1932).

⁵ Although this is referred to as white, it technically represents the entire luminosity range, from white light to the absence of all light (blackness).



Figure 2.2. Illustration depicting Maxwell's Colour Triangle.

In mapping the entire colour spectrum around the CIE RGB colour space, all wavelengths, besides the CIE RGB points, extend beyond the triangles boundaries, forming a locus containing all spectral colours (Figure 2.3). With the most chromatic spectral colours represented for every wavelength along the perimeter of the spectral locus, every possible mixture of colour could be represented inside. Since the RGB colour space was a two-dimensional description of a three-dimensional space, it was recognised that the spectral locus extended beyond the RGB colour space, leading to negative colour values. The CIE XYZ colour space was established, using non-colour representative primaries to encapsulate the entire spectral locus. This ensured positive numbers could be used to represent all spectral colours (Figure 2.4). (Chamberlin and Chamberlin, 1980, pp. 52-53)

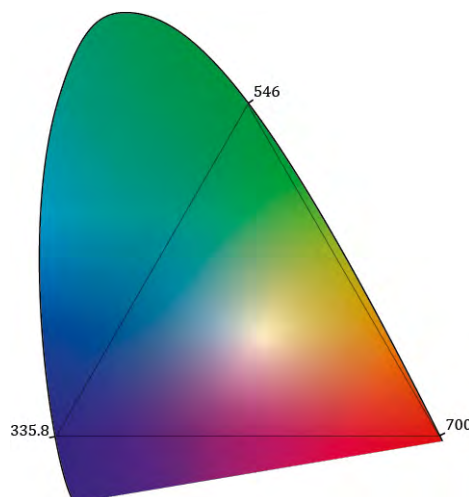


Figure 2.3. Illustration depicting the CIE Spectrum Locus.

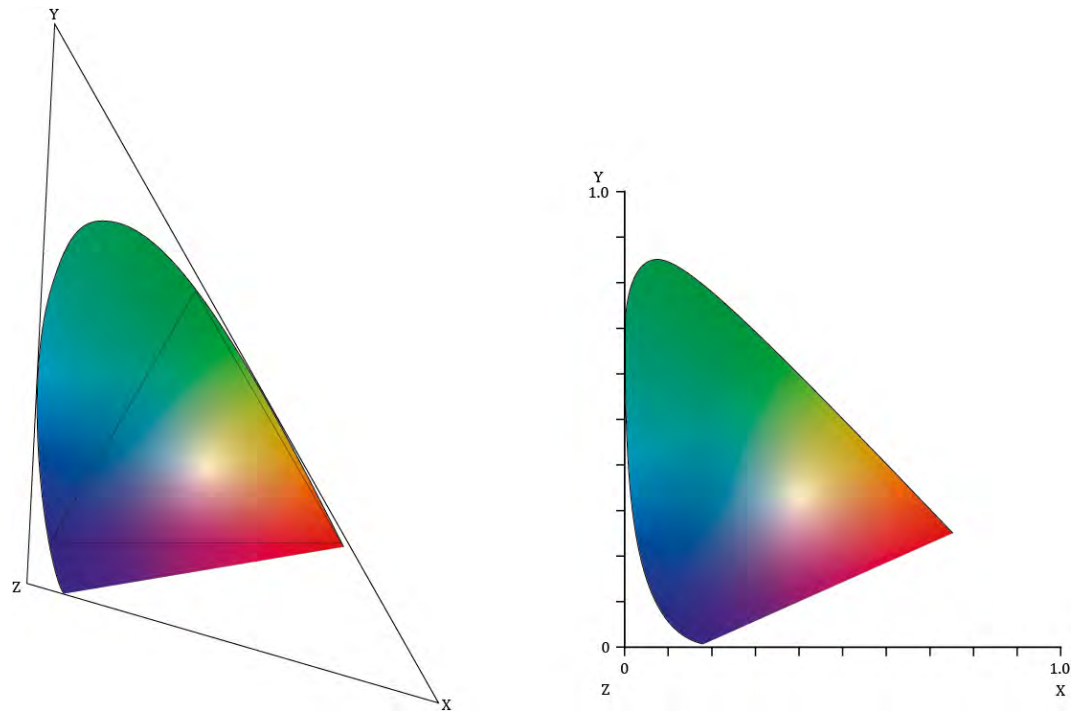


Figure 2.4. Illustration depicting the XYZ coordinates drawn to encompass the spectrum locus (left) and the transition into a readable scale (right).

In order to describe how spectral colour measurement would appear to a human observer with normal colour vision, further work was required to establish mathematical functions that compensate for human perception. Research undertaken independently by William David Wright and John Guild on human vision led to the integral definition of the CIE Standard Observer (Smith and Guild, 1932). With the addition of CIE defined standard illuminants, mathematical compensation could also be made to account for changing light conditions. The original CIE Illuminants were tungsten illuminated, defined as *A*, and two daylight conditions simulated by filtration of the tungsten source, defined as *B* and *C* (Smith and Guild, 1932). However, following a proposal by Deane B. Judd, David L. MacAdam, and Günter Wyszecki, three new standard illuminants were added to better describe daylight. The CIE settled upon the average of these new illuminants and recommended daylight at 6500 degrees Kelvin, referred to as D65 (Judd et al., 1964, CIE, 2004b). Following the guidelines later set forth for the graphic arts industry, I will use an alternative daylight standard for my research, the

CIE Supplementary Illuminant D50 (British Standards Institution, 2009a, British Standards Institution, 2009b).

Toward Perceptual Uniformity in the CIE Colour Space

With the defined colour matching functions of the CIE 1931 Standard Observer and standardised Illuminants, spectral reflectance values could be quantifiably defined as tristimulus values⁶ and plotted in the CIE 1931 XYZ Colour space on an x,y chromaticity diagram (Chamberlin and Chamberlin, 1980, p. 54). The CIE x,y chromaticity diagram still needed improvement, most significantly because it was not perceptually uniform. William David Wright in 1941, and David Lewis MacAdam in 1942, published research on the human eye's sensitivity to small colour differences, which illustrated that it was not equally sensitive to the distribution of colours on the chromaticity diagram (Wright, 1943, MacAdam, 1942). While Judd had published work even earlier in 1935, proposing lengthening the x,y chromaticity diagram to extend the red and blue regions (Judd, 1935), it was never adapted due to the complexity of calculation (Chamberlin and Chamberlin, 1980, p. 59). It was later MacAdam's u',v' chromaticity diagram (MacAdam, 1937) that was adopted by the CIE as an improvement of the x,y chromaticity diagram. Yet, even in the 1960 version, the darker yellow, orange, and red regions, with colours tending to brown, were compressed (Chamberlin and Chamberlin, 1980, p. 60). Inevitably it was determined that a three-dimensional colour space was required.

In 1976 the CIE established their CIE 1976 ($L^*a^*b^*$) Uniform Colour Space following the recommendation of an international subcommittee from the CIE colourimetry technical committee (McLaren, 1976). The CIE 1976 ($L^*a^*b^*$) Uniform Colour Space, shortened as CIELAB, was established as a non-linear distortion to the CIE XYZ colour space. It comprises of plotting L^* , a^* , and b^* quantities on axes intersecting at right angles, where L^* indicates

⁶ Hunt and Pointer define tristimulus values as "the amounts of three matching stimuli, expressed in units adopted for them." (2011, p. 28)

lightness and the a^* and b^* axes are intersecting colour planes. Following Hering's opponent colour theories, negative values on the a^* axis tend toward green while positive values tend toward red, and negative values on the b^* axis tend toward blue while positive values tend toward yellow (Figure 2.5). The intersection of the a^* and b^* axes represents the neutral axis from which all hues travel outwards as chroma increases.

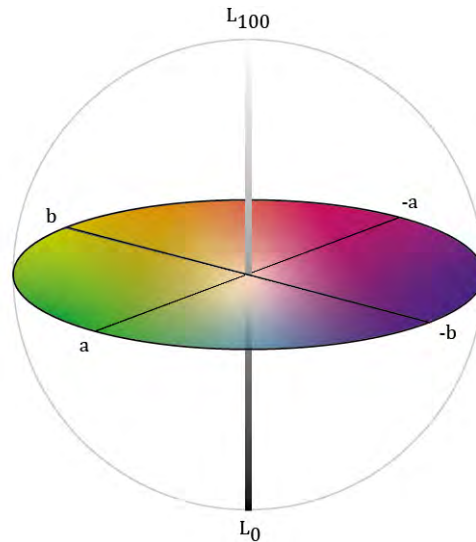


Figure 2.5. Illustration depicting the CIELAB Colour Space.

Other uniform colour spaces have been established, including the CIE 1976 ($L^*u^*v^*$) Uniform Colour Space that derived from the u',v' chromaticity diagram. Shortened to CIE Luv, this colour space was designed to adapt the intermediate CIEUVW colour space to the same brightness scale as CIELAB. While both the CIELAB and CIE Luv remain recommended colour spaces by the CIE, in addition to others not mentioned here, only the CIELAB will be discussed and depicted in this thesis from this point forward. This is due to the established prominent use of CIELAB in the colour printing sciences (Luo, 1999). Unfortunately the CIELAB colour space cannot be credited with indisputable perceptual uniformity, as the review of colour difference formulas in the next section addresses a number of its shortcomings.

2.4. Colour Difference Formulae

For this research I have chosen multiple methods to quantify colour differences, both for comparing printed samples, and measuring the error between a printed sample and colour reference. The first is presented as a continuation of the previous section covering the CIE and the CIELAB Uniform Colour Space, which accounts for the human visual system. However, despite recognition as a print industry standard, there remains no agreed certainty to the accuracy of available colour difference formulas to date. This, along with the rise in spectral printing applications (as will be discussed in the next chapter), led me to incorporate a spectral difference equation into my research. Each is described in the sections below.

2.4.1. CIE Colour Difference Formulas

In conjunction with the recommendation of CIELAB, the CIE 1976 ($L^*a^*b^*$) colour difference formula was also published. The colour difference formula measures the change in colour sensation between a sample and a reference colour using the Delta E 1976 metric (shortened here to dE76). If assuming the CIELAB colour space is perceptually uniform, then any colour on a spherical shape surrounding the reference would have the same perceived deviation in colour. For the dE76 metric, a deviation of 2.3 would indicate a just noticeable difference between reference and sample (Sharma, 2003, p. 31), independent of whether the direction of change was in lightness, hue, or chroma. However, in reality this was not found to be the case. Ideally all possible hues should travel out from the centre neutral axis in a straight line as chroma increases. Instead Gustav J. Braun, Mark D. Fairchild, and Fritz Ebner, in plotting “lines of constant perceived hue” from referenced data, found the hues to distort on the a^* , b^* plane, particularly in the blue region (Braun et al., 1998). Furthermore, as previously witnessed by MacAdam on the CIE XYZ chromaticity diagram, chroma differences that are perceived as

equal changes from a reference colour are represented as ellipsoids, even in the spatially corrected CIELAB colour space (Pointer, 1981).⁷

In addition to calculating the overall colour difference, the dE76 formula is comprised of mathematical expressions to independently define differences for lightness, hue, and chroma. A change in lightness, or Delta L (DL) is a direct indication of change on the L* axis. The hue difference (DH) is directly related to the rotational change in angle around the central L* axis, and the chroma difference (DC) is the straight outward change from the L* axis. In an effort to compensate for the distortions to CIELAB, alternative colour difference formulas have evolved, applying advanced functions to these individual components. In 1984 the Colour Measurement Committee of the Society of Dyes and Colourists of Great Britain developed CMC(l:c) for use in the textile industry. The CMC(l:c) equations compensated for the hue distortion in CIELAB by applying a function to the hue difference (Kuehni, 1999). This Colour Measurement Committee further applied corrections in the relationship between lightness and chroma, recognising that the human eye is two times as sensitive to chroma as it is lightness (Upton, 2005). A simplification of CMC(l:c) lightness to chroma correlation was later integrated into the CIE d94 equations published by the CIE in 1994 (Ohta and Robertson, 2005, p. 143).

The latest recommended CIE colour difference formula is CIEDE2000 (shortened dE2000). The appointed technical committee built the dE2000 formula following a complete re-evaluation of preceding colour difference equations. The formula includes corrective weighting functions for lightness, hue, and chroma, as well as additional scaling factors specific to the a* axis and blue axis (Luo et al., 2001). While there exists some debate among researchers as to the significance of these improvements compared to CMC(l:c) and DE94 (Luo, 1999, Kuehni and Kuehni, 2002), for this research I

⁷ Pointer's calculations incorporated the modified CIE XYZ to CIELAB equations recommended by the CIE, which were published in an appendix in 1978.

have chosen to utilise the dE2000 formula published by Gaurav Sharma, Wencheng Wu, and Edul N.Dalal (2005) for the computation of all colorimetric evaluations. This includes the dH2000 component in select instances as explained in the relevant sections of this thesis. This decision is directly a result of the corrections to the neutral, and subsequently, near neutral colour regions, which certain aspects of my work specifically address (Chapter 5). Furthermore the dE2000 formula has been identified to improve colour difference measures for references and samples with a small colour difference (CIE, 2004a).

It is necessary to mention that not all colour difference metrics have the same tolerance for a just noticeable difference (JND). The DE2000 formula indicates this calculated threshold to be 0.5 (CIE, 2004b). While I use 0.5 as an indicator of a JND, I also acknowledge that in practice, the printing industry tends to have a higher tolerance for small colour changes. Therefore I have assigned a further threshold of 2.5 to indicate a colour difference constituting a definitive deviation from the reference colour, as it should guarantee a colour variation will be observable by any observer with normal colour vision.

2.4.2. Calculation of Spectral Reflectance Differences using Root Mean Square (RMS) Errors

Calculations made using CIE colour spaces, and subsequently all CIE colour difference equations, rely on the predetermination of an illuminant. Spectral reflectance data, as acquired through the processes described in section 2.3.1, requires the selection of an illuminant for the transformation to the XYZ colour space, as this influences the reference white point for the transformation. This illuminant selection then effects the calculated colour difference between two samples as some colours may appear to match under one illuminant, but not another, in a phenomenon known as metamerism. While colour reproduction based on this colorimetric workflow can accurately represent the reference colour in a controlled viewing

environment, this workflow is incapable of producing a colour with the same physical response as the reference.

To compare the differences between the physical properties of colours, the spectral reflectance curves of the sample and reference should be used. Calculating the Root Mean Square (RMS) error is one of several comparison methods. The RMS equation calculates the deviation between a sample and reference by averaging the difference between the measured reflectance of two colours at set intervals of the colour spectrum. Here there are no transforms applied to the colour stimuli to account for human colour perception, thus providing an absolute measure of difference between reference and sample unaffected by observer and viewing condition variables.

As this basic RMS difference does not account for the human visual system, it is better at eliminating metamerism, however it does not take into account that human vision is more or less sensitive to different regions of the visible spectrum. Therefore studies have been conducted evaluating modified RMS equations that incorporate weighting functions aimed at correcting for these sensitivities. In 2002 Francisco H. Imai, Mitchell R. Rosen and Roy S. Berns compared the basic RMS calculation with both CIE colour difference formulae and two weighted RMS equations. The weighted RMS included one that gave more importance to the magnitude of error in dark colours, where human vision is more sensitive, and another that applies weighting functions based on a specified CIE illuminant and observer (Imai et al., 2002). This study found that while the weighted RMS equations could be considered as a viable error metric, each only addressed one consideration for applying human vision sensitivities, and no single recommendation could be made.

In 2004 J A Stephen Viggiano revisited Imai, Rosen, and Berns' finding and re-evaluated it with the addition of his own Spectral Comparison Index (SCI) and a new set of test spectra (Viggiano, 2004). The SCI metric incorporates colorimetric principles, calculating the error between spectral reflectance data using CIELAB difference calculations on individual wavelengths

(Viggiano, 2001). In his 2004 evaluation Viggiano found the basic RMS formula to outperform the previously proposed weighted RMS metrics. While he did find his SCI metric provided a more convenient definition of error compared to the basic RMS, it required a more complex calculation.

In this thesis the difference between the spectral reflectance curves will be calculated using the basic Root Mean Square (RMS) error metric:

$$\sqrt{\frac{X_{400}^2 + X_{410}^2 + \dots X_{700}^2}{31}}$$

where X is the measured difference between the reflectance of the reference and the sample.⁸ In this equation differences are calculated at every 10nm from 400nm to 700nm. The final error was found by calculating the square root the mean of these thirty-one squared differences. It is understood that other metrics, such as Viggiano's SCI formula, may have the ability to identify the amount of error with greater consideration to the human visual system. However, the Basic RMS provides a simple calculation allowing for many comparisons to be made quickly, which meets the requirements of this research as will be described in Chapter 5.

2.5. Chapter Summary

The historical elements of colour study presented in the first section of this chapter provide the foundation for the development of digital colour printing applications, which will be described in the following chapter. The methods of colour acquisition and comparisons will also be expanded upon in Chapter 3, where current methods of application into existing and developing workflows are evaluated.

⁸ All calculations were conducted on normalised spectral reflectance data where the spectral intensity ranged from 0 to 1.0.

3

The Current State of, and Practices in, Digital Printing

3.1. Chapter Overview

This chapter introduces current research and development of inkjet printing systems by scientists and artists alike. It builds upon the introduction to the thesis by presenting the on-going research in the field of printing science, taking a more concentrated look at the technological development relating to the mixing and application of ink colourants. The second portion of this chapter addresses how advancing inkjet technology has been used in practice. By focusing on fine art practices, this chapter aims not only to highlight the disparity between the rationale and methods used in the arts and sciences, but also highlight how the incorporation of the two has informed my research as presented in the subsequent chapters.

3.2. Advancing Scientific Research in Inkjet Printing

At its most basic level, an inkjet print is the result of the deposition of ink onto a substrate, such as paper. Therefore, before leading into the advanced computational components of the printing process, it is necessary to consider how ink interacts with paper, and what parameters are put in place to ensure optimal quality in the print. From there this chapter will cover methods for

colourant selection in CMYK+ printing. This begins with an account of the early expansion beyond CMYK, and carries through to recent advancements in spectral reproduction. This section will conclude with an appraisal of the presented research and identification of key themes that will carry forth to the applied research in this thesis.

3.2.1. The Limited Gamut of Paper

In order to gain control of the ink and paper configuration, referred to as media characterisation, raster image processing (RIP) software is required.¹ RIP software offers direct control over many of the features that are built directly into the print driver algorithms, including linearization, ink limiting, screening (or halftoning), direct channel printing controls, and colour management. Linearization is conducted per channel for every ink colourant employed by the printer. It forms a smooth transition of ink from zero to 100%, limiting the ink at the point when dispensing additional ink onto the paper would achieve no greater tonal density. This prevents unwanted print artefacts, such as bleeding, that would result from printing with too much ink while also allowing smooth gradations to be produced in the final print. In addition to over inking, the linearization process corrects for the hue shifts that occur as a result of the nonlinearity of some inkjet inks as density increases, due to their possessing less than ideal properties (Pauler, 2012, p. 118). The hue shifts occur predominantly when printing layers of cyan, magenta, and yellow colourants. In many colour characterization workflows the linearization purposefully caps the amount of these colourants before they shift in hue, curving in the CIE colour space. This is primarily done for computational reasons, as a curve would create significantly more complexity in modelling equations (Upton, 2004, Quinn, 2013).

¹ RIP software is not required for all inkjet printing applications. All printer manufacturers provide a proprietary driver that will allow the user to forgo the need to purchase additional software. However, printer configuration is limited, often to the selection of subjective paper descriptions. The RIP software was integrated into this research to meet the demand for more advanced control of media characterisation.

The ink limit, more specifically the total ink limit, builds upon the linearization by controlling how much ink will be jetted onto the paper when multiple colourants are combined. This limitation is aimed at minimising ink bleeding and bronzing due the amount of ink exceeding the absorbency of the paper. Here, if an output file was sent to print calling for 100% of each cyan, magenta, and yellow, but the paper could not handle that volume of ink, then the RIP software will minimize the amount of each colourant to limit the total ink amount. To maintain the relative appearance of the CMY mixture, proportions of these three colourants can be minimised and replaced with black ink following the grey component replacement (GCR) approach. The concept of the GCR is that certain combinations of complementary, or triadic primaries (typically CMY) will obtain a neutral tone when combined, which can be replaced with black. This is done to reduce the amount of chromatic ink being used in the printed output. Since black ink is inherently darker than the CMY colourants, less ink is required to achieve the same tonal appearance, therefore reducing the total ink coverage required in printing (Upton, 2005). Despite the benefits to lowering the total ink coverage needed to print dark colour, it also needs to be considered that the implementation of GCR methods can result in a neutralizing of dark colour when too much black replaces the chromatic inks (Quinn, 2013).

Recent research by Jan Morovic, Peter Morovic, and Jordi Arnabat addresses reducing the amount of ink used in printing through a halftone optimisation process referred to as Halftone Area Neugebauer Separation (HANS). The reference to Neugebauer relates to incorporating the Neugebauer's Primaries into the colour separation stage of the printing process to determine area coverage, as opposed to ink amount (Morovic et al., 2012a). By examining the difference between printing the same area coverage of the CM primary (equal parts cyan and magenta) printed with the different halftone patterns, the authors found significant changes between the printed appearances. The

comparison of dot-on-dot and dot-off-dot halftoning² exhibited a 50% increase in lightness and the chroma dropped to 11% of its original value. In enhancing the effectiveness of the halftone patterns for all NPs, HANS led to an increase in total gamut volume, particularly in the darker regions of the green and red hues.

3.2.2. Extending Colour Gamut Boundaries with CMYK+ Inkjet Printing

Motivated by disappointment in the colour match between screen and print,³ researchers in the early 1990s began to explore the possibility of adding additional colourants to the traditional CMYK print process. In 1993 Victor Ostromoukhov proposed heptatone printing to increase chromaticity in order to better match a CRT display. In order to achieve this he observed the gamut would have to expand in the three deficient regions of “blue/violet/purple, turquoise/green/yellow-green and orange/red” (Ostromoukhov, 1993). Regardless of colourant selection, Ostromoukhov recognised the need to first establish a colour model that could accommodate the additional colourants. With halftone screening established for 4-colour printing, it was determined that the 7-colour gamut should be subdivided into six 3-colour gamuts, as illustrated in Figure 3.1. As with CMYK, each gamut subdivision can be printed using two chromatic colourants plus black. With an even number of chromatic ink colourants, each could be assigned one of two screen angles, which alternated around the outer gamut, as no two colourants assigned to the same angle would be chosen to print at the same time. Ostromoukhov further proposed an extension to 9-colour

² In digital halftoning the placement of individual dots of ink can be either superimposed over one another, or placed side by side. This is referred to as dot-on-dot and dot-off-dot, respectively. Because the optical blend of two colourants placed side-by-side does not match the colour sensation of the two colourants superimposed over one another, especially as dot-on-dot placement leaves more of the white of the paper exposed, the juxtaposition of two colourants can have a significant effect on colour appearance. (Hains et al., 2003: 435-437)

³ This sentiment was expressed in a paper published by Ostromoukhov (1993) and Takaghi, Ozeki, Ogata, and Minato of Toyota Motor Corporation in Japan, who sought to colour match the highly chromatic colour of auto exteriors from screen to print using a 9 ink printing system containing 7 chromatic ink plus a black and grey (Takaghi et al., 1994).

printing, majorly modifying both colourant sets to include alternatives to the traditional CMYK process colours.

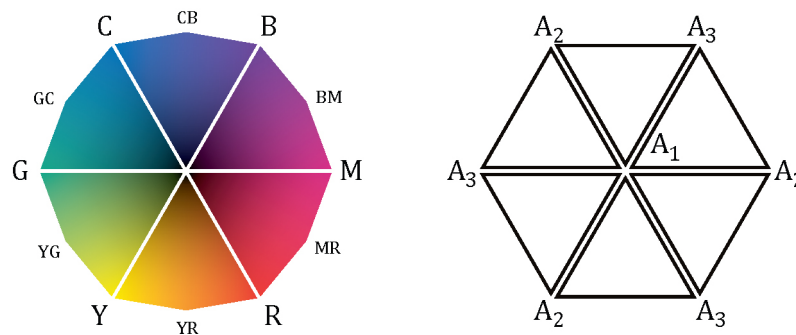


Figure 3.1. Illustration of Ostromoukhov's 7 colour, 6 subgamut division. The diagram on the left shows the 6 subgamuts using CMYKRGB colourants. Black is not labelled, but represented by the centre. The diagram on the right labels the 3 screen angle assignments (A_x) for each colourant in the 7 colour printing process.

While discredited by Ostromoukhov for a lack of success, Harold Boll recognised Harald Kueppers as the forerunner in developing the 7-colour printing process in 1989 (Boll, 1994, Kueppers, 1989). Replicating Kueppers's inkset, Boll added red, green, and blue (RGB) colourants to the traditional CMYK. However, he created an alternative subdivision that allowed any one colour to be printed with up to 4 inks, recognising that the additional ink expands the shadow region and the added chroma expands the gamut of midrange colours. Boll devised 6 subgamuts comprised of 4-ink groupings, each made up of three chromatic ink colourants plus black, as illustrated in Figure 3.2. Each subgamut then overlapped the one adjacent to form the total "supergamut," which Boll stated "maximizes the likelihood that the entire set of 6 targets constitute a reasonable sampling of all colors producible with 7 inks" (Boll, 1994). For printing, Boll preserved the screen angle assignments for CMYK and assigned the RGB colourants to each print at the same screen angle as its complementary.

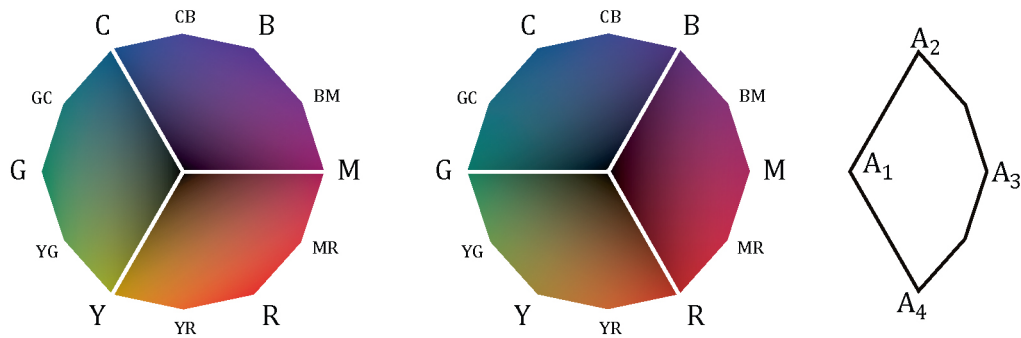


Figure 3.2. Illustration of Boll's 7 colour, 6 subgamut division. The two diagrams to the left show the 6 subgamuts using CMYKRGB colourants. Black is not labelled, but represented by the centre. The diagram on the right depicts the 4 screen angle assignments (A_x) for any of the given subgamuts, where A_1 always refers to black.

Research into expanded colour gamuts continued with the development of the Pantone Hexachrome colourant set, patented in 1998 (Herbert and DiBernardo, 1998). Not unlike Ostromoukhov's results, the Hexachrome colourants deviated from the traditional CMYK ink set to include yellow, orange, magenta, cyan, green, and black. The recommended colour separations were those of Boll's design, as the system was easily adaptable from Boll's 5-, 7-, and 9-colourant sets to the Hexachrome 6. That same year, prompted by rising interest in "hi-fidelity"⁴ printing, J.A. Stephen Viggiano and William J. Hoagland sought to develop a computational method to approximate gamut size of a six colour ink set (Viggiano and Hoagland, 1998). With their developed method they sought to find the optimal 6-colourant ink set containing process black and five chromatic colours from a possible 16 preselected Pantone inks. Similar to the Hexachrome set, the computed outcome indicated orange, blue, purple, red, and yellow would produce the largest gamut.

Marc Mahy and Francis Verbeek of Agfa Graphics patented an alternative method for colour separations using the 6-colour hexachrome ink set as an example of one CMYK+ separation method (Mahy and Verbeeck, 2011). Here the primary subgamut is the CMYK gamut, and the other subgamuts are

⁴ Hi-fidelity printing, or a "High Fidelity System" as Pantone referred to it, came to represent a colourant set that included more than the traditional CMYK inks between the late 1990s and early 2000s.

formed from one of the additional colourants, the two adjacent colourants, and black (Figure 3.3). It is my understanding of this patent that the primary aim is to improve the printing of colour trajectories that cross one subgamut and enter another. As the majority of colours are already contained within the CMYK gamut, Mahy and Verbeek's method prescribes which of these colours remain to be printed using only these colourants. The additional colourants are transitioned in only at the point where colours begin to extend beyond the CMYK gamut. An orange colour, for example, would only include the use the orange ink colourant when magenta and yellow alone could not produce the desired colour. This method prevents colour gradations from abruptly switching between colourants at the subgamut boundary wall. For example, to follow Ostromoukhov's model, the transition from orange to green would require the orange to first be entirely removed as the colour transitioned to only yellow and black at the subgamut boundary before the green colourant could be introduced. By Mahy and Verbeek's instruction, orange would first give way to magenta and yellow, then magenta would transition out so only yellow and black remained at the boundary with cyan, with the addition of green colourants at the end as necessary. For trajectories that travel through the central CMYK gamut, the colourant combinations would incur additional intermittent changes.

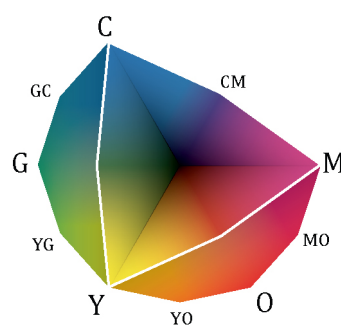


Figure 3.3. Illustration of Mahy and Verbeek's 6 colour, 3 subgamut division. The diagram shows the 3 subgamuts using CMYKOG colourants. Black is not labelled, but represented by the centre.

3.2.3. Minimising Metamerism through Spectral Printing Workflows

Metamerism, as defined in Chapter 2 (2.2.4) is of concern in colour reproduction, particularly when physical properties of pigments cannot be

replicated. An example of this is easily described using the painting *Whistlejacket* (about 1762) by George Stubbs (1724-1806), which hangs in the National Gallery, London. As first described by David Wood, a digital imaging specialist in the Gallery's Photographic Department, the hue in the background colour of this painting appears to shift between green and brown as the lighting conditions change over the course of the day.⁵ It became apparent that his was not an isolated observation through both my own viewing of the painting and by a separate conversation had with Jane Hyne, Production Manager at the National Gallery Company (NGC).⁶ As Hyne and I discussed the print services offered by the NGC, particularly the challenges related to reproducing certain imagery, she recounted discussions held with her team on which colour hue to reproduce for the background of this particular painting. The need to choose between the dominant green or a more neutral brown stems from the fact that the printed colourant combination achieved through their current inkjet workflow does not possess the same physical properties as the original, and does not react to changing light conditions the same way. If the colour in the painted background of *Whistlejacket* could be produced as a spectral match, then a compromise would not have to be made in producing an accurate reproduction.

The possibility of defining a feasible and effective spectral imaging workflow has been greatly researched, and it would be unreasonable to recount even the most significant advances here, especially given the small portion of my research that addresses a spectral printing application. Therefore I aim to address only three considerations as they pertain to my research. These are examining the interest in spectral printing for fine art reproduction, the

⁵ Wood's explanation of this change in colour appearance is a direct result of the fluctuating lighting conditions in the Gallery. Large skylights provide diffuse ambient light during the daylight hours. As a result of the natural light conditions, passing clouds can cause frequent and considerable changes in colour temperature. (personal communication, 21 June, 2013)

⁶ Distinctions between the Photographic Department within the National Gallery, London, and the National Gallery Company are described in the introduction to Chapter 5 (5.2).

methods and considerations that have developed in relation to colourant selection, and the forward outlook for advancing spectral printing towards a standardised and accessible application.

With the expansion of inksets to include additional colourants beyond CMYK, a new opportunity presented itself for minimising metamerism resulting from changes in illuminants and also between human observers. Where the subgamut divisions described in section 3.2.2 focused on minimising the number of possible colourant combinations for producing a single colorimetric match, researchers at the Munsell Colour Science Laboratory took advantage of the opportunity to select from multiple colourant combinations to maximise colour constancy⁷ in colour output (Chen et al., 2003).

Perhaps the largest research area related to spectral reproduction is in defining the transforms from spectral reflectance data to colourant combinations. In early inkjet work Lawrence Taplin and Roy Berns (2001) implemented the Yule-Nielsen Neugebauer Model⁸ to printing with a six-colourant printer. The additional colourants increased the number of Neugebauer Primaries to 64, as it exponentially increased the number of possible combinations. Although the 64 NPs would achieve up to 600% total area coverage, the authors restricted the maximum to 300%, presumably to prevent over inking. It is acknowledged that this method, which occurs in an uncompressed spectral space, is not feasible due to computational complexity (Imai et al., 2003). This has been addressed by both compressing spectral data (Rosen et al., 2001), and through a “hybrid” method as later introduced by Mitchell Rosen and Maxim Derhak (2006). Rosen and Derhak’s combination spectral and perceptual LabPQR space works by identifying a match to the input spectra first in CIELab, and then in the PQR spectral space

⁷ Colour constancy is defined as the human visual system’s ability to perceive colour of an object as unchanged when undergoing changes in lighting condition. (Johnson and Fairchild, 2003: 148)

⁸ The Yule-Nielsen modification to the Neugebauer Model accounts for light scattering on the substrate. (Bala, 2003: 349)

corresponding to that location. While the LabPQR presents a more feasible working model, it is still restricting ink mixtures. For example, while sampling from all 64 NPs, a total area coverage of 220% was set during characterisation (Tsutsumi et al., 2007, Chen et al., 2004).

An alternative method, developed by Philipp Urban and Berns (2011), limited the number of colourants in any given combination to four, and uses colorimetric gamut mapping, but for multiple illuminants. By ranking the illuminants by importance, all the possible colourant combinations that would reproduce a selected input colour below a threshold colour difference can be identified for the first illuminant. Subsequently, the colourant combinations capable of reproducing the same colour under the second illumination are selected, reducing the number of possible combinations. This continues until the optimal colourant combination is identified. While this method showed some success, artefacts occurred in regions with smooth tonal transitions. While the two source colours of neighbouring pixels are quite close, the colourant selection may differ, resulting in banding artefacts. While solutions have since been provided by Sepideh Samadzadegan and Urban (2015) to eliminate these artefacts, they continue to recognise the small size of the spectral gamut and the improbability of finding a true spectral match to the reference remains.

In 2012 Peter Morovic, Jan Morovic, Jordi Arnabat and Juan Manuel Garcia-Reyero conducted a study comparing colorimetric and spectral colour reproduction. This included printing a colour sample set through a custom colorimetric workflow using ICC colour management, and a spectral reproduction workflow. The authors introduced a new colour difference metric, MIPE, which presents the minimum, mean, and maximum colour difference calculated from a sample of 173 measured light sources. After presenting results showing a “mixed bag” of advantages, the authors concluded that while spectral printing is an “exciting” opportunity, it remains limited in application due to the significant increase in computation yielding a small margin of improvement (Morovic et al., 2012b). Months later Jan

Morovic gave a talk entitled *The Spectral Printer: from Technical Challenge to Business Case* where he expanded on the conclusion from his earlier publication, stating the limitations in spectral printing could not be overcome by software alone. Attention must be given to the fact that the printers used in current research were not designed for spectral printing, and optimization of ink and paper would be equally as critical for expanding the still small spectral gamut (Morovic, 2013).

Spectral printing remains a specialised print application, limited to research labs. At this time no recommendations have been made to address industry standardisation, and the research presented in this thesis does not aim to recommend a computational method for colourant selection or halftoning. As will be further expanded upon in Chapter 5, the spectral component seeks only to assess the developed print methodologies' ability to improve upon the colourmetric results of colour reproduction through an ICC workflow, as was seen in the work by Morovic, Morovic, Arnabat and Garcia-Reyero.

3.2.4. Response to Advancing Colour Computation

With the ability to increase the colour gamut into lower lightness levels while optimising ink consumption, Morovic, Morovic, and Arnabat have presented a possible alternative to the GCR method. The potential to lower dependency on black ink exists in instances where printed colour appears darker through the modulation of area coverage. Subsequently, when black ink is less dominant, the remaining ink colourants are able to better preserve their chroma. This begs the question if the traditional sequence of colour separation independently before halftoning is a limiting factor to the colour mixing capabilities within inkjet printing.

It is also worth revisiting the early assumptions made in relation to subgamut division of CMYK+ colourant set. With recent advancement in hardware and software these may no longer be qualifying limitations to the inkjet printing process. Although CMYK+ inkjet printing has expanded the achievable colour gamut, each of the discussed subgamut methods restrict the number of colourant combinations that can be used to create the printed colour. The

literature suggests that black ink can be used, rather than complementary colours, to print a colour towards neutral. However, from an arts perspective, mixing complementary colourants to reduce the chromaticity, or dull a colour, is one of the most basic colour mixing principles. It is taught using black to darken or lower the intensity will inadvertently diminish the hue, while mixing in the complementary, or alternative dark colourants, the colour can maintain chromaticity as the colour darkens, or more subtle transitions in intensity as it neutralises (Edwards, 2004, pp. 70,80-81).

While Boll recognised that printing with four inks improved the range of shadow colours, he did not feel there was more to be gained by increasing the number of ink colourants and that it would only lead to moiré issues and add to drying time (Boll, 1994). Several rebuttals can be made to this sentiment. First, with the introduction of frequency modulated, stochastic halftone patterns the restriction to ink colourants according to available screen angles is no longer a concern. Second, unrestricted by screen angles, painters such as Georges Seurat combined as many as five colourants into his paintings, including complementaries, to produce a single colour appearance at a viewing distance.⁹ Finally, while the drying time is of concern for high speed, commercial printing application, artists will oftentimes accept longer production times in order to achieve the desired final product.

These considerations have directly informed my practical research, which examines how additional changes in the deposition of ink colourants can affect the printable gamut. This will be discussed throughout Chapter 4.

⁹ This statement is informed by personal observation of Seurat's *The Channel of Gravelines, Grand Fort-Philippe*, which hangs in the National Gallery, London. This painting is an example of the pointillism technique developed by Seurat in the 1880s, where small dots of paint optically blend when viewed at a distance to form the coloured elements of the painting.

3.3. Contemporary Context of Printing from an Arts Practitioner Perspective

While the standard print workflow is able to produce a print satisfying the user's needs in the majority of applications, there exists a subset of the fine art market that demands more from the technology than its capabilities straight out of the box. Art practitioners, particularly those that have migrated from traditional print practices, have a penchant to push the limits of processes, developing their own customised inkjet printing methods that better inform an ideology for technique, method, and approach.

In this section I will review the practices of select print studios and practitioners, providing insight into the motivation and rationalisation for taking an alternative approach in their use of inkjet printers. It begins by reviewing the onset of professional print studios working in collaboration with artists to produce previously unattainable artworks. It then expands to contemporary practitioners beginning to amend the way the printer functions, in order to produce printed works by an alternative means.

3.3.1. Implementation of Digital Printing in Arts Practice

Nash Editions pioneered digital inkjet printing for the fine art market. Graham Nash created the business to produce quality prints that met the scrutinising aesthetics of artists and photographers. Giving precedence to the printing of original works rather than reproductions, Nash sought to approach the printed output not as a colour matching exercise, but as a collaborative process involving dialogue with the artist or photographer (Holbert, 2007, p. 11). This began with utilising IRIS inkjet plotters, primarily used for architectural prints, and examining the technology and inks incorporated into the devices. In the early stages of development this entailed defining workflow standards with the aim of achieving predictable colour and image permanence. They extensively tested the machines and developed their own colour look-up tables, establishing the technology for use in an entirely new market (Holbert, 2007, p. 39).

Another pioneer, working at the same time as Nash, was Jon Cone. He focused on developing ink sets that met artists' need for archival products. Working as a technology developer while running his own editioning practice, Cone had a hand in developing the quality standards the market meets today.

At the Centre for Fine Print Research, Paul Laidler established CFPR Editions, a print editioning studio founded on the idea that digital printing extends beyond that of 'just pressing print'. The founding principles for this developed out of prior research into the investigation of alternative practices using inkjet technology to produce fine art prints. One example of this is the work produced in collaboration with Jack Youngblood in 2003. Here the artist expressed concern that the current technology could not produce a black as dense as what he aimed to achieve. The solution for this was to reconfigure an inkjet printer to accept a previously printed sheet so it could be passed back through the printer to apply another layer of ink. Youngblood's *Spate*, 2003 was created by printing a second image, adjusted to include only the portion of the original underlying image where an extra layer of black ink was desired. (Laidler, 2011, pp. 129-132)

The methods with which these digital printing processes began to incorporate the considerations practitioners held in traditional printing gave attention to broader questions that resonated with a large portion of the fine art market: What are the limitations practitioners are encountering in prescribed inkjet printing workflows? With much modern investigation looking into the concerns of reproduction, how can workflows be altered for those creating digital originals?

3.3.2. Adverse Effects of Prescribed Print Dialogues

While inkjet printer manufacturers aim to provide practitioners with a complete solution to their printing needs, they oftentimes create barriers for artists who are accustomed to working in a more iterative fashion. Traditional print processes incorporate the final print into all stages of production, through the design of plates, the manual mixing of ink, and so

forth. Digital processes generally create a divide between design and print, where the intention is to create first and print later.

By presenting users with pre-packaged software restricted by standard interfaces concealing self-contained systems, practitioners are automatically giving up extreme amounts of control to their process. Without the ability to accurately pre-visualize the printed output, artists can easily be underwhelmed by their results without a necessarily intuitive fix. CMYK+ inkjet printers now offer a larger colour palette with the addition of new ink colourants, but precise knowledge of how these colourants are mixed, or even their actual hue, remains proprietary information. With source files either being sent with RGB or CMYK colour values, it is difficult to accurately identify how the printer's conversion engine transforms mathematical data to physical ink distribution. As all this is done by the printer driver, it does not allow an artist full control, and can be limiting to the potential colours that can be produced.

In traditional practice it is the process of testing and working through individual parts of a piece that allow artists to become masters of their craft. When the production process stops being fluid and becomes prescribed, it is often difficult to understand how and why colour management may have failed to achieve a desired result. If ink mixing approaches were applied to inkjet printing that reference traditional printing processes, there is a potential to achieve colours beyond the capabilities of standard print drivers simply by allowing for the artist to make decisions rather than the machine.

3.3.3. Contemporary Art Practitioners Addressing These Limitations

The implementation of alternative practices into the inkjet printing process is not isolated to collaborative print studio environments like Nash's. As inkjet printing equipment became more affordable, practitioners have been able to purchase their own printers for use in their personal studio, where they can experiment and explore methods for the production of their work in a way that marries their previous knowledge base with this new technology. This has led to the development of various nonconventional approaches to inkjet

printing, including multiple pass printing, which has been employed to overcome observed limitations within current inkjet printing systems. This has afforded artists the opportunity to make changes and enhancements to the image as the print evolves iteratively into the final product.

In this section I will present the arts practice of two individuals whose methods and approach to inkjet printing are similar to my own. The review of these practitioners has led to a more critical evaluation of my own work by recognising and articulating the similarities and differences. I will highlight a number of ideologies that support the argument I have formulated for my research, particularly in relation to the need to develop alternative methodologies in order to overcome the noted limitation to the current technology and associated workflows.

Richard Benson

In late 2006 George Jardine interviewed Richard Benson, a photographer and educator, for an Adobe Systems video podcast. With a long career as a photographic printer, Benson has migrated from analogue to digital, and brought with it all the sensibilities that can only come with years of manually tweaking tonality and colour in the darkroom. He found that colour management training tutorials were always focused on small trivial details, never directly related to how you could get what you wanted out of the printer. Despite his best efforts using ICC colour management, and also third party RIP software, he found the printed colours were unexpected. In conversation with Jardine, Benson attests

"I was never able to get colour management to work. It's the creation of a mad man... It's the stupidest system I've seen in my life, and I could never get it to work." (Benson, 2006)

In response Benson come up with an alternative to colour management and modified an inkjet printer by applying the thought process and methods he developed over years in the photographic darkroom.

Benson uses a process he calls multiple impression inkjet printing. He does this with the use of a custom rig that extended in front of and behind his Epson 4000 series printer, lined up with the straight feed paper path. This allows the paper to be fed back into the printer in perfect register. With the ability to reload, and print on, the same sheet of paper Benson is able to “build the picture up in stages” by incrementally adding new layers of colour, and making changes in the print according to the results. He begins by printing a faint impression of the image, and from here he can make changes to the file before he prints an additional layer. This allows him to analyse the printed colour and decide what corrections he needs to make before moving forward.

Using this process Benson accounts that the colours not only looked the way he wanted, but the process showed him what they could be. This resulted in a colour picture that he could not have made otherwise. He recognised that this does not mean these colours extend beyond those the printer is capable of generating if using ICC colour management, but that these are colours he personally could not have achieved by doing the printing process any other way. What he finds most important about this process is it enables him to work iteratively. These methods are considerably different from the process of working with digital files where colour is corrected on the computer and soft proofing methods are used to confirm colour before it goes to print.

Campbell Laird

Campbell Laird also utilises the multiple pass printing process, but with a different intent from Benson. Laird’s use of this method is not solely about colour, but is significantly more about composition and the process of making. Laird states, “I want to use the printer as a tool for making Art rather than a machine to output a complex digital image composed in the computer” (Laird, 2012c). To break away from the complex design files he previously produced, Laird discovered a method for producing new prints that only contained a small number of elements in the file, but over time could become more complex in printed form than previous work. He finds that:

“This is the only way to make these prints. Trying to layer all the passes on one image file can’t work as the file becomes overloaded with millions of lines and intersections and appears as just an unrecognizable blob on the screen. Even if I could see the image properly the file is too complex to be printable.” (Laird, 2012c)

Laird describes his work as “hand drawn vectors passed endlessly through an inkjet [printer]” (Laird, 2012a). Beginning with one simple shape, he prints his first layer before returning to the computer to make a modification to the file and print on the same sheet of paper again. In this way he finds he can work iteratively, building up layer upon layer where “each new element suggest[s] the next” and the “image is slowly developed over time into something complete and unique” (Laird, 2012b). The interactive way in which Laird engages with his inkjet printer is reminiscent of analogue printmaking processes.¹⁰ Each time a decision is made and ink is applied to the paper, he reflects on what he has created thus far, and using that information to inform his next step. Here there is no longer a distinction between creating the design and printing it, as these two are intertwined in his process.

Summary

The unifying aspect of these methods is the action of reloading the same sheet of paper into the printer multiple times. While the terminology established by these artists has varied, in this thesis the process will henceforth be referred to as multiple pass printing. While the process has been the same, the rationale for its use has been quite varied. Multiple pass printing was used to increase the total ink density on the black region of Youngblood’s print *Spate* which highlighted the artist’s desire to achieve a denser, richer black than could otherwise be achieved with the technology at

¹⁰ This sentiment, which is my own, was later found to be shared by LACDA: “But like traditional artists, Laird directly interacts with the physical printed piece, putting the unique signature of “the hand of the artist” into what would otherwise be a completely automated process.” (Los Angeles Center for Digital Art, 2013)

that time. Benson found he could better control output colour through the iterative process of building layers slowly, while Laird was interested in building colour and density incrementally and making corrections as he went. My use of multiple pass printing, which will be discussed in the forthcoming chapters, aims to develop a methodology that can expand beyond an individualistic approach to something that can be integrated into a larger output methodology.

4

Development of Test Procedures

4.1. Rationale for Chapter

In the Introduction I described how the implementation of an ICC colour managed workflow allows input colour values to be converted by a colour management module to determine the combination of ink colourants used for printed output. While accurate colour can be reproduced in the majority of applications, the automation causes the user to surrender control of the colour mixing process. For an arts practitioner this restricts and limits the number of ways colour can be constructed. The work described here implements methods for mixing ink colourants in ways that are considered unconventional for standard inkjet printing practices, and more akin to arts practice.

One of the methods integrated into my research is multiple pass printing. Conducted in a manner similar to the practices of artist Campbell Laird and photographer Richard Benson, whose work was described in Chapter 3 (3.3.3), the multiple pass printing process refers to the physical act of loading a single sheet of paper into the printer multiple times. Each time the paper is loaded into the printer a unique file is printed onto the paper over the top of the previously printed image. Unlike Laird and Benson, my use of multiple

pass printing is less about an individualistic arts practice, and more about establishing techniques for the generation of previously unachievable colour. Although Benson was also interested in achieving colour by an alternative means to standard colour management workflows (Benson, 2006), the distinction between his and my use of multiple pass printing is that I aim to control colour through a formulaic and repeatable process that can be later integrated into printing applications.

4.2. Chapter Overview

In this chapter I will discuss the practical work undertaken in defining and refining alternative printing methods, including the generation of custom colour charts used for the analysis of these methods.¹ In the previous two chapters I have discussed the current state of the disciplines in which I am situated: both the scientific/technical aspects of colour printing, and the qualitative aesthetics in the field of fine art printing. Through this exploration I have highlighted the strengths and weaknesses of the current inkjet printing process in relation to its associated equipment, the computational aspects of its colour rendering, and the subjective reactions of practitioners in the field. The culmination of knowledge gathered through this survey has informed my hypothesis: modifications to the standard printing workflow, adapted from traditional printmaking and painting practices, can extend the reproducible colour gamut of a fine art inkjet printer compared to the standard ICC colour managed workflow.

My research seeks to employ the colour mixing principles used in painting and traditional print processes. This is realised through the incorporation of direct channel and multiple pass printing (DC/MP) methods, each of which is outside the scope of typical inkjet printing practices described in the introduction of this thesis (1.2.2). The direct channel control occurs on a

¹ Portions of this research have been published in *AIC Colour 2013, Proceedings of the 12th Congress* (Olen and Parraman, 2013), and the *Proceedings of SPIE 9015, Color Imaging XIX: Display, Hardcopy, and Applications* (Olen et al., 2014).

channel-by-channel basis, where each channel carries one of the ink colourants through the printing system. This allows any colour channel, or more specifically, ink colourant, to be controlled independently.

The second printing method, multiple pass printing, is a control of the physical printing process, as opposed to direct channel printing being controlled by the software. With each print the paper passes through the printer, allowing the ink to build up in layers on the surface. Through this process I am able to control the order in which colourants are applied to the paper, once again allowing for control of the colour mixing process. Through this process I am able to employ colour mixtures that are not typically used by printer drivers, and also incorporate colour mixtures that would not be possible otherwise.

The investigation and analysis of these two printing methods was undertaken through designing, printing, and evaluating custom colour printing charts. From the very beginning of my research I identified the need to create my own test charts to evaluate different elements of the research due to the lack of any readily available or standardised options. This is due primarily to my incorporation of printing methods that have only been used selectively in creative practices seeking solutions to the technical shortcomings of the inkjet printing equipment. At this time these methods have not been introduced to the fine art printing market to widely address their advantages. The charts I have constructed aim to integrate both qualitative and quantitative methods for appraisal. This implementation of mixed method research allows for not only the analysis of measured colour, but also for visual assessments to be made.

The following sections in this chapter will discuss my equipment parameters and the process of developing my DC/MP printing methods. First I will describe the equipment I have selected for my testing parameters, along with the rationale behind the choices I have made. Following this I will begin to discuss the series of custom colour charts I have designed, which have developed iteratively over the course of my research. In these sections I will

address the rationale for each chart's development, method of production, and analysis. In the summary I will abridge these findings and draw attention to potential incorporation into practical applications, which will be further expanded upon in the forthcoming chapters.

4.3. Equipment & Consumables Specification

I have given thorough consideration to the software and hardware used for this research. Through an extensive survey of the market, along with previous experience gained through years of working in these environments, I have acquired a comprehensive understanding of the unique requirements of a fine art digital studio. This has provided me insight into the advantages and disadvantages of the range of equipment available. It is with this knowledge that I have assembled my own digital setup, ensuring my research maintains relevance to the field in which it is situated. The following states the rationale for my selection.

4.3.1. Imaging Software

All design work has been undertaken using the Adobe range of imaging software, including Photoshop, InDesign, and Illustrator. As these are the industry standard for both the fine art and commercial print markets this choice ensures later transferability to application-oriented practices. It is understood that alternative software applications, such as MATLAB,² would have allowed for faster generation of some of my print files. However, this software is not prevalent in the fine art market, and its use would limit the transferability to those unfamiliar with this type of computing software. Furthermore, it has been through the manual process of designing and constructing these files that I have expanded upon my understanding of the process and how to control it. The insight I was able to gain also proved

² MATLAB, a product of MathWorks, is computing software used to perform image processing, analysis, and algorithm development through its Image Processing Toolbox (<http://uk.mathworks.com/products/image/>). The software is popular in scientific research fields related to colour, including image enhancement and printing.

valuable to the later implementation of my printing methods into the creation of original designs, which will be discussed in Chapter 6.

4.3.2. Multi-Channel Inkjet Printers

Significant debate exists over the ‘best’ inkjet printer available, particularly within the fine art market. Fuelled by promotional campaigns put out by the manufacturers, and a vast amount of reviews published online, hype and brand loyalty can have as much influence as the technical specification and price of the printer.³ Based on the quantitative evaluations I have made of several leading inkjet printers,⁴ as well as evaluating the technical requirements for my research, I have chosen to work with the Canon imagePROGRAF 8000 series inkjet printer. In addition to the standard colour set of cyan, magenta, yellow, and black (CMYK), these printers include red, green, and blue (RGB) ink colourants. Including additional light colourants, these printers are designed to utilise twelve ink channels.

The preliminary testing and development of my printing methods was undertaken using the iPF8000 model, and as the research began to confirm my initial hypothesis, the research was transferred to the latest iPF8400 model to ensure the research was compatible with the most current technology available. Appropriate testing and refinement of my working

³ Current manufacturers’ advertisements allude to capabilities through vague adjectives rather than specifications. HP’s tagline of “Versatile. Efficient. Easy.” states nothing of the tangible capabilities of their wide format machines (<http://www8.hp.com/us/en/large-format-printers>). In a 2015 promotional video discussing Canon’s “Light to Ink” campaign, one photographer described the inkjet prints as “crisp and clean” (<https://www.usa.canon.com/internet/portal/us/home/explore/see-impossible/FromLightToInk>). This use of nonspecific terminology extends beyond the advertising platform. Several professional photography websites and supply company blogs, including luminous-landscape.com, northlight-images.co.uk, and breathingcolor.com, try to give factually based reviews of the latest printing technology on their websites, the ambiguous terminology remains present with the use of phrases such as “improve[s] the rendition of extremely fine detail,” “more realistic” colour, “a greater range of vibrant colors” without the support of quantitative evaluation.

⁴ The market addressed by this statement is the fine art inkjet printing market, which predominantly utilises the aqueous inkjet printers produced by Canon, Hewlett Packard, and Epson. A statement on the comparison between the Canon and HP printers is made at the end of this section. Epson’s fine art printers, the Stylus Pro Series, were removed from consideration due to the limited colourant sets. Only one model, now discontinued, ever expanded beyond CMYK colourants.

method confirmed consistency in my results when upgrading to the newer model, and all media loading and printing parameters proved transferable.

Out of the twelve ink channels in the iPF8000 series, seven were used for the testing parameters: cyan, magenta, yellow, red, green, blue, and black. I disregarded the additional light inks (photo magenta, photo cyan, photo grey, grey), as light colours are typically used in printing only densities below 75% for the benefit of improving the visible appearance of the printed droplet of ink (Caldera, 2013). Of the two black ink options available, photo or matte, I used only the one corresponding to my paper type.⁵

To validate the transferability of my methods across different devices, I chose to replicate several of my tests using the Hewlett Packard DesignJet z3200 printer. The transfer of methods to the z3200 printer allowed for this research to be assessed using a second set of inks, ensuring the observations made with the iPF8000 series printer were not exclusive to a single device. Similar to the iPF8000 series, the z3200 possesses a twelve-colour inkset including red, green, and blue inks. This allowed all test charts to be compatible with both devices without the need for reconfiguration. While the same general effects could be achieved with the z3200, the iPF8000 series remained my primary machine as it produced better print quality and a greater dispersion of chroma in a sample set of dark colours. An overview of the comparisons made between the Canon iPF8400 and HP z3200 printers can be found in appendix B.

Moving forward the seven colourants of cyan, magenta, yellow, black, red, green, and blue will be referred to as C, M, Y, K, R, G, and B, respectively, to provide brevity.

⁵ While concerned with print quality, I have chosen not to use these lighter inks as the majority of my research only incorporates full strength colour printed at 100% output values. Furthermore, when incorporating light inks a transition curve must be generated individually for each light and dark combination to determine at what point the primary ink colourants start to replace the use of the light version. This was deemed to add unnecessary complexity into the initial research question. The choice between blacks, a photo black or a matte black, is designed specifically for use with lustre and glossy surfaces, or matte surfaces, respectively.

4.3.3. Raster Image Processor (RIP) Software

A short series of tests, conducted by printing through Adobe Photoshop using its proprietary colour management dialog boxes in conjunction with the Canon print driver, confirmed the inability to control the ink channels independently of one another. This is due in part to the fact that the inkjet printers' colour ink sets are typically modified according to manufacturer specifications and therefore require combinations of multiple colourants to reproduce the standard process colours of CMYK typically seen in other methods of colour reproduction, such as offset lithography. To compensate for this, custom colour transforms are needed to generate the colour separations in order to match the expected appearance of colour using a combination of inks (Lammens, 2008).

In order to selectively control the ink colourant combinations through direct channel printing, a direct dialogue needs to be established between input colour data from the image file and the printer's ink output. The integration of a third party, raster image processor (RIP), software was identified as necessary for gaining this increased level of control in the printing process. The Caldera VisualRIP software was selected for my research as it offers the ability to print using an integrated print option, *Direct NColor*, which allows colourant combinations to be defined in design and image editing applications, such as the Adobe software, and communicated directly to the printer, overriding all colour rendering modifications. For example, Figure 4.1 shows microscopic image captures of yellow, first printed from Adobe using the Canon print driver (left), and then with Caldera's *Direct NColor* option (right). The appearance of green and magenta or red ink is visible in the printed colour produced using a standard ICC colour management workflow. The *Direct NColor* output on the right illustrates the direct channel method's ability to print only the yellow ink onto the paper.

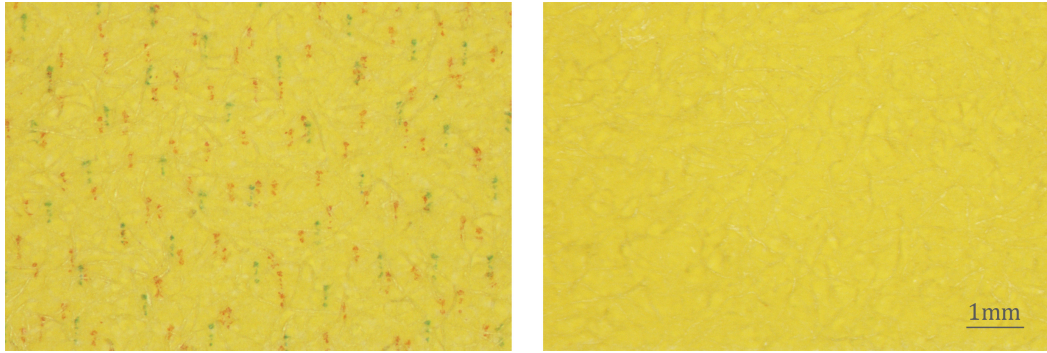


Figure 4.1. Microscopic image capture of printed yellow outputs using colour management (left) and direct channel capabilities (right).

While the direct channel printing capabilities are not exclusive to this research, as they are achieved using a readily available function in the Caldera RIP, there is no clear indication of Caldera's intended use of the feature. None of Caldera's software manuals for version 9.2 (the version used in my research) make mention of this feature. Hovering over the text accesses the only information provided when a pop up window appears describing its capabilities and file eligibility. Regardless, identification of this feature during a trial period of the software led me to successfully negotiate a licence of the software for the duration of my doctoral studies. Since this agreement was originally made, Caldera started distribution of a newer version of the software. I have chosen not to upgrade as none of the advertised new features pertain to the function I am working with, and to eliminate unnecessary migration issues. However, I have confirmed the features employed in my research are still available with the newer version.

4.3.4. Paper Selection

The options for fine art inkjet printing papers are vast. Larger manufacturers can offer up to ten paper options in their matte range alone, made from everything from traditional wood pulp to bamboo fibre. Through years of previous experience selling these papers to digital printmakers and photographers, along with working with several manufacturers on colour profiling, I have gained intimate knowledge of the characteristics of the leading products available. For the majority of this research I have chosen to work with the Somerset Enhanced range of papers. This 100% cotton paper

possesses many of the qualities discerning printmakers and photographers require, mainly as it is archival, absorbs ink well, and has low levels of optical brighteners.⁶ These papers, which are identical aside from three choices in surface texture (smooth, velvet, and textured), possess a matte surface. A matte paper was chosen for this research as it can handle larger quantities of ink, allowing the ink to partially absorb into the surface of the paper in addition to the inkjet receptive coating on top. This quality was particularly important to the multiple pass printing process, as the ink could dry into the fibres as additional layers were applied without bleeding. As part of my selection process, alternative papers were tested to evaluate suitability for my printing methods, including both matte and lustre surfaces.⁷ However, in this chapter and the following chapter, I will only discuss the results achieved using Somerset Enhanced papers, as these provided the strongest overall qualities for compatibility with my research methods meeting a fine art practitioner's requirements.

4.3.5. Measuring Devices

Various colour measurement devices have been used over the course of this research. For the majority of my initial measurements I used the XRite i1 Pro spectrophotometer. This handheld device, an industry standard in the graphic arts fields, allows for fast measurement of many colour samples. This, along with its ability to output spectral data, was essential to my quantitative evaluations. However, as my research progressed and I began to evaluate colour differences between dark colours that were close in hue, I found I had reached the limitations of this device's capabilities. At this time I identified the need for a device that obtained more accurate measurements of short wavelengths and eliminated variability between measurements, and found

⁶ Optical brightening agents are commonly used in paper manufacturing to make the paper appear whiter, compensating for the natural colouration of the raw material. However, these brighteners can degrade, largely from exposure to ultraviolet light, causing the surface of the paper to yellow over time.

⁷ A portion of the research conducted into the absorbency of various papers was conducted in collaboration with CP7.0 project partners from Gjøvik University College in Norway. (Slavuj et al., 2014)

the Konica Minolta FD-7 spectrodensitometer as the most appropriate device for measuring the dark colours produced in my research. While this device was not obtained until later in the course of my research, all measurements (unless otherwise stated) were retaken using the FD-7 in order to validate earlier quantifiable evaluations.

For the occasions where a handheld device was not suitable, particularly when obtaining measurements from a painting at the National Gallery, London, the Konica Minolta CS1000a spectroradiometer was used. This device allowed for measurements to be taken without touching the surface of the painting, ensuring the appropriate handling of the artwork. A more detailed account of this will be presented in Chapter 5, which covers one of the potential applications for my research.

In addition to the device itself, careful consideration was given to the data that was recorded. All original measurements were recorded as spectral data. This ensured that if any errors or questions of validity arose in the analysis of the data then there was a raw source to return to, which had no transforms applied (other than automatic correction to discount the device's illuminant). For analysis and representation I worked directly with the spectral information, which will be described further in Chapter 5, and also CIELAB calculated values. In converting spectral data to Lab values I chose to use the graphics arts standard illuminant D50, and the 2-degree observer using CHOMiX ColorThink Pro Software (version 3.0.3). This was kept consistent for all transforms.

4.4. Development and Refinement of Direct Channel & Multiple Pass Printing Methods Using Colour Charts

The following sections outline a selection of the colour chart based experiments I conducted throughout this research.⁸ Each chart is built upon the observations and analysis of preceding charts, which progress from simplistic to more technical, as they address the increasing parameters for control over the printing process. Each test chart is described in its own subsection following the evolution of their design and integration into my research. These charts were designed to meet the requirements of visual assessment and providing colour data for quantitative evaluation. The five colour charts covered in this chapter are:

1. Colour Bar Chart
2. Colour Circle Chart
3. Custom Ink Limit Chart
4. Colour Permutation Chart
5. Maximum Variable “MAX” Colour Chart

4.4.1. Preliminary Evaluation Using a Colour Bar Chart

Rationale and Design of the Colour Bar Chart

The objective of the first colour chart was to verify the correct implementation of direct channel printing, and to evaluate the effects of layering colour in different permutations through multiple pass printing.⁹ It also was used to refine the registration process, which was essential to printing each pass consistently in line with the previous one. The chart is

⁸ Additional colour charts will be described in the following chapter, as they pertain directly to the work carried out on colour matching for fine art reproduction at the National Gallery, London.

⁹ Recalling the research conducted by J. Morovic, P. Morovic, and Arnabat, discussed in Chapter 3 (3.2.1), where the printed output was modified by changes to the halftone patterns through HANS, a distinction should be made between their approach and mine. Where HANS alternated the arrangements of colourants side-by-side, my research does not address the halftoning of the printed output, but consistently implements Caldera’s stochastic setting. Instead the change in colourant arrangement is made laterally, by modifying the sequence in which each colourant is applied to the paper.

comprised of a simple crosshatch pattern that included the seven ink colourants and consisted of three separate layers. Details on the Colour Bar Chart design specification can be found in appendix C. This will be the same for all colour charts presented in this chapter.

When printing this test chart, or any other DC/MP print, care was taken to avoid over inking, scuffing, and misalignment between layers.¹⁰ The time between print passes was at least 2 to 4 minutes for up to 3 layers. This delay was not found to have an effect on the appearance of the printed colour,¹¹ but was instead necessary to allow the print layer to dry between passes so that when the paper was reloaded into the machine the guide rollers did not scuff the print. Additionally this drying time ensured the next layer of ink was not applied to a wet layer. If the previous layer of ink was wet when printing the following layer on top it could lead to ink bleeding across the paper. For this reason, as the volume of the ink increased with each layer, more time was allocated for the ink to dry before the next pass was printed. To ensure accurate registration for each printed layer, guide marks were used either on a table positioned directly in front of the printer, or on the printer itself. The printed version of this chart is shown in Figure 4.2.

¹⁰ Hans E. Neugebauer, discussed in the introduction of this thesis (1.2.1), addressed the registration process as it pertained to his colour prediction models and transferability to practice. Neugebauer attests that when printing using a stochastic dot placement, slight shifts in registration will not affect the final printed colour, as the relative positioning and proportions remain the same (Wyble and Kraushaar, 2005). The same had been found true in my research, which is quantifiably supported by the next footnote (11).

¹¹ To verify that the time between print passes had no significant effect on the final printed colour, one of the later described test charts was printed both with minimal delays between passes and with an hour between each pass. The colour differences between the two printed version were calculated using the dE2000 and RMS metrics. Of 293 colour patches 73% had a dE of less than 0.5. 24% were calculated to be between a dE of 0.5 and 0.9. The remaining 8% fell between a dE of 1.0 and 1.46. In the RMS calculation 94% measured an error less than 0.005. The remaining 6% spanned RMS error rates between 0.005 and 0.01.

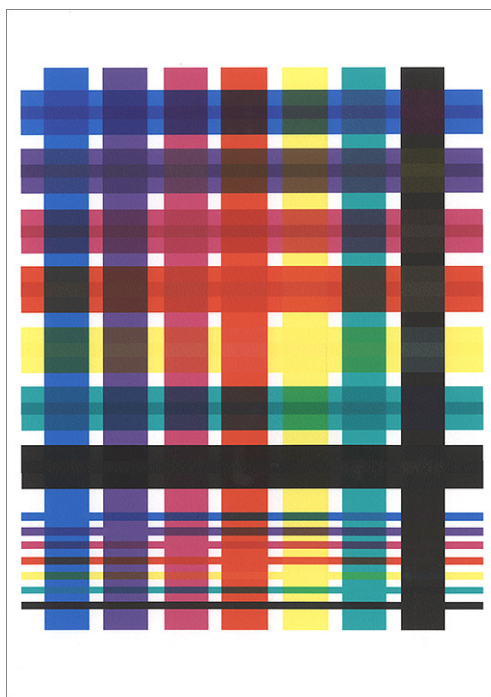


Figure 4.2. Scan of the Colour Bar Chart.¹²

Evaluation of the Colour Bar Chart

The results from the Colour Bar test displayed several observable results. Two of these results directly followed expectations inferred from basic colour mixing principles. The first was the effect of a colourant printed as a single layer, being covered with a second and third layer of ink in subsequent passes, which showed a significant increase in density with each additional layer while maintaining an observably consistent hue. This effect is consistent with the layering of any semi transparent ink or paint pigments where layers are built up incrementally to produce darker hues. The second observation was made on the effect of the change in colourant order. Colourant order is defined by the order the ink colourant is applied to the paper. For example, if cyan was printed as the first layer (in the first pass), and blue was printed as the second layer (in the second pass), the order

¹² All colour charts and presented imagery labelled as a scan in the image caption have been colour corrected using an X-Rite ColorChecker in an effort to reproduce all imagery as faithfully as possible. However, given the obvious differences between the printed originals and reproductions, both in print and on screen, some loss in detail and colour accuracy is to be expected.

would be cyan, then blue, or cyan could be called the base layer, and blue the second layer. This change in colour was confirmed to have an effect on the final colour appearance of layered prints, depending on the order in which they were printed. Figure 4.3 shows this change in colour appearance, along with diagrams showing the structure of the colourant orders for six sampled areas. The colour variance produced in this print extends beyond the pre-existing capabilities in inkjet printing where any given ink colourant would not exceed 100% coverage. Also, the combination of cyan and blue would only produce a single hue, as there is no layering option to modify.

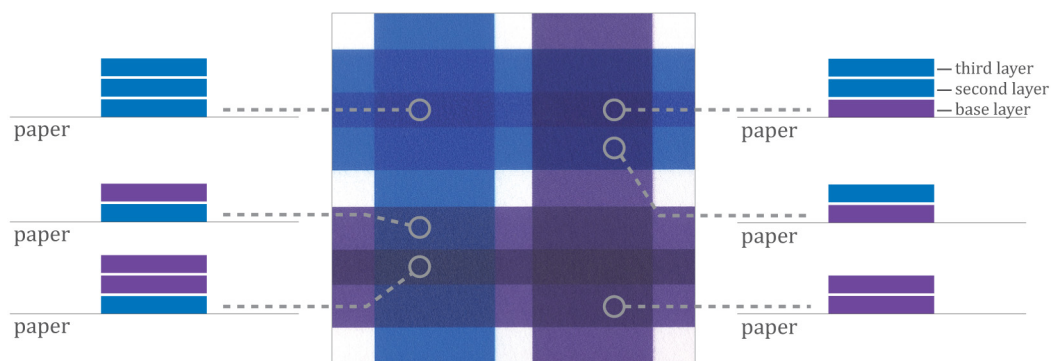


Figure 4.3. Scanned section of the Colour Bar Chart with diagrams showing colourant orders. The scanned print illustrates the change in colour appearance as a result of printing using multiple layers with variations in colourant order. The diagrams show the order in which each colourant was applied to the paper for the sampled areas.

The final observation made on this chart was a colour appearance phenomenon caused when printing with the black colourant as the base layer. Here I found the other colourants, when printed over black, produced hues quite dissimilar to the colours incorporated in the combination. This can be seen in Figure 4.4, where the base layer is black, and the cyan overprint produces a deep ruby colour. The blue ink (which is observably purple in hue) created a bronze when overprinted, and layers of yellow over black appear as a light grey. While this phenomenon was unexpected, it was considered to have a similar appearance to the bronzing effects that occur in many lustre and gloss papers due to a gloss differential.¹³ While widely

¹³ The bronzing effect occurs in areas of dense blacks, where not all ink is absorbed into the coating. This results in the ink sitting on top of the coating to exhibit a different surface

considered a detriment in the inkjet printing market, the occurrence of the effect in a controlled printing method created the potential to incorporate it intentionally into the creation of original works. The application for the bronzing effect will be discussed further in Chapter 6.

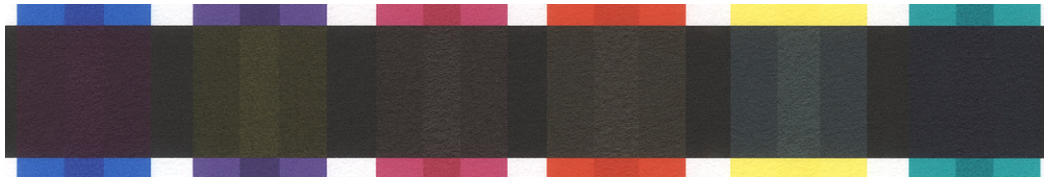


Figure 4.4. Enlarged section of the scanned Colour Bar Chart showing all colour created with black as the base layer.

All the observations made on the colour bar test were strictly qualitative. These judgements, however, were sufficient to confirm the combination of DC/MP printing methods were producing results that extended the ability of standard inkjet printer functions. In order to better evaluate the full potential of these printing methods I identified the need to increase the colour combinations to account for all combinations of colours, not just the limited two colour combinations that appeared in this first chart, along with every permutation of colour order. It was also observed that the distance between like colours made it difficult to make comparative observations without cutting the sheet to allow for rearrangement. The next colour chart addresses these requirements, and was also designed to allow for quantitative evaluation in addition to the visual analysis.

quality to the rest of the paper, causing light to reflect differently in these regions. This reflection commonly causes a bronze hue shift. While widely reported in blogs and articles written for the inkjet printing market, literature is far less prominent in the scientific community. Following a presentation in which I addressed this effect at the Electronic Imaging Symposium in 2014, and a subsequent discussion with Mathieu Hebert from the University of Lyon, Hebert and his colleagues conducted research of their own to scientifically explain this phenomenon (Hébert et al., 2015).

4.4.2. Further Investigation of Colour Order Effects Using the Colour Circle Chart

Rationale and Design of Three Layer / Six Colourant Colour Circle Chart

To further investigate the colour produced by DC/MP printing, I formulated a test chart comprised of the six ink colourants printed with an increased number of colour order arrangements. Initial calculations of colour mixtures that included all possible colour order permutations, including where any single colourant could be layered multiple times, produced a number of total colour patches exceeding 960,000. Therefore, in order to limit the number to a manageable quantity, I chose to maintain the maximum number of print layers to three, remaining consistent with the Colour Bar test. Black was omitted from this chart, not only to manage the total number of patches, but because it would overshadow the chromatic hues of the underlying colourants if layered on top, or produce the bronzing effect if printed as a base layer (as seen in the Colour Bar Chart, Figure 4.2). The Colour Circle Chart was designed to evaluate the variations in hue resulting from layering ink colourants in alternating sequences, and therefore the inclusion of black, or near black patches was not required.

The two pages of the printed Colour Circle Chart are shown in Figures 4.5 and 4.6. The first page of the test chart is laid out as an anamorphous shape formed by clustering patches with similar hues. The second page of the test chart includes the three-colour combinations where each colourant appears only once. Here the six variations in colour orders for the layered patches are arranged around the direct channel, single pass (DC/SP) combination of the three colourants. These groupings were then arranged by hue, in the same manner as page one.¹⁴ It was not considered necessary to restrict the forms

¹⁴ The original arrangement for this colour chart was made with colour patches printed from the Canon iPF8000. While it was acknowledged that the arrangements of these two pages could have been improved upon when transferring the research to the Canon iPF8400, the task was deemed non-essential. The Chart is still successful in serving its original purpose, and by maintaining one arrangement it could be used as a universal test file for multiple printers.

to a grid pattern, as the charts were to act as an illustrative example of the capabilities of the DC/MP printing method, and measurements could be taken without automation on an XY device.¹⁵

¹⁵ The Konica Minolta FD-7 spectrodensitometer can be used as a handheld device, manually placed directly over each sample to be measured, or it can be attached to the ColorScout XY Table (www.colorscout.com) for automated colour patch readings.

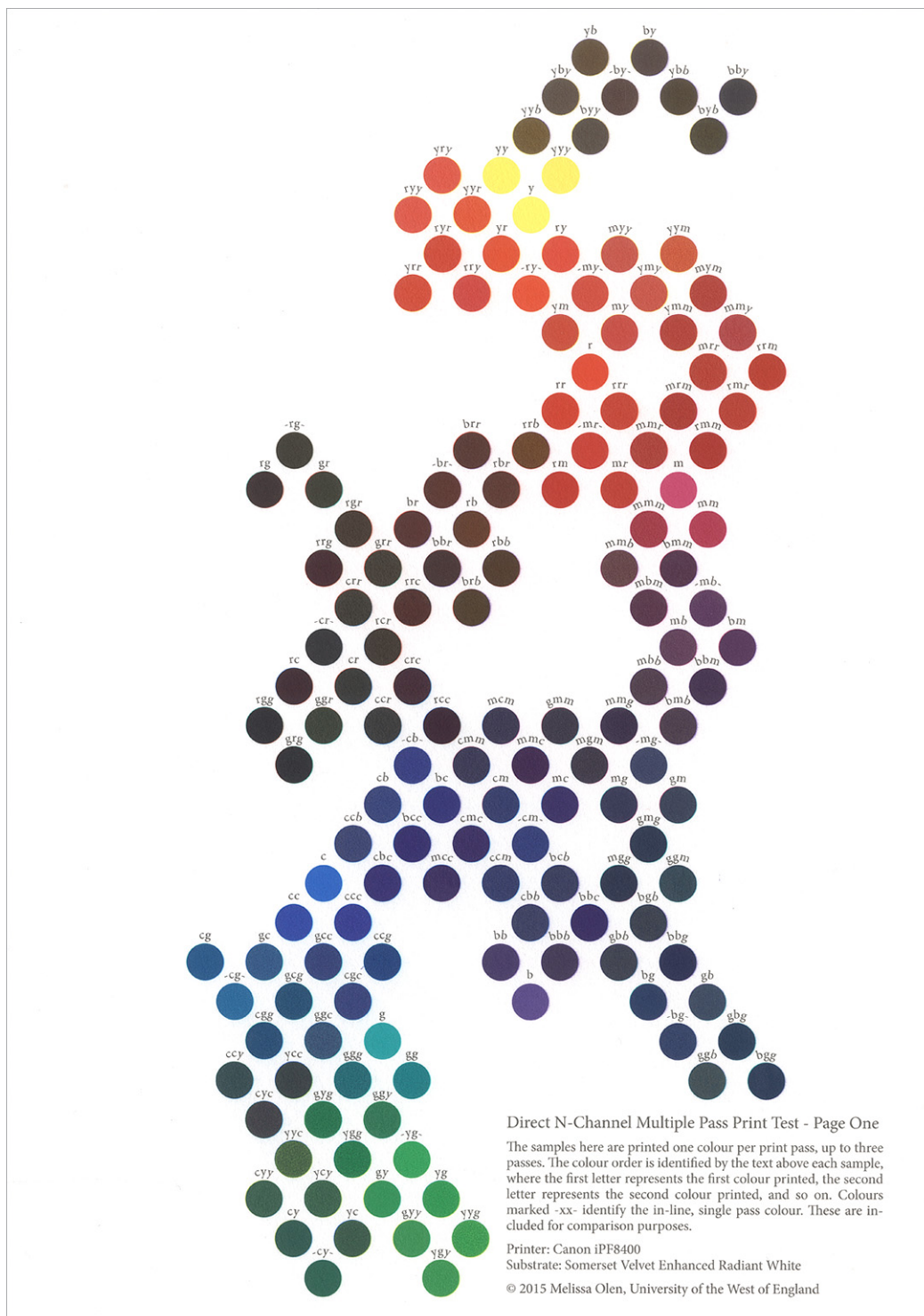


Figure 4.5. Scan of page one of the Colour Circle Chart.

Evaluation of Three Layer / Six Colourant Colour Circle Chart

The colour density of the patches containing one, two, and three layers of a single colourant increased in an easily discernible fashion for each of the colourants, except yellow. The spectral reflectance curves in Figure 4.7 show that while the reflectance percentage in the spectral power distribution drops, and the colour darkens, the shape of the curve maintains relative consistency in shape.

The consistent shape of the curve as the colour darkens indicates the colour's hue being maintained, as the reflectance percentage remains highest at the hue's dominant wavelength. To illustrate this statement, Figure 4.8 compares the green colourant printed using multiple layers to darken the colour with samples that use black to darken the green hue. Scans of the printed patches are shown alongside the measured spectral reflectance curves. It can be seen that the use of black to darken the colour broadens the curve, signifying less prominence of the green colourant. The effect can be verified in the scanned colour patches, as the increasing amounts of black ink dull the green as each colour patch is darkened.

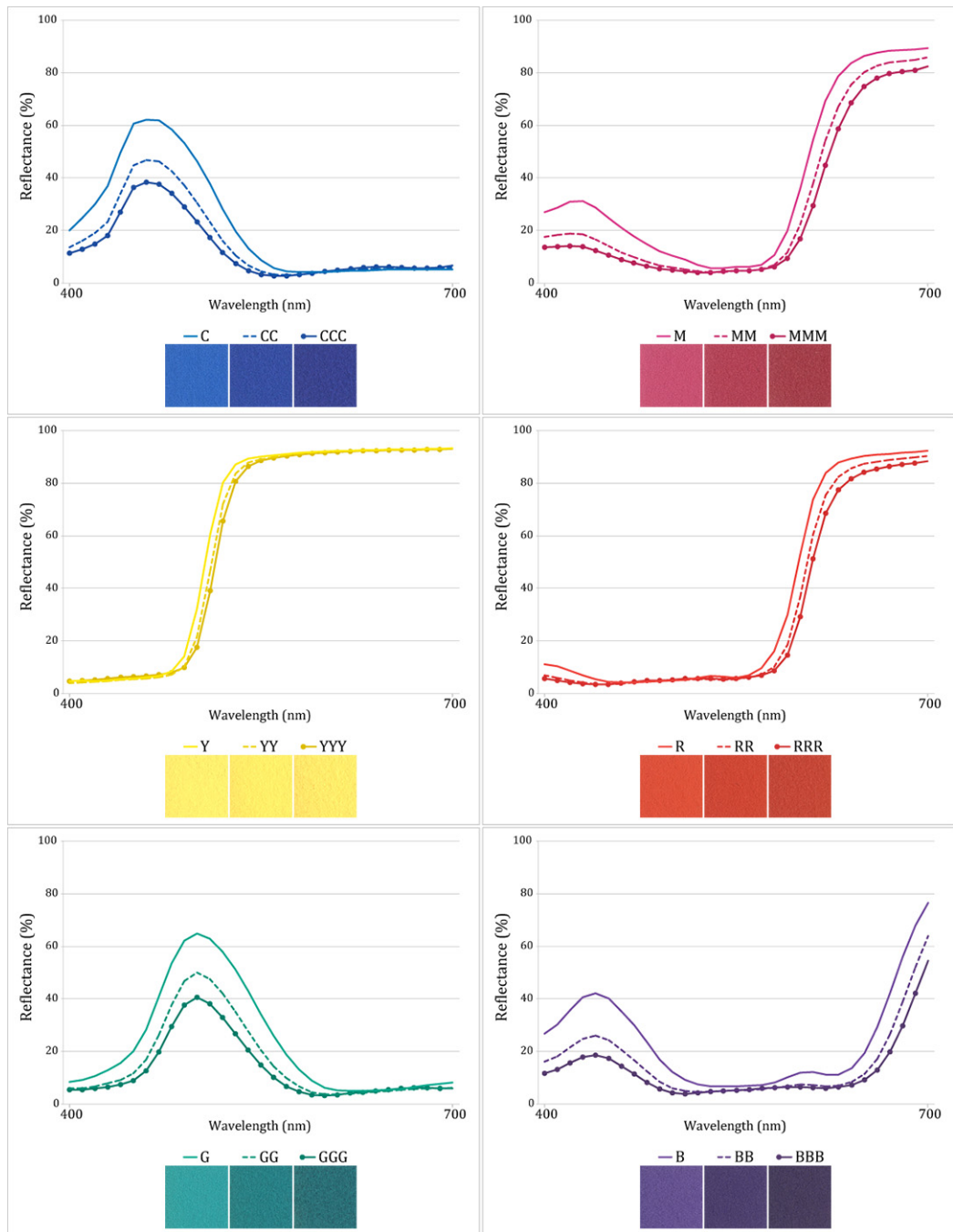


Figure 4.7. Scanned colour patches and spectral reflectance curves for each ink colourant printed as one, two, and three layers.

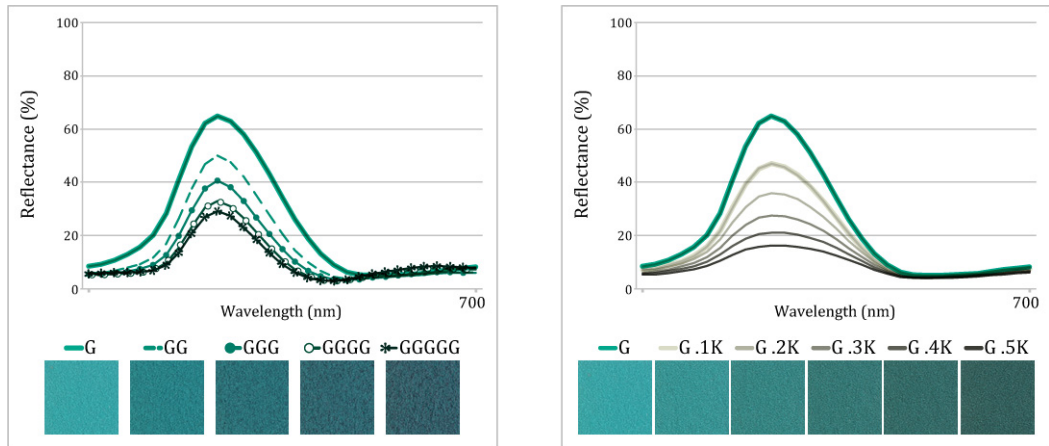


Figure 4.8. Scanned colour patches and spectral reflectance curves comparing the colour generated by printing layers of green and darkening the green by printing percentages of black. The green colourant was layered up to five times (left swatches), and then as a single layer of green with 10% through 50% black printed as a second layer (right swatches, decimals indicate percentage black).

The curves of the increasing layers of each colourant also depict a more significant change in value when a second layer is applied to the first than when the third layer is added to the previous two. This is due in part to the second layer of colourant effectively doubling the volume of ink on the paper, while a third layer will only add 50% more to this volume. Therefore, as additional layers of colour are added, the effect they impart on the final printed colour will begin to have less impact than the first. The small change in density between each of the yellow layers is a result of the inherently light colour, as multiple layers of a light colourant will not create as drastic of a density difference as multiple layers of a darker colour. The calculated RMS differences in Table 4.1 confirm that the difference between one layer and two layers is higher than the difference between two layers and three.

	dH'	RMS		dH'	RMS		dH'	RMS
C & CC	12.85	0.093	M & MM	9.3	0.083	Y & YY	-3.54	0.036
CC & CCC	6.54	0.044	MM & MMM	4.52	0.042	YY & YYY	-2.22	0.021
C & CCC	19.14	0.136	M & MMM	13.59	0.123	Y & YYY	-5.69	0.056
R & RR	-0.57	0.051	G & GG	-0.25	0.093	B & BB	0.73	0.101
RR & RRR	-1.26	0.030	GG & GGG	0.6	0.047	BB & BBB	1.22	0.047
R & RRR	-1.83	0.080	G & GGG	0.38	0.139	B & BBB	1.99	0.146

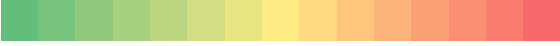
Smallest Difference  Largest Difference

Table 4.1. Calculated colour differences between one and two, two and three, and one and three layers of each CMYRGB ink colourant. The differences are calculated as CIE Lch hue differences (dH') and as RMS errors.¹⁶ The differences are highlighted with a colour scaling from green (small difference) to red (large difference).

Although the DC/MP printing methods produce darkened colour that maintained some of the chroma when compared with using black to darken the colour, not all the ink colourants maintain a consistent hue. This is shown in Figure 4.9, where the colour measurements plotted in the Lab colour space show a curving path across the a^*b^* axis. Table 4.1 further provides the quantified deviations between measured samples by listing hue differences (dH')¹⁷ and RMS errors between each one and two, one and three, and two and three layer combination for each colourant. Confirming the observations made of the curving paths in Figure 4.9, the cyan, magenta, and yellow colourants measured the largest hue differences. The cyan and yellow colourants shift toward red, and the magenta toward yellow, as the density is increased. The straight lines connecting the measured red, green, and blue samples indicate minimal hue shifts as they follow a path toward the central axis and measure significantly lower hue differences.

¹⁶ In order to implement the colour scaling of the hue differences, all measured differences are represented by positive numbers. Therefore the hue difference does not indicate a hue angle direction between the first and second combination in the listed pair, only distance.

¹⁷ The hue difference, which is calculated using the Lch (lightness, chroma, hue) colour space, provides a single metric to signify the degree of difference between two samples around the hue circle (it does not account for lightness or chromatic differences).

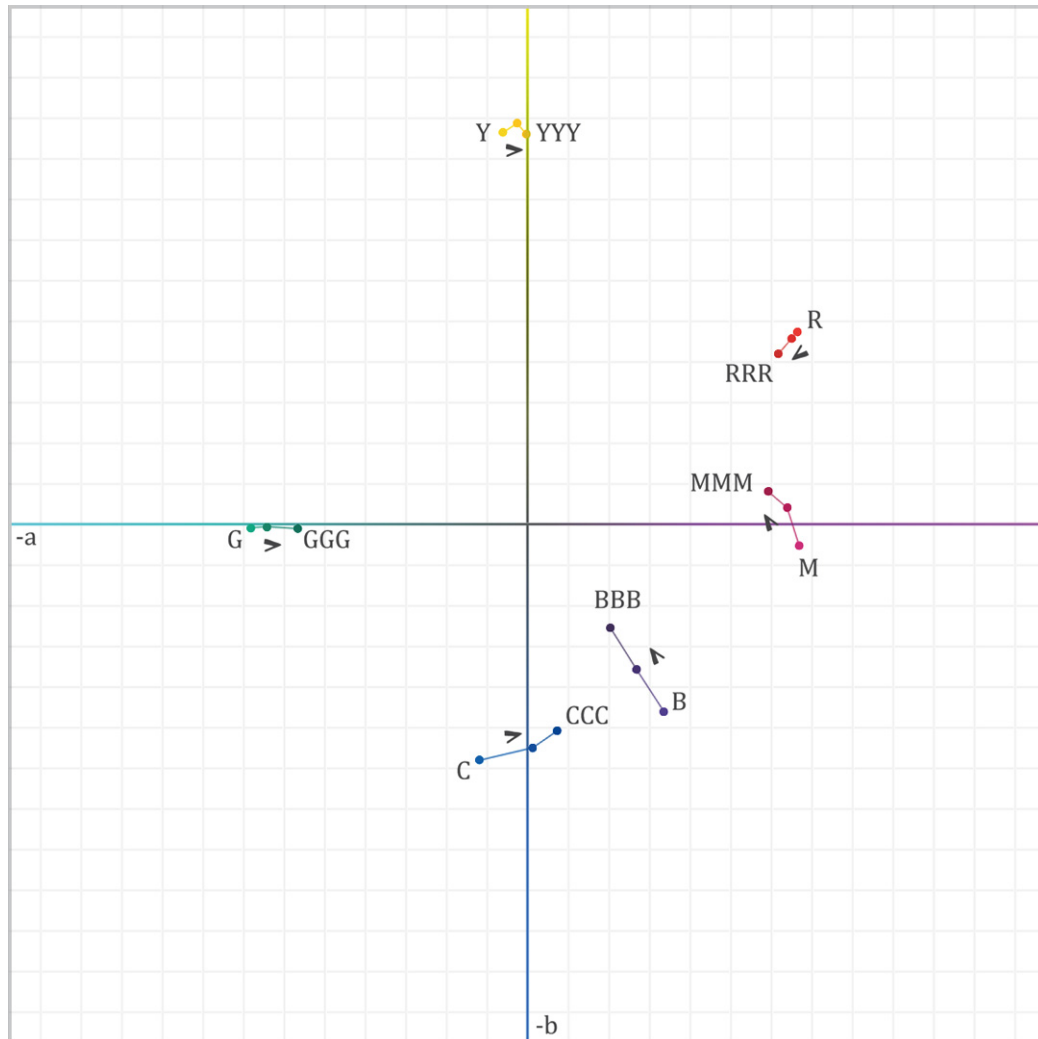


Figure 4.9. Measurements of ink colourants printed as one, two, and three layers plotted on the Lab a^*b^* axes. The measured colours are identified as points, with lines connecting the one and two, and two and three layer printed samples.

I further surveyed and calculated the observable colour difference between colour pairs with different ordering sequences. While a small number of the hue shifts between colourant pairs are subtle, and within a just noticeable difference of 0.5 dE2000 (as referenced in 2.4.1), others demonstrate a considerable colour deviation from the DC/SP printed colour. For example, the difference between red layered over green (GR) and green layered over red (RG) were quite significant, giving a dH of 15.54, followed closely by the different layer orders of cyan and red, which measured a dH of 12.62. Table

4.2 provides the dH calculated for each of the two colour pairs.¹⁸ For all two colour combinations the base colourant was much more prominent to the final hue than the second layer colourant. For example, the yellow over blue combination printed with a more dominant blue hue in comparison to the blue over yellow combination, as can be seen at the topmost section of Figure 4.5.

	dH		dH		dH		dH
CB & BC	4.52	CM & MC	8.45	CR & RC	12.62	CY & YC	7.70
-CB- & CB	2.17	-CM- & CM	0.95	-CR- & CR	3.54	-CY- & CY	2.46
-CB- & BC	2.42	-CM- & MC	7.80	-CR- & RC	3.65	-CY- & YC	5.54
CG & GC	4.29	BM & MB	5.14	BR & RB	5.37	BY & YB	5.94
-CG- & CG	4.29	-BM- & MB	1.06	-BR- & BR	1.64	-BY- & BY	0.09
-CG- & BG	0.21	-BM- & MR	4.11	-BR- & MY	3.87	-BY- & MG	6.33
BG & GB	3.73	MR & RM	0.28	MY & YM	7.57	MG & GM	9.05
-BG- & BG	0.15	-MR- & MR	0.48	-MY- & MY	4.01	-MG- & MG	5.92
-BG- & GB	3.56	-MR- & RM	0.77	-MY- & YM	3.63	-MG- & GM	3.51
RY & YR	9.01	RG & GR	15.54	YG & GY	5.37		
-RY- & RY	5.49	-RG- & RG	9.85	-YG- & YG	3.68		
-RY- & YR	3.54	-RG- & GR	4.43	-YG- & GY	1.77		

Smallest Difference
Largest Difference

Table 4.2. Calculated hue differences between layer orderings for all CMYRGB colourant pairs.

When comparing the colour differences that occurred when printing up to three colourant layers, where one of the colourants was printed more than once in the sequence, an even greater deviation from the DC/SP printed colourant combination was achieved. For example, the measured colour difference between the DC/SP colourant patch -MG- and the three-layer combination GGM achieved a measured result of 21.76 dH. Furthermore, in the instance of comparing the combination of magenta and green colourants where one layer sequence contained a layer of magenta printed on top of two

¹⁸ A complete recording of all calculated measured Lab values and recorded colour differences from the Three Layer / Six Colourant Colour Circle Chart can be found in Appendix D (D.1.). The data provided in this chapter is limited to providing specific examples.

layers of green (GGM) and the other sequence contained two layers of green on top of one layer of magenta (MGG), a ΔH of 17.58 was measured. Figure 4.10 provides a visual depiction of the variance in hue resulting from this change in colourant layering. Here the measured colour patches are plotted on the two-dimensional $a^* b^*$ plane of the Lab colour space. Lines are drawn between the DC/SP printed -MG- patch and each of the DC/MP combination of GGM and MGG.

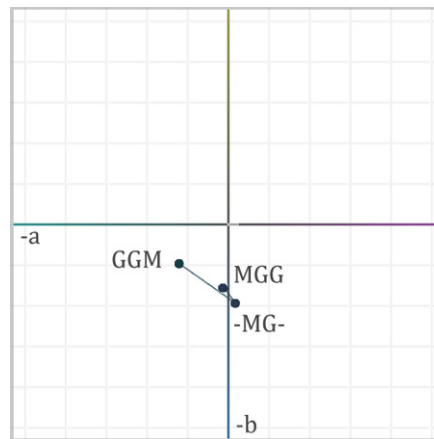


Figure 4.10. Measurements of the -MG-, GGM, and MGG printed patches plotted on the Lab $a^* b^*$ axes. The measured colours are identified as points, with lines connecting the direct channel, single pass (DC/SP) MG combination to the direct channel, multiple pass (DC/MP) printed GGM and MGG colour samples.

The Colour Circle Chart demonstrates a number of colours obtainable that extend beyond the abilities of a DC/SP method. While it is possible to constrain proportions of inks in DC/SP printing, this happens at the expense of the individual colourants' total area coverage (TAC),¹⁹ resulting in lighter printed colour. The variations of each two colourant combination can be seen in Figure 4.11, where the measured colour patches from page one of the Colour Circle Chart are plotted on the $a^* b^*$ axes of the CIELAB colour space. This figure illustrates how changing the number of layers, and the order, of two colourant combinations creates a variety of hues. In the instance of the

¹⁹ This chapter differentiates the total area coverage (TAC) of individual ink colourant from the total ink coverages (TIC) attained through DC/MP printing. The TAC is the range from 0-100% that any single colourant can attain in a single print pass. The TIC is the total ink, regardless of colourant, that is layered in one position, as a colour patch, on the paper. In this chapter the TIC can range from 0-700%.

MG colourant sequence in Figure 4.11, the multiple layers of green cause the hue to shift significantly toward the $-a^*$, or green, axis. The observable hue shifts that occur with each of the layer permutations is only able to gravitate towards the ink colourant's hue in the given combination, but it is able to do so with a measureable difference. To try and replicate the printed colour of the GGM patch using the green and magenta colourants in a DC/SP would require reducing the level of magenta included in the combination, which would simultaneously lighten the colour without necessarily matching the hue. Alternatively, while combinations of cyan, yellow, and black could substitute for the extra layer of green, these additional colourants cannot obtain the same level of chroma attainable by a single colourant.

On page two of the Colour Circle Chart (Figure 4.6), where the three-colourant combinations are printed in each of the six possible sequences, the colour variations were able to extend in more directions. Expanding to three colour combinations inherently expands the number of colours that can be achieved, especially when analysing the triadic colour combinations, such as cyan, magenta, and yellow. As these are the established colour primaries for full colour reproduction print processes, it is unsurprising that the DC/MP permutations had the greatest measureable colour differences. CMY had the largest colour differences, as great as 28.06 dH when alternating the colourant order from MYC to CYM. The MYC sequence alone varied from the DC/SP printed colour by a dH of 23.29. These changes in hue can be observed in Figure 4.12, where each of the twenty three-colourant combinations are plotted in the CIELAB colour space.

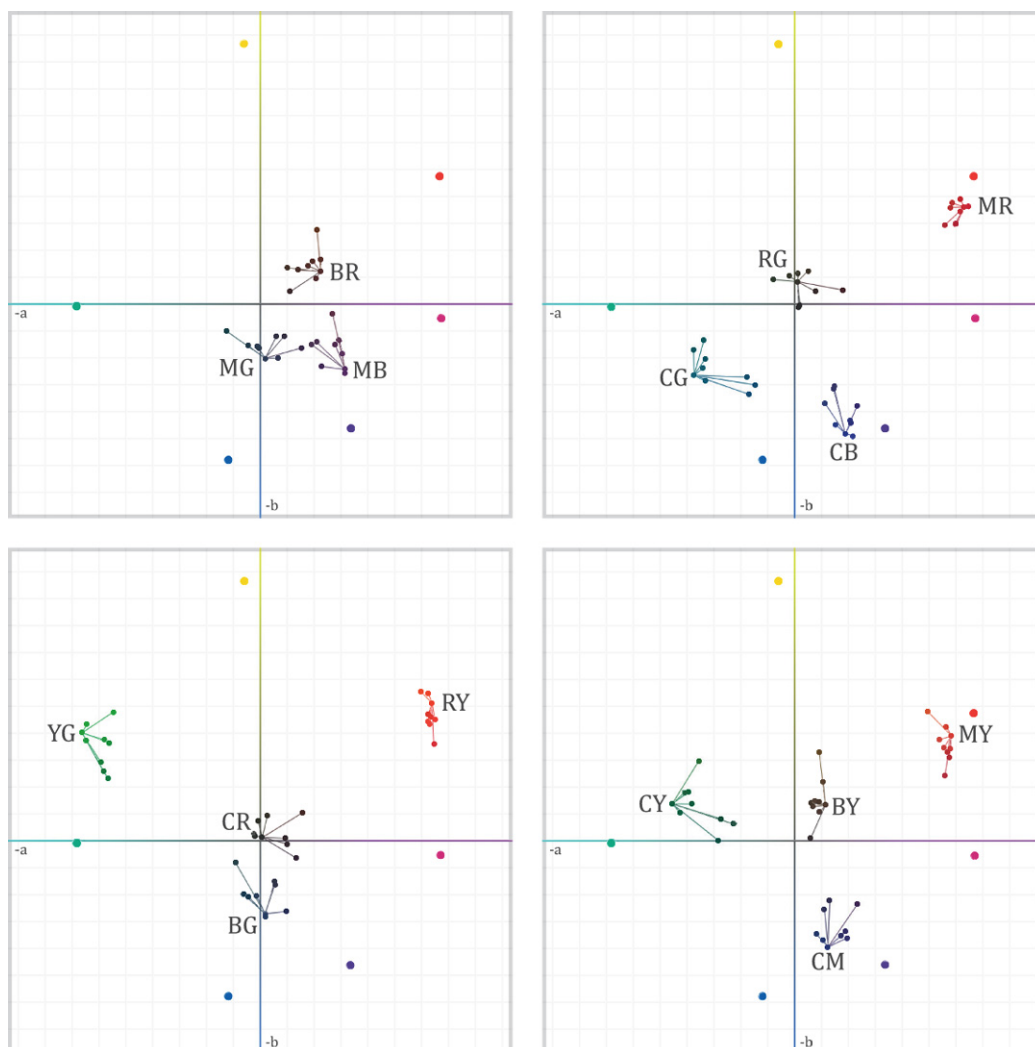


Figure 4.11. Measurements of all two colourant combination variations plotted on the Lab a^* b^* axes. The measured colours are identified as points, with lines connecting the DC/SP combination to each of the DC/MP printed samples.

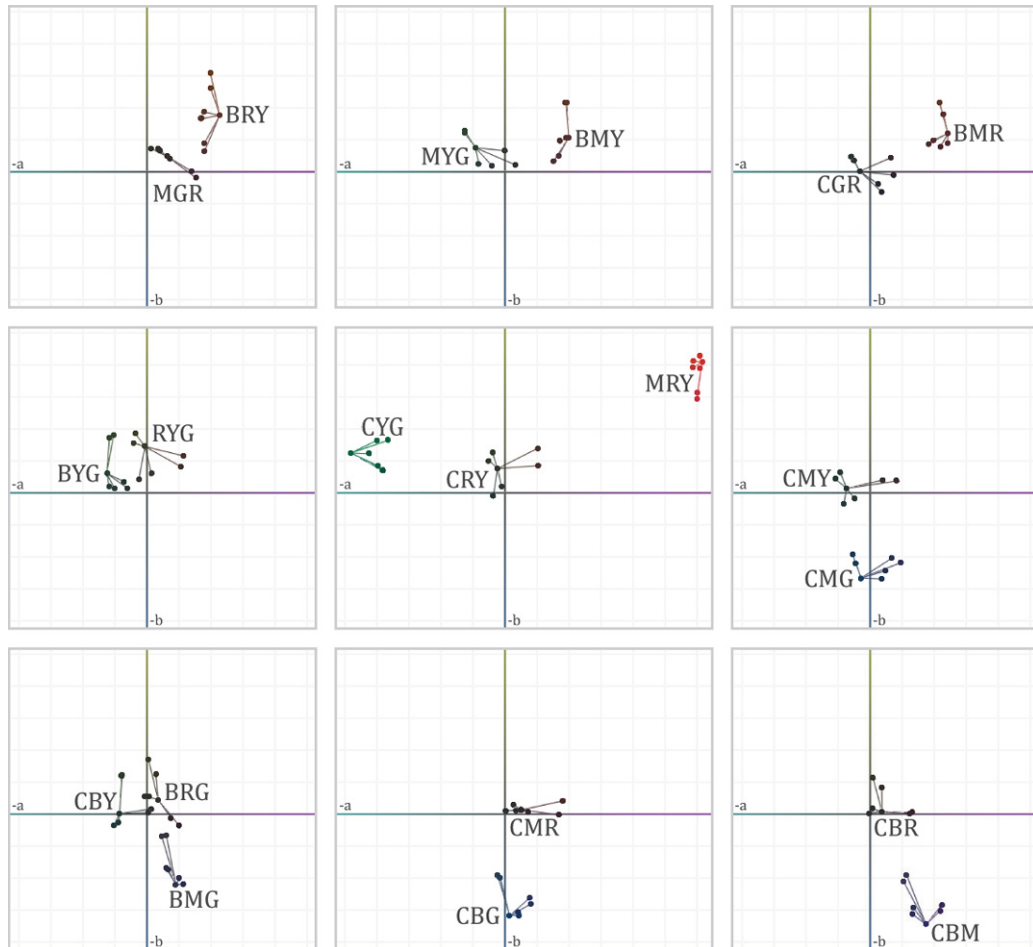


Figure 4.12. Measurements of all three colourant combination variations plotted on the Lab a^*b^* axes. The measured colours are identified as points, with lines connecting the DC/SP combination to each of the DC/MP printed samples.

In comparison to the two-colourant combinations, the measured colour differences of the three-colourant combinations are not as significant, and do not necessarily exceed the pre-existing gamut of the printer. This can be primarily attributed to each colourant only being printed as a single layer in each combination, limiting the maximum achievable chroma that led to the results on the first page of the colour chart. Therefore I concluded that the second page of this test chart, while confirming the ability to change the final hue of the printed colour depending on layer order, did not offer substantive evidence that DC/MP printing methods, using only the single layer of each colourant, gained the ability to control the output colour in a previously unobtainable way.

To gauge the number of unique colours printed on this two page chart that exceeded the reproducible colour gamut using an ICC workflow, all measured colours were mapped to a correlating colour profile's gamut.²⁰ This mapping used the absolute colorimetric rendering intent in order to compare each measured colour patch to the closest colour match available within the colour gamut. Figure 4.13 shows each of the measured colour patches from the two-page chart plotted in the CIELAB colour space alongside a wire frame representing the exterior boundaries of the colour profile's gamut. For this analysis I calculated the dE2000 colour differences, which takes into account the lightness and chroma in addition to hue, providing a total colour difference measurement. This analysis revealed that 45.1% of the 293 colour patches measured a dE2000 of 2.5 or greater, the threshold for a definitive colour variation referenced in Chapter 2 (2.4.2). Out of all the patches only 2 calculated a dE2000 of 0.5 or less, equalling .7%. This indicates that 99.3% of the colours achieved through the layering of the colourants could not be matched when implementing an ICC workflow to within a just noticeable difference. The chart in Figure 4.14 provides the frequency distribution of the measured dE2000 for the 293 patches. The counts in this chart have been separated into three colour coded clusters: the DC/SP printed patches, the one and two colourant combinations printed in up to three passes, and the three colourant DC/MP print patches. It can be seen that while the one, two, and three colourant combinations have a relatively equal distribution of dE2000 measurements, the DC/SP printed patches maintain respectively lower measures.

²⁰ The colour gamut used in this evaluation, and every other printer gamut comparison in this chapter, is that of a custom printer profile made with the same printer/paper combination, as well as using the same printer characterisation as the custom test charts. The profiling chart was measured with the Konica Minolta FD-7 spectrodensitometer, and built using Color Care Profiler.

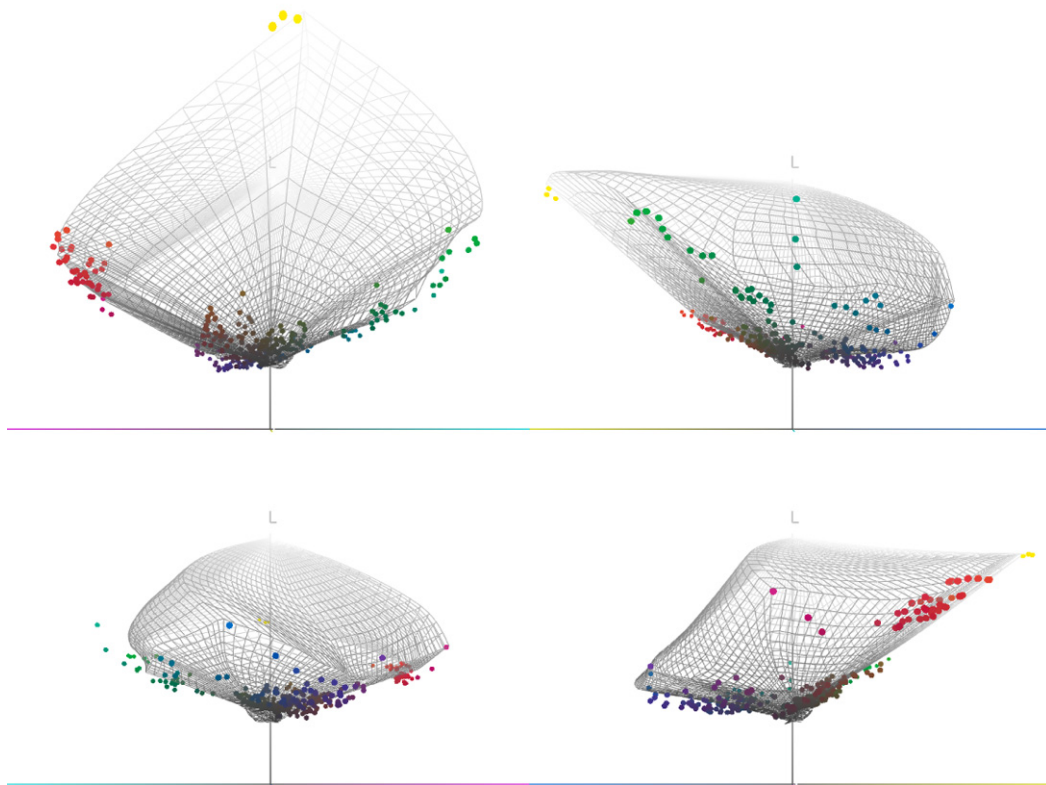


Figure 4.13. Illustration of all DC/MP colour patch measurements from the Colour Circle Chart plotted in Lab colour space alongside a wire frame representing the comparative colour profile's gamut.

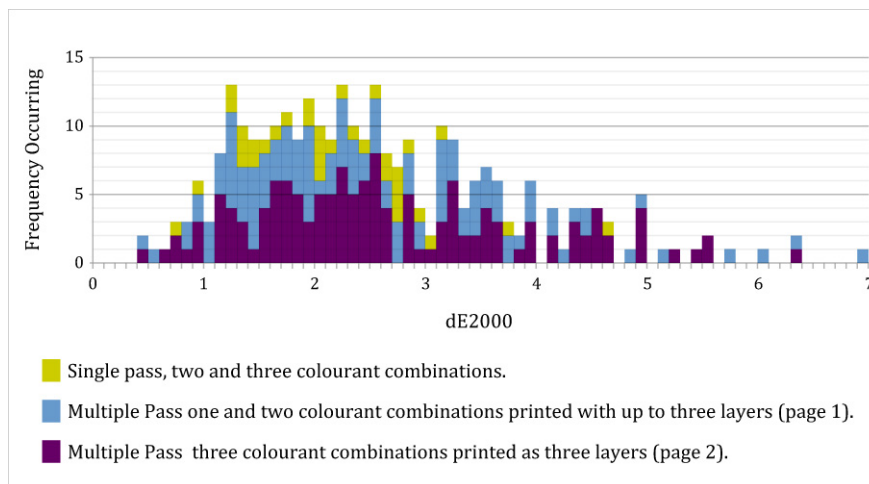


Figure 4.14. Distribution of calculated dE2000 between measured DC/MP print patches of the Colour Circle Chart and the colour profile's gamut.

While the gamut comparison results were promising in regards to depicting the generation of colour outside the capabilities of an ICC print workflow, it must be acknowledged that this can be attributed not only to the methods I implemented in my research, but also to pre-existing limitations in the

Caldera RIP's colour management module. This is made apparent by the fact that each of the direct channel printed red, green, and blue ink colourants were plotted outside the colour profile's gamut boundaries. This occurrence highlights that the sampling chart used to generate the colour profile did not adequately sample the colour space of THE multi-channel device.²¹ However, this is still representative of the obtainable colour gamut most available profile making software would produce, as the advanced calculations required for CMYK+ colour profiling have not been fully integrated, or become widely available, in consumer software for the fine art and commercial inkjet printing market.

In summary, the two-page colour Colour Circle Chart demonstrated that the printed colourant permutations could exceed the number of colours obtained by a standard ICC workflow. This was achieved by employing DC/MP methods to print colourants over several layers. This process provided the ability to exceed the maximum 100% TAC any single ink colourant is capable of producing in a DC/SP print. The two- and three-colourant combinations further proved an ability to change hue depending on layer order, the majority of which produced colours unobtainable through a standard printing method. Additionally, with the absence of any printed artefacts, such as ink bleeding on the paper surface, I determined that the total number of layers could still be increased beyond the current limit of three. By increasing the total density of the colour by adding additional layers, including black, I hypothesised that the dark colour region of the colour gamut could be further expanded beyond the results of this printed chart. The next colour chart was developed to test this hypothesis by examining the total volume of ink that could be applied to the paper before unwanted artefacts began to occur.

²¹ Caldera's N-Colour capabilities only extend to media calibration processes of ink transitions (when printing with light ink colourant), linearization, and ink limiting. At the stage where an ICC profile is generated, Caldera's Easy Media module reverts back to a CMYK process. N-colour, or CMYK+, colour profiling has not yet been implemented as it is too much of an investment for a feature only a small portion of the market has requested (Arnaud Fabre, personal communication, 23 January, 2013).

4.4.3. Generation of a Custom Ink Limit Chart

Rationale and Design of the Ink Limit Chart

DC/MP printing approaches presented the opportunity to attain colours beyond the gamut achieved with traditional inkjet printing workflows, particularly dark, chromatic colours. While inkjet printers already have the capability to produce a large gamut of dark colours, many subtle variances between hues are lost in the dark regions as black ink is used to replace colourant combinations that would have otherwise been used to create these colours. This incorporation of black is primarily used to reduce the over inking effects from high volumes of colourants, which subsequently becomes a trade off between maintaining colour information and the reduction in the total amount of ink applied to the paper. Furthermore, in a DC/SP method, ink colourants printed at high percentages tend to bleed together on the paper surface, resulting in unwanted print artefacts such as mottling. I found, however, that DC/MP printing could limit the effects of over inking due to the opportunity for ink layers to dry incrementally on the paper surface.

To determine the effects of printing with higher amounts of ink using DC/MP printing methods, a custom Ink Limit Chart was designed, as no pre-existing ink limit chart existed with greater than 400% total ink coverage (TIC). This chart was designed specifically for direct channel, seven colour, printing applications and tested against traditional CMYK ink limiting workflows. Here black was incorporated in addition to the CMYRGB colourants used in previous testing. The design is based on the simple ink limit target packaged as part of Caldera's colour management utility, a variation of which all RIP software generates for every CMYK and CMYK+ media characterisation process. The simple target uses multiple colourant sequences, altering the point where each ink colourant is added to increase the TIC. However, it only applies to four-colour printing using CMYK colourants. For my research purposes this simple chart was modified to determine the TIC for printing using seven colourants, with a total possible ink limit of 700%. Although the DC/MP printing methods could definitively print up to 300% TIC already,

new limits beyond 700% were considered unwarranted for the first stage of testing. Therefore the restriction of incorporating only a single layer of every colourants was set. This limitation also maintained a manageable set of variables for designing the extended Ink Limit Chart.

Print Production and Evaluation of the Ink Limit Chart

The seven colourant custom Ink Limit Chart was then printed in two ways: the first as a DC/SP print, and the second using both DC/MP printing methods. The first print (Figure 4.15) offered a point of comparison against the later DC/MP approach. Observation of the DC/SP print showed that ink bleeding began to occur at 190% TIC for some colourant combinations, as the ink was absorbed along the paper fibres and mixing with neighbouring patches as coverage increased. More significantly, it was observed that no considerable colour information was maintained after 400% coverage, as many of the colour patches appeared black, or while maintaining a lighter colour hue, offered no significant variation. In higher coverage areas, as the inks combined on the paper surface, the inks blended together to form a single colour patch as a result of the total mixture. This resulted in the small increases of any single colourant having little effect on the hue of the final printed colour.

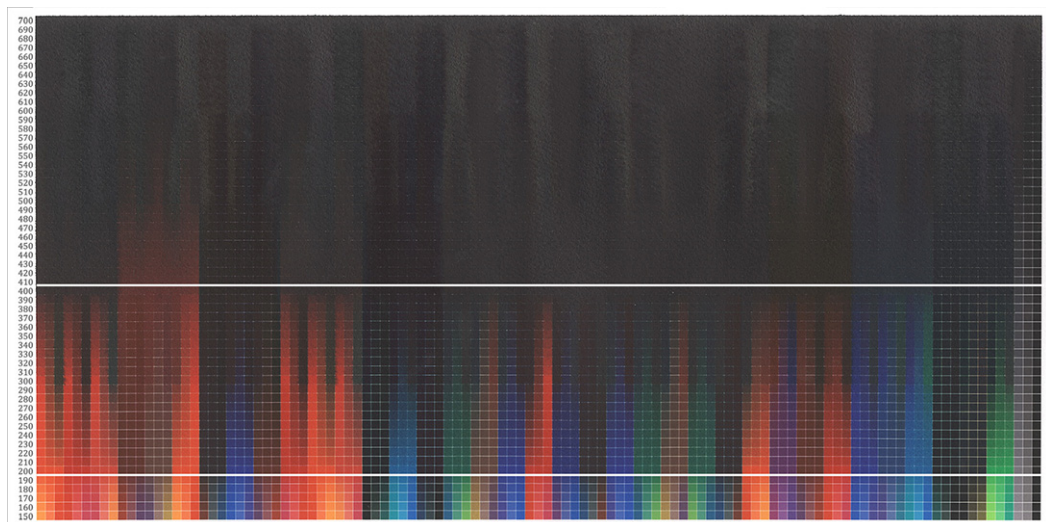


Figure 4.15. Scan of Custom Ink Limit Chart printed using the direct channel, single pass (DC/SP) method. The white lines are drawn across 190% TIC and 400% TIC.

The chart was then printed again using DC/MP printing to assess its ability to better maintain colour information at higher ink coverages. The printed results can be seen in Figure 4.16.

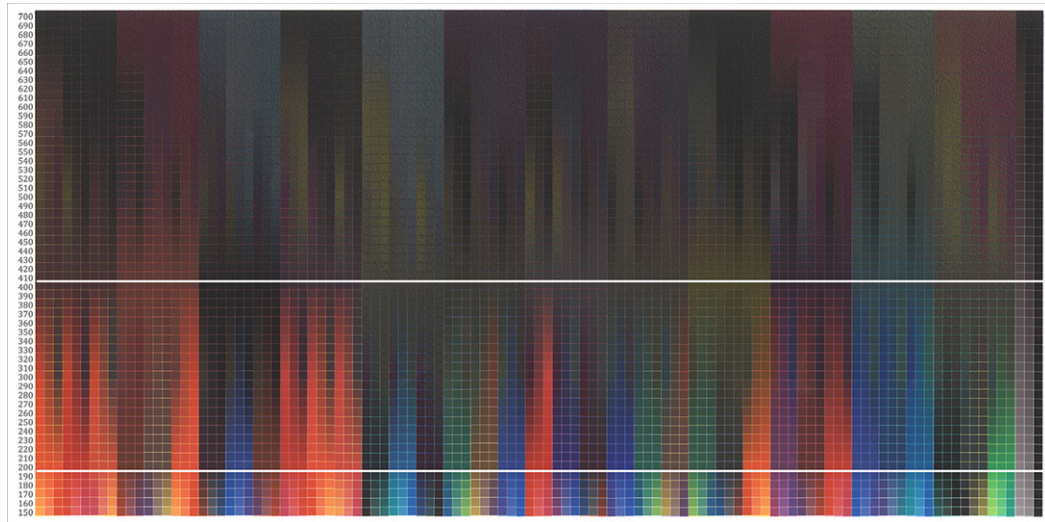


Figure 4.16. Scan of Custom Ink Limit Chart printed using direct channel, multiple pass (DC/MP) printing methods. The white lines are drawn across 190% TIC and 400% TIC.

The presence of maintained patch differentiation, achieved through the DC/MP printing methods, confirmed higher TICs could be obtained through the DC/MP printing process than in a DC/SP method. While the DC/SP print exhibited signs of ink bleeding in densities as low as 190%, the DC/MP print maintained edge definition up to 700% TIC. The ability to print at these higher densities opens up the possibilities to incorporate more unique colour mixtures for the creation of printed colours that are not currently utilised in inkjet printing.

In addition to the presence of visibly discernible colourant hues, additional colours were generated from the DC/MP print through the effects of bronzing. Replicating the phenomenon observed in the first Colour Bar test (section 4.4.1), the printing of certain colourants on top of dark underlying ink layers resulted in the appearance of a new colour. In instances where the first four layers of ink created a dark base, the overprinting of particular ink colourants resulted in the appearance of colour opposites or other types of colour anomalies. The occurrences of these colours are visibly

distinguishable from the colours that appear in the DC/SP print. These anomalies demonstrate a slightly metallic surface appearance, and range from colours of purples and reds, golden yellows, and bluish greys, which have a silvering effect that appear to lighten rather than darken in higher densities.

4.4.4. Standardising the Colourant Sequence

Rationale and Design for a Permutation Test Chart

After confirming the ability to print a range of darker colours using more than three print layers, while avoiding adverse print defects such as ink bleeding, I identified the need to examine how many of these colours were previously unattainable through a standard printing workflow. Yet, due to the increase in the number of print layers, I determined I must first limit another variable in order to keep the collected data manageable. As previously mentioned, certain colourants, when printed over layers of black or dark colourant mixtures, result in a bronzing effect. While this effect could be used intentionally as a special effect in particular applications, I decided to eliminate it as a variable at this time in order to focus on non-bronzing colours. Eliminating colourant combinations that result in bronzing would also reduce the number of patches that would be generated in the forthcoming tests. This further allowed for more accurate colour measurements of my sample sets, as the bronzing effects are viewing angle dependant, and the geometry of the FD-7 could not obtain a recording of the colour change accurately. Therefore a test was carried out in order to find the colourant sequences where no bronzing occurred. For this test I printed out all 720 permutations for the six colourants CMYRGB. Black ink was not included in this experiment, as I had elected to use black as only the top layer. Printing black as a final layer over all other colour layers follows in line with analogue print techniques, where black was used as the final “key” layer, used to add detail to the underlying image (Upton, 2005).

Visual Analysis of Colourant Permutations

The 720 test samples were evaluated visually. Of the large number of options, only one of the colourant sequences was found to meet the requirements described in the rationale for this Permutation Chart: the colour order of yellow, blue, red, magenta, cyan, and green (YBRMCG), where yellow was the base layer and green the sixth, or final, layer. All other patches contained the appearance of bronzing, either on the top layer or as one of the intermittent layers. Furthermore, most every sequence where yellow was not the base layer seemingly changed in value from dark to light as the number of layers increased. Each of these effects, along with the YBRMCG sequence, can be seen in Figure 4.17.



Figure 4.17. Scanned samples from the colourant permutations test. The first two samples (left and middle) show bronzing and an inconsistent transition from light to dark as the layers increase. The sample on the right was chosen as the optimal colourant sequence.

Due to the small size of the initial test patches, an additional series of step and gradation charts were designed as larger scale variations of the Permutation Test Chart's patches. This series of tests confirmed the selected colourant order was free from adverse print effects, such as bronzing or lightness fluctuations. Additionally, the neutral ramps provided a check for maintaining neutrality and smooth tonal transitions. Scans of the three printed ramps are presented in Figure 4.18.



Figure 4.18. Scanned print output from YBRMCG colourant sequence step wedge test with gradated transitions, and with 0 to 100% coverage gradation.

The final test, a colour hexagon, was created to ensure the transition of hues around the outer edge. The purpose of the print was to ensure the

appearance of hue transitions around the hexagon, without any major shifts, which it did by maintaining a dominant hue along the appropriate edge (Figure 4.19). In the absence of hue variation it would have been deduced that either the colourant sequence, or the layering process itself, was masking portions of the colour gamut.

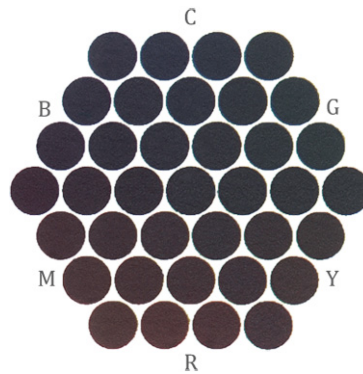


Figure 4.19. Scanned print output from YBRMCG colourant sequence hexagon test.

Although the results of these prints were not quantified, the visual assessment was sufficient to confirm the selected colourant order did not produce any unpredictable colour phenomenon when employed in the DC/MP printing process. In all subsequent colour charts the YBRMCG colourant sequence was used to standardise this one parameter. This allowed for the incorporation of new variables, such as increasing the total number of printed layers, into future test charts without the need to exponentially increase the amount of colour patches.

4.4.5. Unification of Findings into Culminating Maximum Variable "MAX" Colour Chart

Rationale and Design for a Maximum Variable Colour Chart

Following the series of test charts presented in this chapter, two further colour charts were designed to specifically address dark, chromatic colours. As these specifically relate to the reproduction applications addressed in the following chapter, they are not included here. However, for the sake of continuity, it must be stated that each used the single colourant order of YBRMCG and addressed various combinations between two and six CMYRGB or CMYKRGB colourants. These test charts did not incorporate multiple

layers of any single colourant in the combinations. This led to the final colour chart presented in this chapter, which evolved iteratively from the design processes and analysis of the preceding colour charts.

The objective for the chart presented in this section was to further examine the extent to which DC/MP printed colours extended beyond the capabilities of the ICC colour managed workflow. Named the “MAX” chart, my goal was to incorporate the maximum number of variables, using the parameters set by the preceding test charts. The MAX colour chart builds upon the Colour Circle Chart discussed in 4.4.2 by reintroducing black into the colourant set, and also increases the total number of printed colour layers based on the results of the custom Ink Limit Chart. However, despite results indicating the paper could handle to up 700% ink volume, the MAX chart only expands to 500% total coverage. This includes up to 400% coverage of CMYRGB combinations, plus an additional black layer up to 100%. This limitation was considered a trade-off between the ability to maintain a greater variety of colourant combinations and the feasible creation of the chart. The chart also used the singular colourant sequence of YBRMCG, as specified by the Permutation tests. It further ensured the accuracy of colour measurements in relation to the observable colour.²²

Analysis of the “MAX” Colour Chart

For the evaluation of the MAX colour chart, I repeated the comparison method used with the Ink Limit Chart. The MAX chart was printed as a DC/SP print and a DC/MP print (Figures 4.20 & 4.21). The first DC/SP print was printed with a total ink limit applied to avoid the over inking that resulted in inappropriate densities of the Ink Limit Chart, as would be done in any

²² The observable colour resulting from the bronzing effects could not be measured using a 0°/45° geometry of the X-Rite i1Pro Spectrophotometer used at this stage of the research. This device illuminates the sample from a 90° angle, with a detector located 45° from the light source. The appearance of bronzing in the printed output is not prominent unless illuminated from an acute angle.

standard colour management workflow.²³ As the patches on the MAX Colour Chart have combined ink coverages up to 500%, this results in many of the colourant densities being adjusted in the printing process. Consequently the same density cannot be achieved in the DC/SP chart as is possible with the DC/MP printing. Although the colour differences were maintained between patches where a single colourant did not exceed 100% coverage, the limitation in the total achievable density could be observed. This is evidenced in Figure 4.22, which contains a selection of scanned BMCG combination patches, where each colourant appears only once in the combination as either 50% or 100% coverage. Here distinctions can be made between the patches printed using each method, but the DC/MP printed patches contain a greater range in the colours' Lightness (L^*) values as a result of the increased ink densities.

²³ The ink limit was set in accordance with Caldera's integrated dynamic ink limiting procedure in Easy Media. While the custom ink limit chart indicated the limit should be set at 190, inputting this value into Caldera's sliding scale produced inconsistent results. This is due to Caldera's ink limiting using a post-linearization method (the total ink coverage limit is the sum of all ink channel restrictions) while my method was input referred (ink coverage references input densities from the design file).

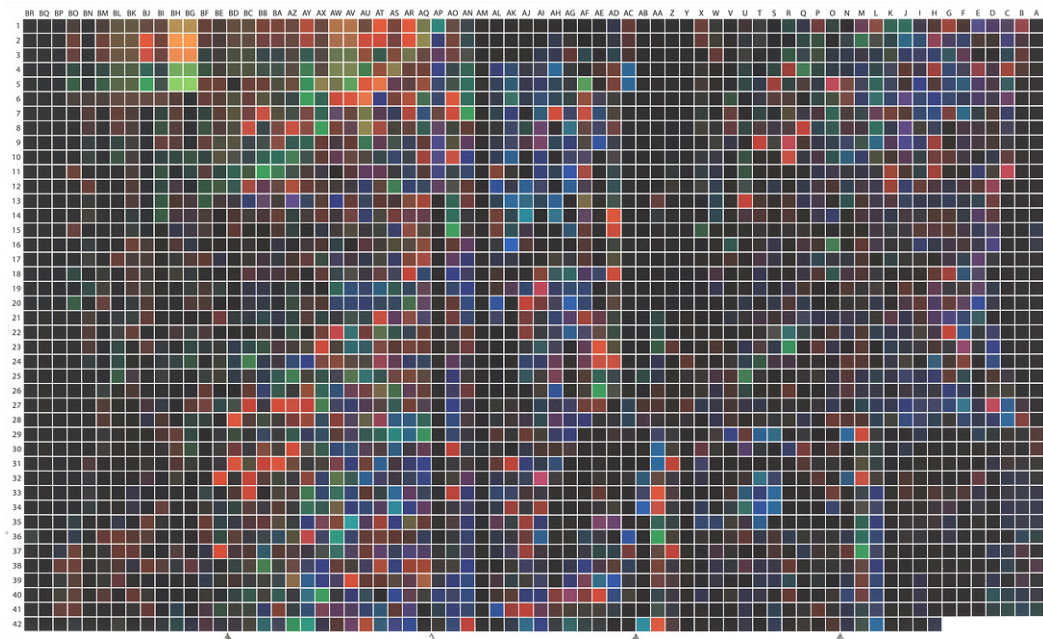


Figure 4.20. Scan of the MAX Colour Chart printed using DC/SP methods.

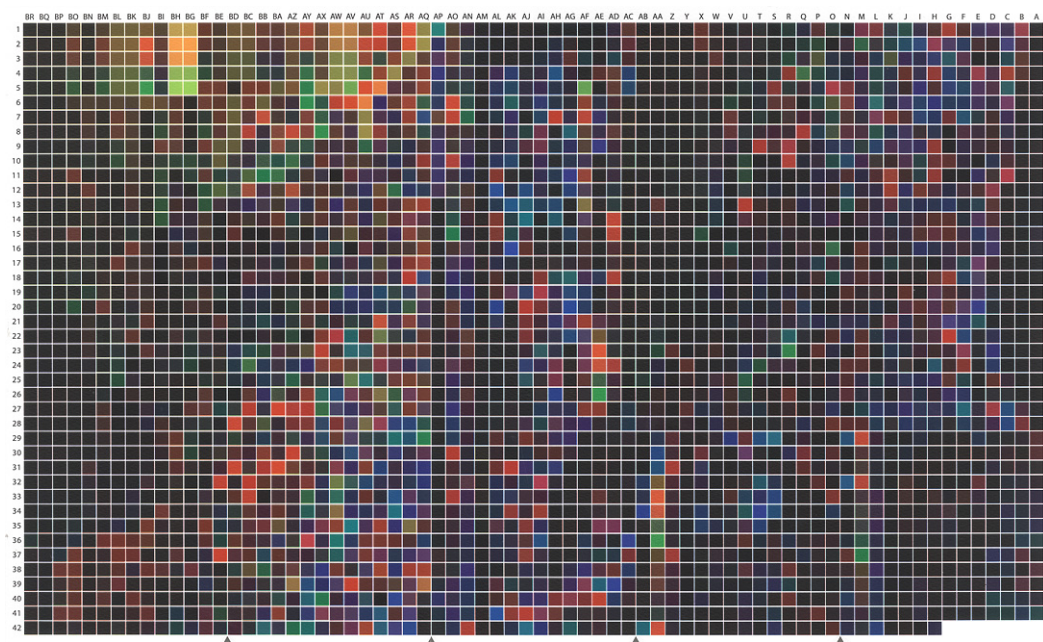


Figure 4.21. Scan of the MAX Colour Chart printed using DC/MP printing methods

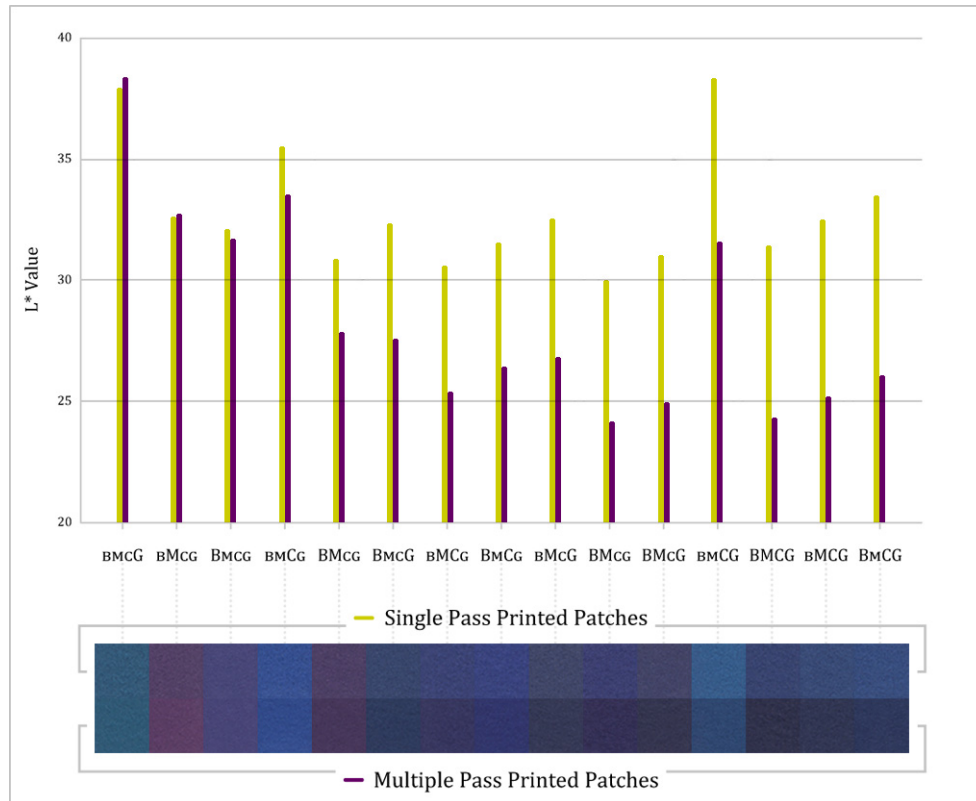


Figure 4.22. Selection of BMCG combination patches demonstrating the increased range of colour Lightness values achieved with DC/MP printing. Each small cap letter in the colourant combinations represents 50% total area coverage.

The more significant changes between the DC/SP and DC/MP printed MAX charts occurred when multiple layers of a single colourant were included in the combination. Since the DC/SP printing method cannot exceed 100% coverage of any single colourant, the layering effect could not be replicated, leading to many of the combinations producing a limited number of colours in the printing output. This can be seen in the example of various yellow and green combinations where the colourant was printed in combinations ranging from one to three layers for each colourant (Figure 4.23). This reiterates and builds upon the analysis presented from the Colour Circle Chart (4.4.2). The DC/SP version printed each combination with the maximum 100% TAC, eliminating the additional coverages of either colourant and making each print with identical proportions of the two colourants. With the added ink coverage of the DC/MP printing, the colour of each patch obtained a unique hue. Notably each DC/MP patch printed darker

than the DC/SP printed patches. This was to be expected, as the total ink limit applied to the DC/SP print had an effect on the colour's density.

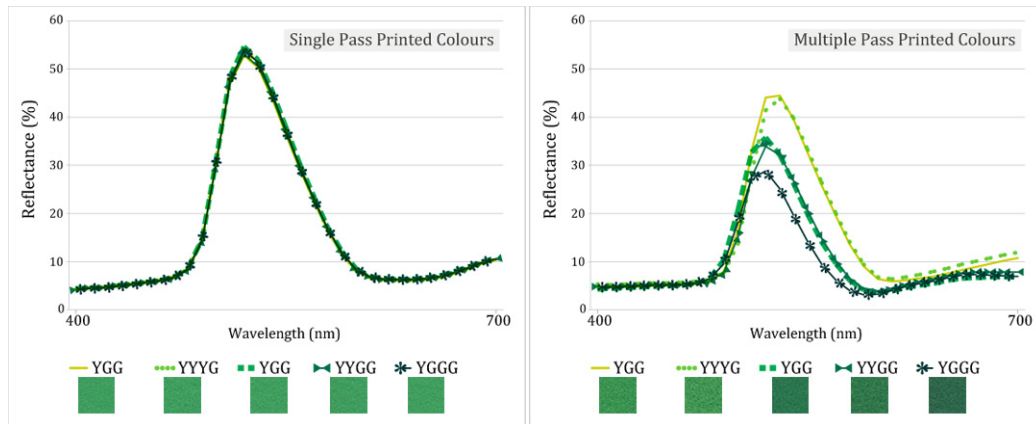


Figure 4.23. Scanned colour patches and spectral reflectance curves comparing the colour generated by printing combinations of yellow and green with both DC/SP and DC/MP methods.

The changes in colour distinctions between DC/SP and DC/MP patches of the same colourant combinations can be further demonstrated with a larger sampling. In a set of fourteen patches from the MCG colourant combination, shown in Figure 4.24, the coverage values range between 50% and 200% for each of the three colourants. Despite each colour patch containing a unique mixture of the colourant combinations and coverage, the DC/SP printed set only generated five distinct colours. As before, the same colourant combinations, printed using the DC/MP printing method, produced significantly more unique colours.

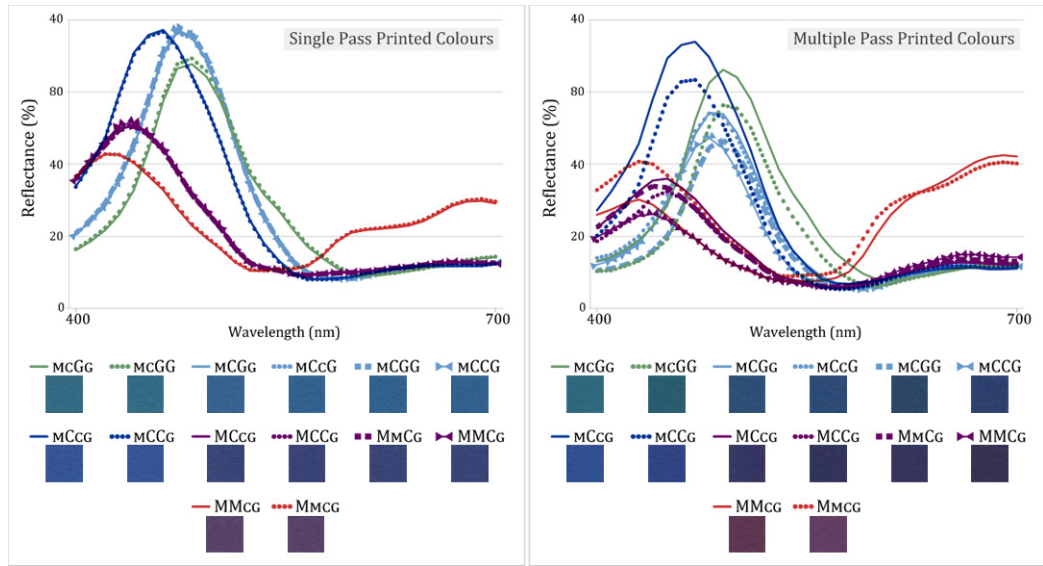


Figure 4.24. Scanned colour patches and spectral reflectance curves comparing the colour generated by printing MCG colourant combinations with both DC/SP and DC/MP methods. Each small cap letter in the colourant combinations represents 50% total area coverage.

In addition to achieving more colour distinctions between patches, the DC/MP printing method also expanded further into the shadow region of the gamut by attaining lower Lightness (L^*) values in comparison to the DC/SP equivalents. Furthermore, the patches maintained a higher chroma due to the layering of a single colourant to achieve the output density. For comparison, the patches from both printed MAX charts were measured and plotted in CIELAB colour space. Figure 4.25 illustrates the variance in lightness and chroma between the measured colours, shown in cross section slices of the Lightness axis. The slices begin at an L^* value of 19, where the first measured colour appears, and increases by one Lightness value in each image up to L^* 33. The DC/MP chart is seen to start at a lower Lightness level, as it begins at L^* 19, than the DC/SP data set, which is 2% lighter at L^* 21, demonstrating its ability to produce a darker colour. More significantly, the DC/MP colour set expands wider than the DC/SP set as the Lightness values increase, indicating the patches possess a higher chroma.

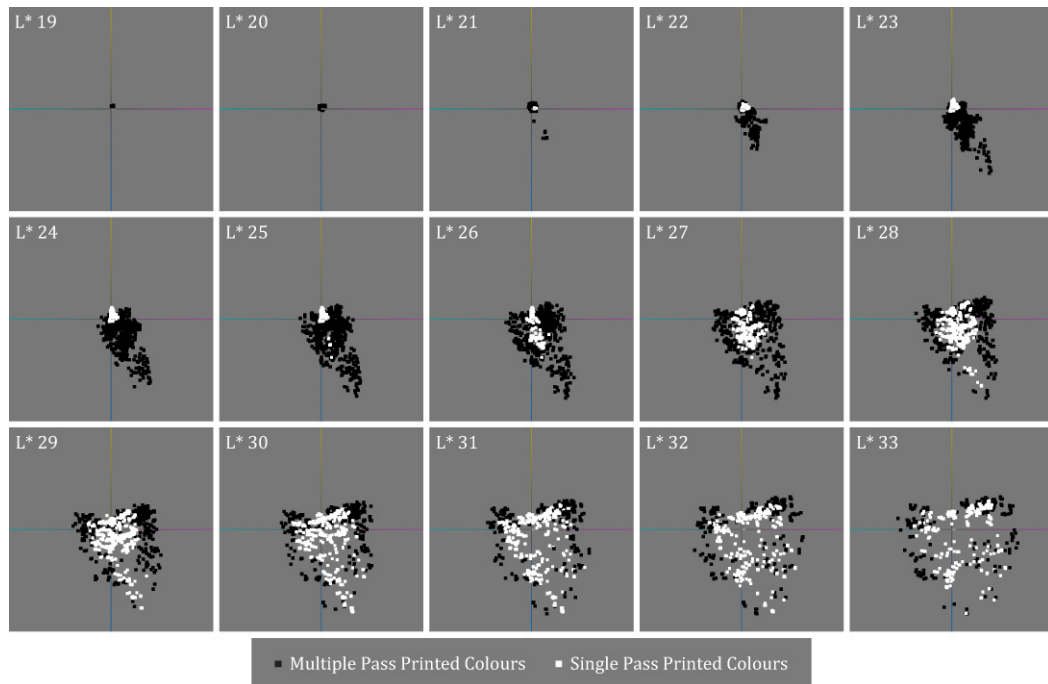


Figure 4.25. Measurements of the DC/MP and DC/SP printed patches from the MAX Colour Chart. The measurements are plotted on the Lab a^* b^* axis at various L^* values. This illustration shows the two lower limits for the DC/MP and DC/SP data sets at Lightness values of L^*19 and L^*21 , respectively.

To quantify the extent to which colour produced in the DC/MP printed MAX Colour Chart can extend beyond the previously achievable gamut, I replicated the analysis of the Colour Circle Chart (section 4.4.2) and mapped the measured colours to the same correlating profile's gamut. Figure 4.26 illustrates the range of colours achieved that are extended beyond the printer's gamut. The quantifiable data in this instance revealed 86.7% of the patches measured a dE2000 of 2.5 or higher, denoting a definitive perceivable difference. The greatest of these calculated differences was a dE2000 of 9. Of the 2,840 unique colour patches in the MAX chart, a mere 6 did not measure beyond a just noticeable difference with a dE of less than 0.5. The distribution of the calculated differences between each of the colour patches and the printer's colour gamut are displayed in Figure 4.27. In this chart colour denotes the TIC percentages for each patch. Here it can be observed that the calculated dE was greater for the patches with the higher amount of ink coverage, reinforcing the hypothesis that alternative print

methods, incorporating traditional printmaking and painting practices, can expand the reproducible colour gamut.

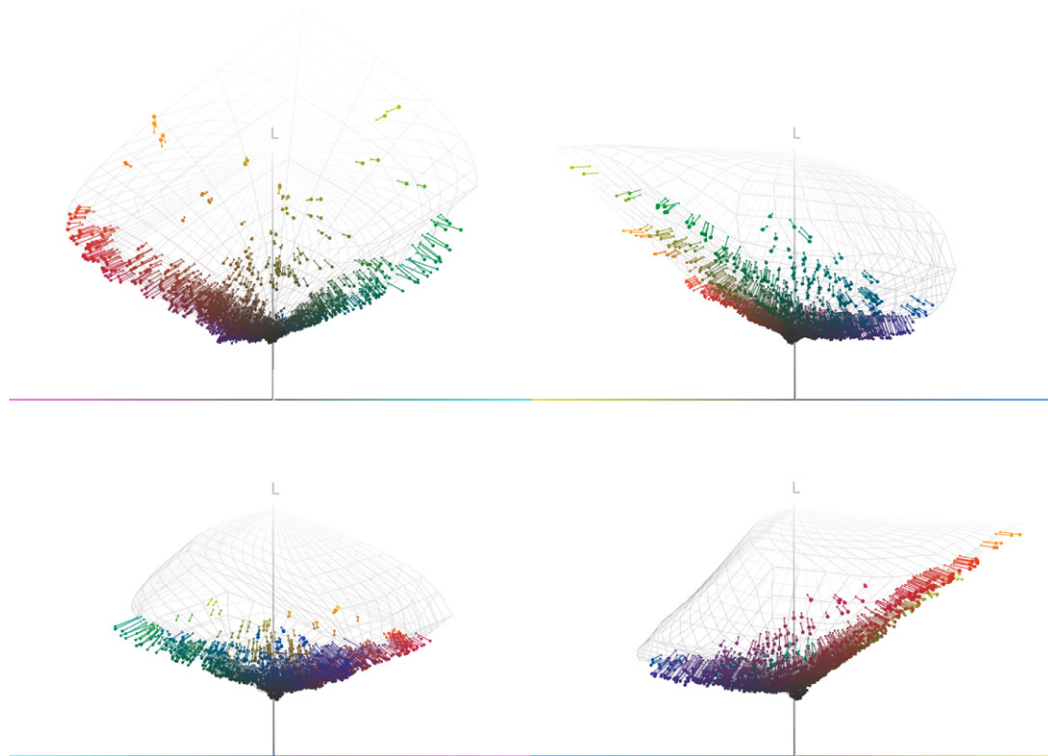


Figure 4.26. Illustration of all DC/MP colour patch measurements from the MAX Colour Chart plotted in Lab colour space alongside a wire frame representing the comparative colour profile's gamut. Lines connect the measured colour points to the closest in gamut colour.

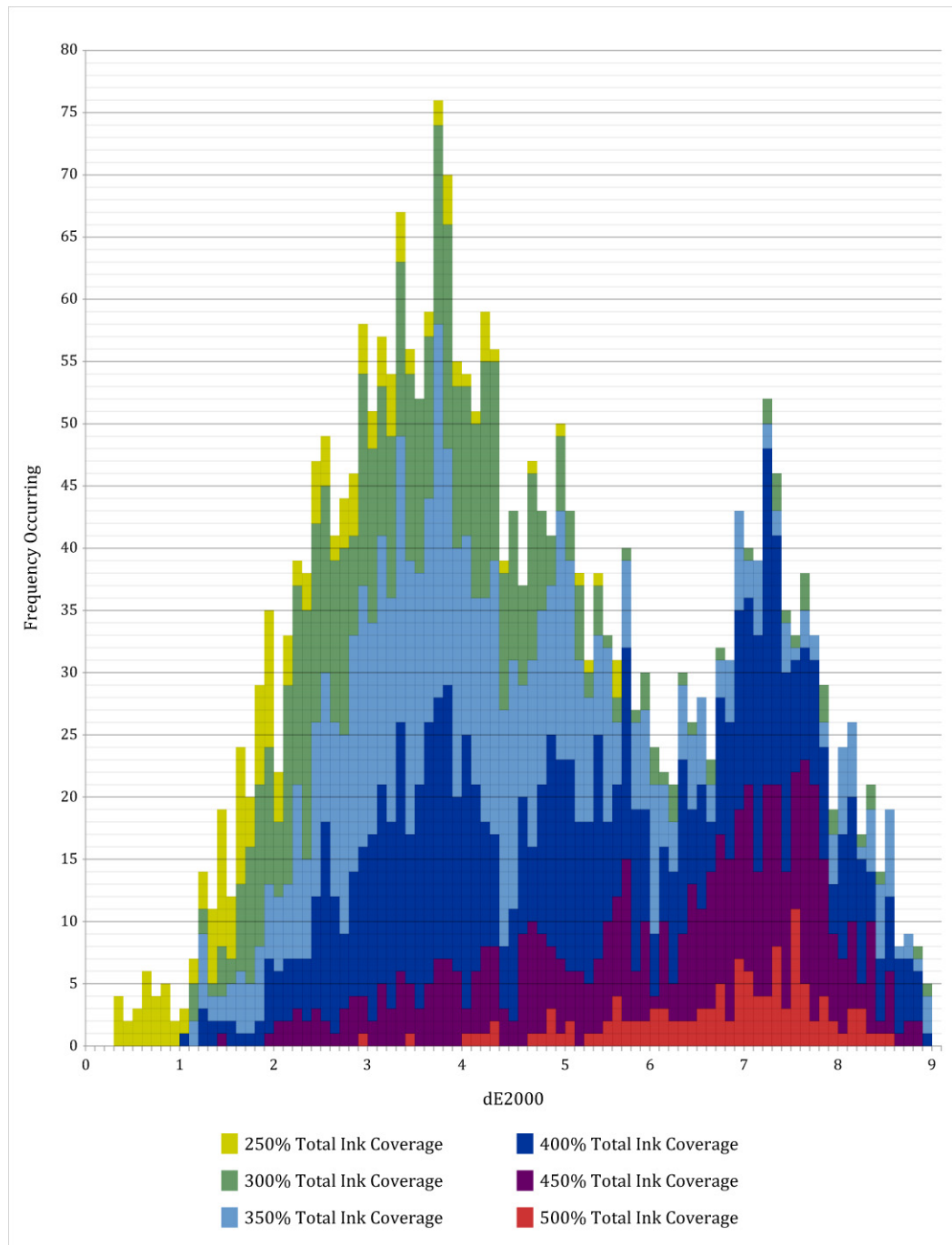


Figure 4.27. Distribution of calculated dE2000 between measured DC/MP print patches of the MAX Colour Chart and the colour profile's gamut.

To analyse the influence the multiple layers of a single colourant had on the distribution of dE differences, all 2,840 patches were divided into subcategories based on the number of times any single colourant repeated in the combination. The first category contained patch combinations where no single colourant exceeded 100% coverage. The second contained all the

patches where colourants were applied in two layers for a total coverage of 150% or 200%. Since these patches contained only two layers, any one patch could only be made up of either two colourants, or one colourant that was printed twice. The third subcategory contained all colour patches where one colourant repeated three times, creating a total coverage of either 250% or 300% for a single colourant in the combination. It was discovered that no single subcategory was dominant in the distribution of dE differences. While it could have been expected that patches containing three layers of a single colourant, that produce darker, yet more chromatic, colours that would increase the distance from the printer's gamut, this was not the case. All three subcategories were found to average 4.7, indicating equal distribution over the range of dE differences. The average, alongside the minimum and maximum dE2000 measurements for each subcategory are presented in Table 4.3.

	Any Single Colorant Total Area Coverage		
	< 100%	150% - 200%	250% - 350%
MIN	0.33	0.37	1.22
AVERAGE	4.70	4.71	4.68
MAX	8.95	9.00	8.88

Table 4.3. Minimum, average, and maximum dE2000 values for patches containing combinations where any single colourant reaches 100%, 150% - 200%, or 250% - 300% total area coverage.

I considered that the percentage of high dE differences could be attributed to the clustering of indistinguishable colours at the lowest Lightness values. To eliminate this bias, I identified and removed all near identical patches from the data set. The Lab values for each colour patch measurement were rounded to the nearest whole number, and all duplicates were removed. This reduction resulted in 1,701 patches, providing a more accurate assessment of unique colours. Of this reduced set, 79.4% measured a dE2000 value of 2.5 or greater, a 7.3% reduction from the original calculations. While the number of patches measuring a dE of less than 1.0 remained the same, the distribution of differences shifted away from the higher values. Figure 4.28 shows the reduced patch set's distribution of calculated differences with comparison to

the original 2,840 set. The peak of the reduced set's distribution remains between 3 and 4 dE2000, yet there is a significant reduction in the number of patches measuring a dE2000 of 5 or greater. This is clearly where the majority of the duplicates occurred. This confirms that the large number of very dark colour patches clustered at the lower Lightness levels measured the smallest differences between each other. However, despite the similarity in Lab values, this does not indicate that only the reduced patch set contains distinguishable colours. When it comes to colour reproduction, the small differences between colour matches can have a significant impact. This will be addressed further in Chapter 5, which focuses on the reproduction of dark colour.

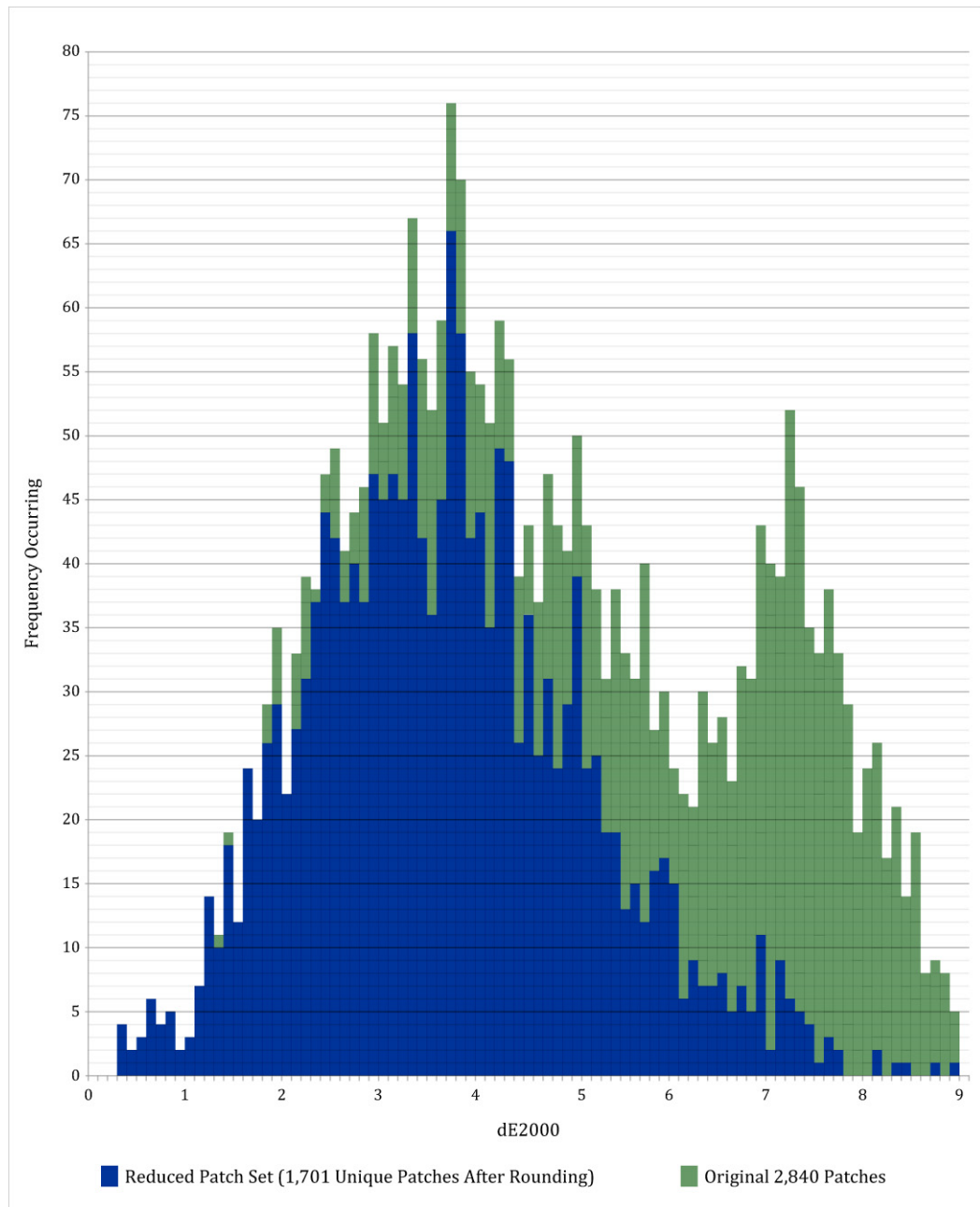


Figure 4.28. Distribution of reduced patch set's calculated dE2000 differences with comparison to the MAX Colour Chart's original 2,840 patches.

4.5. Conclusion

My practical research implemented artist driven colour mixing methods and the multi-layering of pigments using the iPF8000 series printer. By creating a series of colour test charts I was able to investigate the effects of alternative colourant mixtures by selectively controlling the colourant combinations and print sequencing as they were applied to the paper. This chapter described

the initial examination into developing these methods, as well as testing the available colour gamut in a CMYK+ printer. I carried out this experimentation by designing, printing, and evaluating a series of test charts that evolved iteratively based on both quantitative and qualitative analysis. This mixed method approach proved essential as some test charts, particularly those with larger patch counts, relied heavily on computational analysis to describe the printed colours and their differences. Alternatively, the Ink Limit and Permutation tests could not have been assessed by mathematical analysis, and relied exclusively on visual assessment, as the adverse qualities of bleeding and bronzing could not be recorded instrumentally.

Through this research, by implementing a layering process adapted from traditional printmaking and painting processes, I demonstrated a method to control the printed colours' hue and density through the layering of colourants. This provided the capability of alternating and/or repeating colourants in the layering sequences, and to increase the total amount of ink applied to the paper. The early tests, including the two-page Colour Circle Chart indicated the ability to modify the hue of a printed colour by alternating the sequence of the colourant layers. However this variable was eliminated in later testing due to the introduction of bronzing effects in higher densities and to control the total number of variables included in the testing parameters. The instances where an increased number of colourant layers were applied to the paper, such as in the DC/MP printed MAX Colour Chart, proved to substantively lower Lightness values while maintaining a higher chroma, producing colours that exceeded the correlating printer's gamut. These techniques are particularly advantageous for generating dark colour, with a large portion of the printed colours extending beyond what was previously attainable with the standard ICC colour management workflow.

The following chapters specifically address two potential digital printing applications where the DC/MP printing methods can be applied. The first, Chapter 5, focuses on the reproduction of colour sampled from a painting in

National Gallery, London's Collection. This is undertaken through the evaluation of the closest colour approximations achieved using my developed methods against the colour reproduced using a standard ICC workflow. Further on, Chapter 6 demonstrates the advantages these methods provide in the creation of original art prints. This includes the implementation of the bronzing effects achieved by manipulating the sequence in which colourants were applied. While not advantageous for conventional printing, there exists a possibility to incorporate these effects into this particular area of the fine art printing market.

5 Application in Colour Reproduction: Secondment Work with the National Gallery, London

5.1. Rationale for Addressing Colour Reproduction

During my placement at the National Gallery I had the opportunity to meet and interact with staff from a number of departments in order to gain an appreciation of processes and procedures within the Gallery setting. These meetings were particularly advantageous to gaining valuable insight into the different functions inkjet reproductions serve, and the challenges and limitations encountered with them. The two primary users of inkjet printers are the National Gallery's Photographic Department¹ and the National Gallery Company.² The Photographic Department endeavours to faithfully reproduce the original painting using a standardised and systematic workflow from

¹ The Photographic Department at the National Gallery, London, is responsible for photographing the Collection. The captures they obtain are used internally for both web based and printed reproductions of original works. The prints they produce in-house serve other departments by providing reproductions for educational projects, signage, reference and documentation, and exhibitions.

² The National Gallery Company (NGC) is a private organization that manages all the commercial reproduction of the National Gallery, London's Collection. The NGC is tasked with overseeing the variant reproduction processes for all items sold in the Gallery shops and printed publications for exhibitions that portray imagery from the NG's Collection. These products can range from postcards to scarves and bottles of gin. Because of the variety of reproduction types, there are a large number of printing processes used to produce each of their products, each possessing its own limited colour gamut.

capture to output. Here adjustments are limited to establishing the proper exposure for capture, and assigning the appropriate values to points on an X-Rite ColorChecker³ captured alongside the painting. These corrections, in addition to following an ICC managed workflow for output to a z3200 inkjet printer, are said to produce a suitable colour reproduction for 90% of the image files.⁴ The inaccuracies that arise in the remaining 10% are primarily attributed to colour gamut constraints in lightness and chroma, hindering the ability to maintain colour hue in the darker regions.

The aim of my secondment to the National Gallery was to examine how my developed DC/MP printing methods could lead toward future improvements in colour reproductions of the National Gallery's Collection of Old Master works. Having learned one of the main challenges related to colour reproduction in the darker regions of certain images, I recognised my research methods could assist in improving hue variance in the printed output. Therefore the work presented in this chapter builds directly on the research undertaken at UWE, and addresses my research question: Can the use of DC/MP printing methods obtain a more accurate colour match to the dark colours that appear in the National Gallery's Collection of Old Master paintings?

5.2. Chapter Overview

The presentation of my research in Chapter 4 focused primarily on DC/MP printing methods for the purpose of extending the achievable colour gamut. I considered that these colours may possess a closer match to dark colours found in the Collection's paintings than were being attained using the existing inkjet print practices. In this chapter I build upon the methods

³ An X-Rite ColorChecker, consisting of twenty-four colour patches with known values, is customarily included in image capture to facilitate colour correction. During image processing adjustments can be made to match the grey scale patches to their known values, correcting for both colour and tonal inaccuracies.

⁴ This statement was made by David Wood of the National Gallery, London's Photographic Department (personal communication, 21 June, 2013).

previously covered and begin to contextualize my research in a colour reproduction context.

To undertake this research I selected a target painting from the Gallery's Collection that was known to be difficult to reproduce.⁵ The qualities inherent in many Old Master paintings that are known to cause difficulty in reproduction derive primarily from how dark regions were created with little to no edge detail. In order to evaluate the effectiveness of my printing methods against those currently achieved with the National Gallery's established workflows, I took numerous measurements of the spectral reflectance (SR) from the darkest regions of the painting for use as references. I then developed a system for comparing the measured colours printed using DC/MP methods, and those reproduced through ICC managed print workflows, to the reference spectral reflectance curves (SRCs) from the target painting.

The following sections of this chapter will describe the rationale, design, implementation, and evaluation methods used in this research. This begins with an overview of the experimental parameters, including the data collection and analysis methods. It then leads into descriptions of the design, experimentation, and modification of custom colour charts that progressively improved the ability to colour match the reference SR measurements from the target painting. These sections document my methodological approach following the empirical model introduced in Chapter 1. Through both computational analysis and qualitative assessment, each colour chart covered in this chapter directly informed the subsequent chart. The final analysis in this chapter then compares the developed methodology against previously established ICC colour managed workflows. The success of my

⁵ This knowledge was gained from recounted discussions between Joseph Padfield and members of the National Gallery's Photographic Department, as well as statements made by Jane Hyne from the NGC, which specifically addressed this painting. The discussions were primarily based on the dynamic range of the painting exceeding what could be reproduced both on screen and in print. For the NGC's PoD service, this meant a large number of selective adjustments were needed to achieve a satisfactory representation of the original painting.

approach in reproducing the reference SRCs from the painting is discussed in the final section of this chapter.

5.3. Design of Experiment Parameters for Colour Matching

This section provides a detailed account of how the work was carried out to evaluate the performance of DC/MP printed output in reproducing the dark colours measured from the target painting. It begins with describing the measurement process, and then details the specifications for designing and printing DC/MP colour sampling charts, and the criteria for comparison to the reference colours. This section will only address the experimental design components to this study. The rationale for, and formation of, the individual charts will be discussed in section 5.4.

5.3.1. Measurement of Target Painting for Reference Colour

For this work, *The Supper at Emmaus* (1601), by Michelangelo Merisi da Caravaggio, was selected as a target painting (Figure 5.1). In the scene, the bottom edge of a tablecloth is composed of near neutral yellows and reds, which vary slightly in value and hue. Subtle distinctions between these colours, which are quite discernible in the original, become lost in standard colour managed inkjet printed reproductions. This can be attributed to the inherent lightness of the yellow and red ink colourants, which require the addition of black ink to reproduce the darker colour. As black becomes the dominant colourant, the distinction between the yellow and red colourants' hues are weakened. This occurrence can be further observed in many of the dark areas within this painting.



Figure 5.1. Michelangelo Merisi da Caravaggio, *The Supper at Emmaus*, 1601, Oil and tempera on canvas, 141 x 196.2 cm, National Gallery London, NG172. (© The National Gallery, London) Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

A number of colour measurements were taken from the darkest areas of the target painting with the intent to sample the greatest variance in hue.⁶ These included the reds in Christ's drapery, the green of his disciple's shirt, the blue in the pitcher on the table, several samples of the black, yellow, and red along the table cloth, and several more of the drapery from the figure on the right. In total, nineteen points were identified to be reference colours for the colour reproduction experimentations. The location of each reference colour is depicted by a white dot in Figure 5.2 with the associated colours shown underneath. The spectral power distribution of the reference colours were measured using a Konica Minolta CS1000a Spectroradiometer. This device allowed for the measurements to be taken without direct contact with the

⁶ The selection of colours measured from this painting was subjective. A range of hues, and the associated locations within the painting were noted after viewing the painting in situ for a length of time as the lighting conditions in the Gallery changed. The decision to only sample a number of colours from the painting, as opposed to aiming to reproduce the work in its entirety, was made through evaluation of my specific research aims, and in consideration to the length and breadth of my secondment.

surface of the painting, which follows the safety requirements for handling paintings from the National Gallery's accessioned Collection. For each measurement, the spectroradiometer was placed on a tripod directly in front of the painting, roughly perpendicular to the surface.⁷ A portable D50 light bank was then placed to the side, illuminating the target area at an approximate forty-five degree angle. For each measurement the light bank was repositioned along with the spectroradiometer.

For each reference colour three measurements were taken. Two measurements were taken of the white calibration tile, which was placed in front of the spectroradiometer, and directly over the painting's surface. These calibration measurements were taken immediately before and after each measurement of the painting to record the lighting conditions and monitor any changes in the ambient light.⁸ Each measured SR of the painting was then divided by the averaged SRCs of the two calibration measurements to discount the light sources' influence and obtain an illuminant independent measurement for each sampled colour in the painting (Thomson and Westland, 2002). The result of these calculations led to nineteen unique SRCs representing the sampled colours from the original painting. These curves are henceforth referred to as the painting references.⁹

⁷ In an ideal setting exact placement of the spectroradiometer would be ensured, including both distance from and angle to the painting, allowing for precise and accurate colour measurements. However, to avoid disrupting public access, the painting could not be relocated to a controlled environment. The colour measurements were carried out in limited time periods before and after the National Gallery opened. As the measured colours from the painting were only to be used as references to the original work, the unavoidable inconsistencies in the placement of the spectroradiometer was not of concern.

⁸ While the D50 light bank predominantly illuminated the painting, additional ambient conditions in the room included overhead lights on automatic dimmers and natural light entering through skylights. It was fully recognised these could cause fluctuations in both intensity and colour temperature, and therefore a single calibration measurement would not be suitable in this environment, as it would in a controlled setting. Notice was taken of any drastic changes to the measured lighting conditions that occurred in the time between each calibration measurement, and measurements of any sample area was retaken if necessary.

⁹ The spectral power distribution curves for each of the nineteen painting references are plotted in appendix D (D.2), alongside the results from each colour chart presented in this chapter.



Figure 5.2. Nineteen white dots indicating the location each colour measurement was taken from Michelangelo Merisi da Caravaggio, *The Supper at Emmaus*, 1601, Oil and tempera on canvas, 141 x 196.2 cm, National Gallery London, NG172. (© The National Gallery, London. Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.) The corresponding colours, used as the painting reference colours, are displayed as solid patches¹⁰ under the image.

5.3.2 Collection of Data from Inkjet Printed Colour Charts

In order to sample the DC/MP printing method's achievable range of dark colours, I identified the need to customize my own colour charts to this application. As described in Chapter 4, pre-existing colour charts were not available for CMYK+ input referred applications as they are for the four-colour process. Therefore I designed colour charts specifically tailored to sampling colourant combinations from the expanded seven-colourant inkset.

¹⁰ The colour solids representing the measured colour from the painting were converted to Lab values using the Chromix ColorThink Pro software, version 3.0.3 set at the D50 illuminant, and the 2-degree observer (www.chromix.com). This method of conversion continues to be used in all forthcoming colour solids presented in this chapter as representations of the measured colour patches.

These included combinations consisting of conventional CMYK and analogous colourant combinations, and also combinations that sampled across the colour circle. Aside from that of CMY, complementary and triadic colourant combinations are not customarily included in CMYK+ printing applications. This is because such combinations are considered to create repetitive hues to those already attainable through either CMY, or any analogous colourant combination (Bala, 2003, p. 370). While this colourant restriction was also incorporated into early spectral colour printing (Rosen et al., 2004),¹¹ it was later found to limit degrees of freedom, and subsequently the number of colours that can be produced in print (Tzeng and Berns, 2000).

Similar to the layout of the MAX Colour Chart described in Chapter 4, the patches in each sampling chart were arranged in a grid pattern. Each colourant was assigned to its own layer, which corresponded to its own print pass. All colour charts presented in this chapter maintain the standardised colourant order of YBRMCG, which was determined by the Permutation Chart in Chapter 4 (4.4.4). Each chart was printed as a DC/MP print on the Canon iPF8400 printer.¹²

Unlike the target painting, the inkjet printed colour charts could be measured using either the XRite i1 Pro or the Konica Minolta FD-7 devices, as the contact between the device and the printed surface was not a concern. These devices allowed for a large number of patches to be measured in considerably less time than with the spectroradiometer.¹³ The measurements

¹¹ In determining the spectral redundancy of a CMYK+ printer Rosen, Hattenberger, and Ohta set the tolerance for their study to an RMS error of 0.02. However, the authors concluded that a lower tolerance may be better suited for certain applications.

¹² Although the National Gallery currently produces all their inkjet prints on HP devices, the majority of my research continued to employ the iPF8000 series printer. While my research methods can be replicated on the z3200, the comparison made between the two printers in Appendix B established that the Canon iPF8400 could produce a larger range of dark colour.

¹³ As stated in Chapter 4 (4.3.5), preliminary colour measurements were taken with the XRite i1 Pro. It was the series of experiments presented in this chapter that led to the determination that a more precise and consistent measurement instrument was necessary due to the small colour differences that were being calculated. Therefore it is only the early colour matching experimentation discussed in section 5.4 that contains measurements taken

taken with both of these devices were calibrated using the supplied white reference, automatically discounting the illuminant from the measured samples.¹⁴ All measurements recorded the spectral power distribution of the printed patches.

5.3.3. Comparison of Reference and Inkjet Printed Colours

The SRCs of all nineteen painting references were compared to those of the measured DC/MP colour charts in order to identify the best match to each reference using the Root Mean Square (RMS) metric (2.4.2). Through the RMS calculations I was able to ensure that I was matching the colour's physical properties, while also identifying a colour match that was less likely to be metameric.¹⁵ The series of dE2000 calculations are also provided alongside the RMS calculated results as a secondary indication of how well results from the RMS calculations performed, taking into account the sensitivities of the human visual system.

5.4. Early Exploration of Colour Matching for Reproduction

Results of my early work undertaken at the National Gallery indicated that higher densities could be attained by building up layers of ink incrementally through the process of DC/MP printing (Olen et al., 2014). This, in addition to the dark, yet colourful, patches in the Custom Ink Limit Chart's higher coverage (4.4.3), identified the possibility to control hue more precisely by adjusting the colourant combinations, while relying on the layering process to produce density. The experimentation presented in this section describes the rationale and design for a series of colour sampling charts aimed at

using the XRite device. The Konica Minolta FD-7 spectrodensitometer was later obtained for use in the advanced research documented in section 5.5. Any measurements of the earlier colour charts that appear in the latter section were reread with the FD-7 spectrodensitometer.

¹⁴ Steps were taken to ensure consistency in the colour measurements acquired with the Konica Minolta CS1000a Spectroradiometer and the XRite i1Pro using a Munsell colour chart. When the Konica Minolta FD-7 Spectrodensitometer was incorporated into the studies these consistency checks were completed again.

¹⁵ While the results lack a weighting function that accounts for the human visual system, the additional calculations this would require were considered unnecessary at this stage of the experimentation. This has been discussed in greater detail in Chapter 2 (2.4.2).

investigating this hypothesis. It then continues to evaluate the outcomes in relation to how accurately they reproduced the painting references. At each stage the strengths and weaknesses of the printed colour in the sampling chart were assessed, and amendments to the subsequent sampling chart were made accordingly.

5.4.1. Sampling of Dark Colourant Combinations Excluding Black

Rationale and Design for a Dark Colour Sampling Chart

Having observed that the multiple pass print method increased the print density, and the subsequent darkness of the colour, I considered that black may not be as essential for producing dark colours as it is in a traditional single pass print. With the darkness of a given colour achieved by ink volume, there now existed the possibility to eliminate black in order to preserve more of the hue present in the CMYRGB colourants. This approach is contrary to the prominent printing practices where black is used to replace proportions of the other colourants using a grey component replacement (GCR). A disadvantage to the GCR method resides in the fact that the black ink simultaneously reduces the perceivable shift in hue when adjusting combinations of the remaining ink colourants.¹⁶ Therefore, the first test chart did not contain black ink, relying on the layering of the CMYRGB colourants to generate both the hue and density to match the painting references.

The specification for the Dark Colour Chart's composition is presented in Appendix C (C.6), the final output of which is shown in Figure 5.3. Despite the high percentages of ink, not all patches appear dark in print. This was to be expected, as mixtures of analogous colourants, particularly those including lighter colourants, will maintain more of the colourants' hues than complementary combinations. However, even in these instances, the transition between 300% and 400% total ink coverage (TIC) begins to produce noticeably darker colour.

¹⁶ The result of implementing a colour-managed workflow that incorporates a grey component removal method is discussed in Chapter 6.

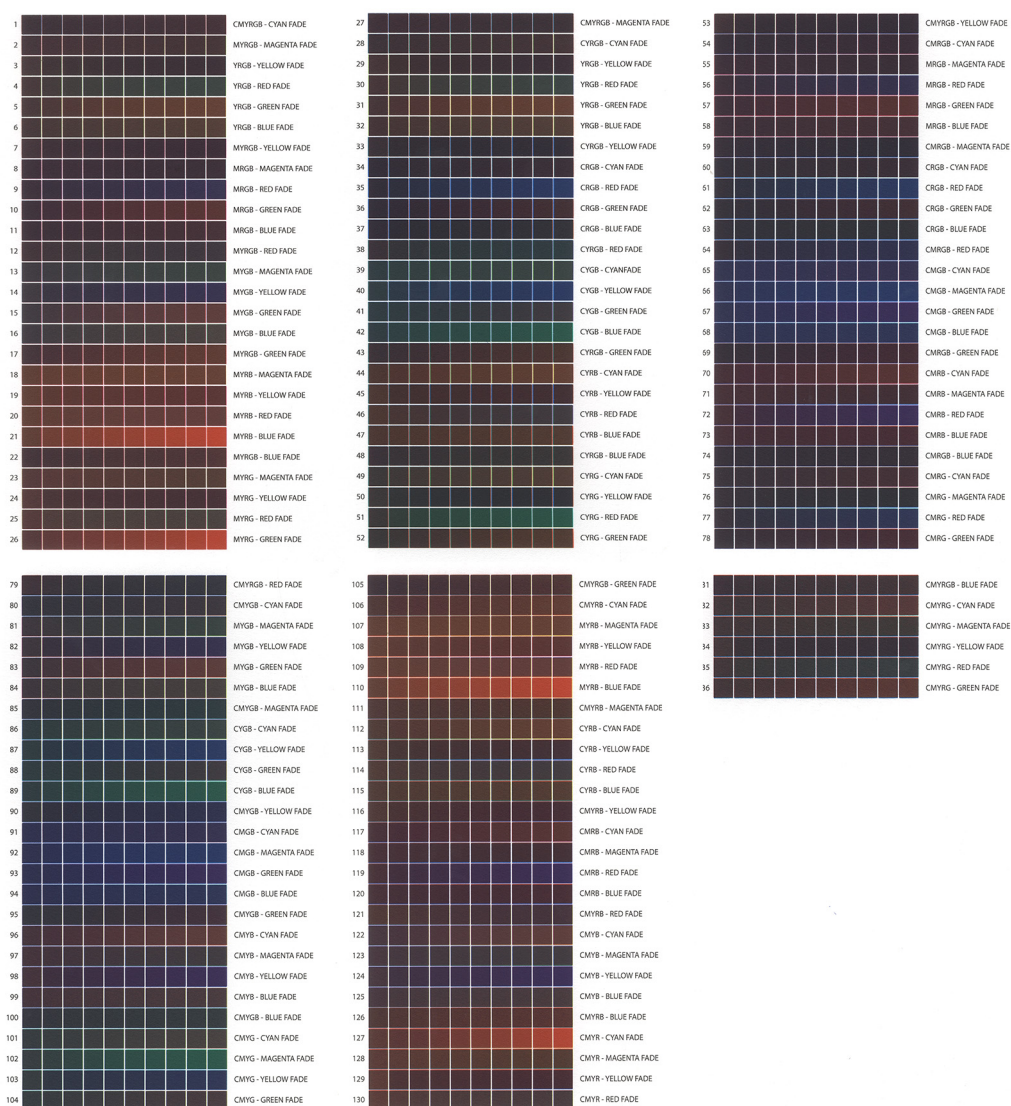


Figure 5.3. Scan of the six page Dark Colour Sampling Chart.

Report and Analysis of Colour Matching Results

Each unique colour patch was measured and compared to the nineteen painting references according to the specification described earlier in section 5.3.3. The RMS errors are recorded in Table 5.1, and Figure 5.4 depicts the colourant combinations of the lowest RMS error alongside the corresponding painting references. These results show that the colour that achieved the best match still remains significantly different in both value and hue to the painting references. While the majority of the painting reference colours can be described as dark reds and yellows, the swatches from the Dark Colour Sampling Chart were primarily a purplish hue. Only three results maintained

any semblance to the reference hue. One, Reference Sample 2, can be credited to the colour's comparatively higher reflectance in the red region of the spectrum. However, none of the colour patches identified from the Dark Colour Sampling Chart produced an acceptable colour match.

	RMS		RMS		RMS
Ref. 1	0.0357	Ref. 2	0.0252	Ref. 3	0.0360
Ref. 4	0.0250	Ref. 5	0.0344	Ref. 6	0.0361
Ref. 7	0.0352	Ref. 8	0.0232	Ref. 9	0.0328
Ref. 10	0.0381	Ref. 11	0.0349	Ref. 12	0.0358
Ref. 13	0.0337	Ref. 14	0.0354	Ref. 15	0.0311
Ref. 16	0.0382	Ref. 17	0.0377	Ref. 18	0.0362
Ref. 19	0.0355				


RMS 0  RMS 0.04

Table 5.1. Calculated RMS errors for the Dark Colour Chart's best match results.

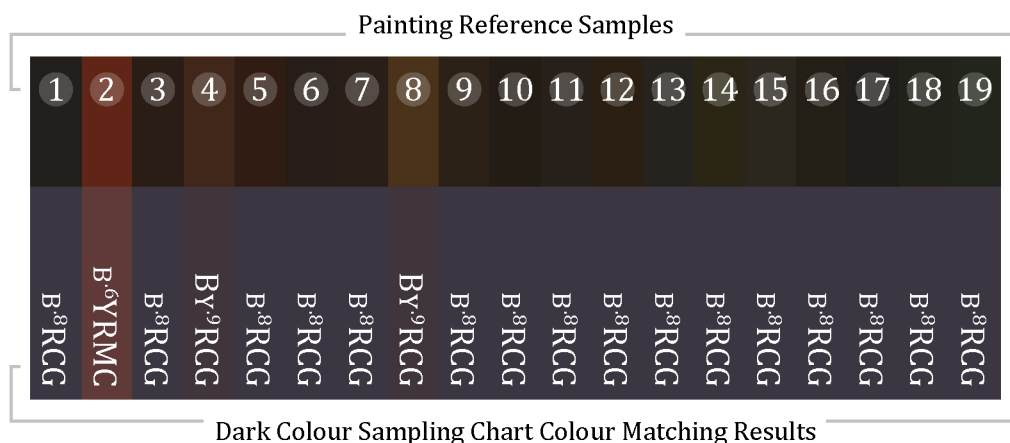


Figure 5.4. Solid colour patches representing the nineteen painting reference colours (top row) and the colour matching results from the Dark Colour Sampling Chart (bottom row). The fractional coverage for any colourant printed at less than 100% is specified following the small capital letter indicating the colourant.

The colour matching inaccuracies found using the Dark Colour Sampling Chart identified a sampled colourant's inability to reproduce the same dark values that were present in the painting references. Due to the drastic differences in intensity between the SR at each measured wavelength, the RMS calculations identified colour matches that were significantly different colours to the reference. For example, in Reference Sample 14 (Figure 5.5),

the painting reference's colour had a peak in the green/yellow region of the colour spectrum. However, the SR of the colour patch with the lowest RMS error is weakest in this region, having more intensity in the violet and red regions of the spectrum.

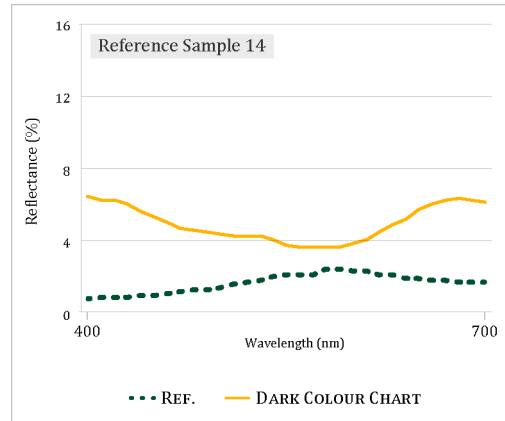


Figure 5.5. Spectral reflectance curves (SRCs) of painting reference sample 14, plotted alongside the lowest RMS results from the DC/MP printed Dark Colour Sampling Chart.

In addition to the observable differences in colour between the painting references and the selected colour patch from the Dark Colour Sampling Chart, it is also notable that sixteen out of the nineteen results all possessed the same colourant combination. This indicates that a complete loss of the colour difference would occur if the original sampled regions of the target painting were reproduced using the colourant combinations selected through these calculations.

The results found in this experiment highlighted the need to produce printed colours that are significantly darker than the colour patches from this chart. Figure 5.6, containing the plotted SRCs for three of the nineteen samples, illustrates the disparity between the reflectance values of the painting references compared to the colour patches from the Dark Colour Sampling chart. If darker patches can be produced, the RMS calculations may be more effective in finding a colour match with the appropriate spectral distribution. Furthermore, review of the SRCs revealed that the colours in this chart possessed a large variance in intensity in comparison to the painting reference samples. In order to improve upon these results, I recognised the

need to examine whether a controlled reintroduction of black, combined with multiple layers of select CMYRGB colourants, could both darken the colour and correct for the overly high chromaticity of the colour's hue, without completely neutralising it.¹⁷ The next section describes this further experimentation.

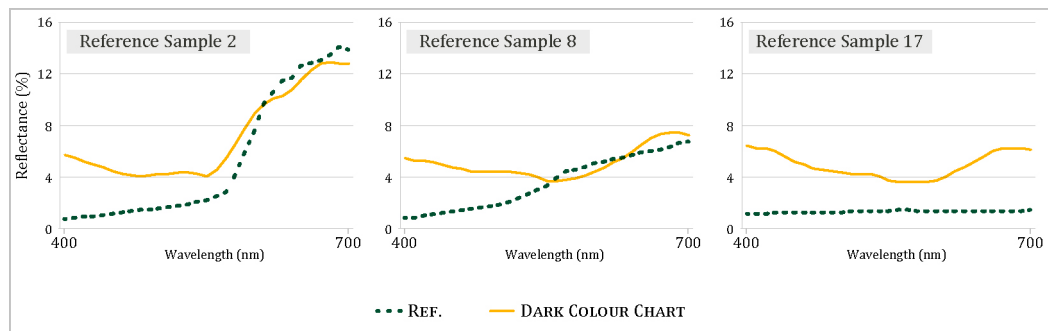


Figure 5.6. SRCs of painting reference samples 2, 8, and 17, plotted alongside the lowest RMS results from the DC/MP printed Dark Colour Sampling Chart. The plotted SRCs for all nineteen reference samples can be found in appendix D (D.2).

5.4.2. Sampling of Colourant Combinations Including Black

Rationale and Design for a Colourful Black Sampling Chart

The Colourful Blacks Sampling Chart aimed to address my adjusted hypothesis that adding black ink to the multiple layers of the CMYRGB colourants could produce a more accurate match to the painting references. The use of black was intended to correct for the overly light and highly chromatic colours printed in the Dark Colour Sampling Chart's SRCs. As the black ink would quickly darken the overall colour of the printed patches, I chose to lower the minimum total ink coverage, allowing a number of patches to contain very low percentages of the CMYRGB colourants. While previous experiments have indicated that more colour distinctions can be made when using a greater number of colourants at higher ink volumes, this sampling chart aimed to see if reduced colourant coverage, when combined with black, would improve near neutral colour reproduction.

¹⁷ It is understood that additional variables, such as paper selection and surface characteristics, exist as alternatives to changing only ink colourants and total ink volume. These additional variables are introduced and discussed later in section 5.5 of this chapter.

From review of the Dark Colour Sampling Chart it was further determined that it would be advantageous to include combinations where multiple colourants' coverage values were reduced simultaneously. This expanded on the previous sampling chart where only one colourant per row was reduced. The rationale for this amendment was to sample a greater range of the colour gamut by sampling more transitional hues. However, as this variable increased the required patch count for covering all possible colourant combinations, a compromise had to be made. This came in the form of limiting the total number of colourants in any single row to four.

In addition to the combinations described above, a further nine rows were added, which contained combinations of each single colourant and black. While these additional rows lowered the total ink coverage even further, the resulting patches examined the extent to which the black had a neutralising effect on the underlying colour. Even with these limited total area coverages, it was anticipated that the printed output would maintain enough of the colourants' hue to improve upon the Dark Colour Chart's results. The printed version of the Colourful Black Sampling Chart is shown in Figure 5.7.

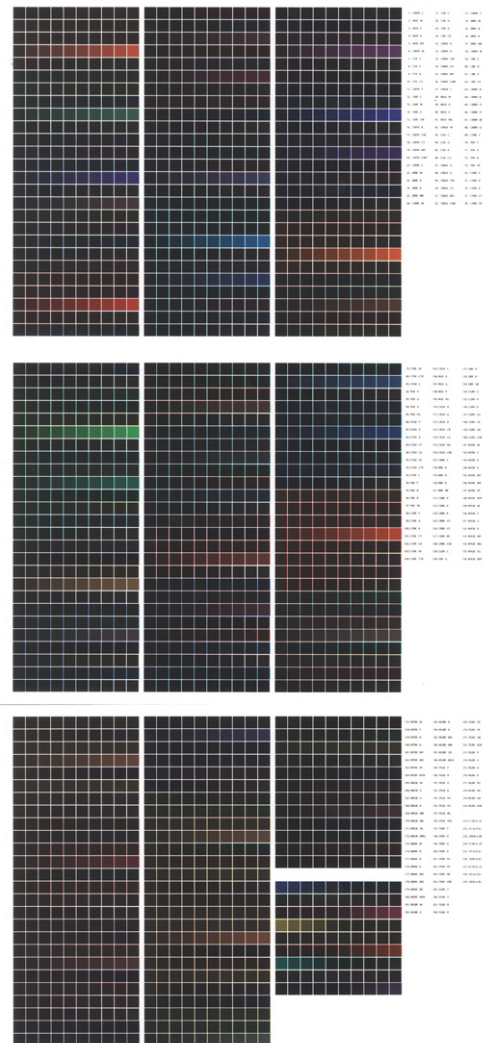


Figure 5.7. Scan of the three page Colourful Blacks Sampling Chart.

Report and Analysis of Colour Matching Improvements and Limitations

For the examination of the Colourful Blacks Sampling Chart I replicated the methods used for the Dark Colour Sampling Chart. Again the RMS errors were calculated between each measured colour patch and painting reference. The results of these calculations can be seen in Figure 5.8 and Table 5.2. In Table 5.2, the calculated RMS errors for the Colourful Black Sampling Chart's best performing colour patches are shown alongside the results from the Dark Colour Sampling Chart. The calculated percentage change included in this chart shows that the RMS error was reduced by more than half for 89% of the reference samples. These improvements are further illustrated in Figure 5.9, where the measured patches' SRCs are plotted for both the

Colourful Black and Dark Colour Sampling Chart's results alongside the SR of three painting references. The result of printing black over multiple layers of colourant combinations exhibits both lower reflectance levels and minimally fluctuating distribution curves, signifying chromaticity closer to those of the painting references.

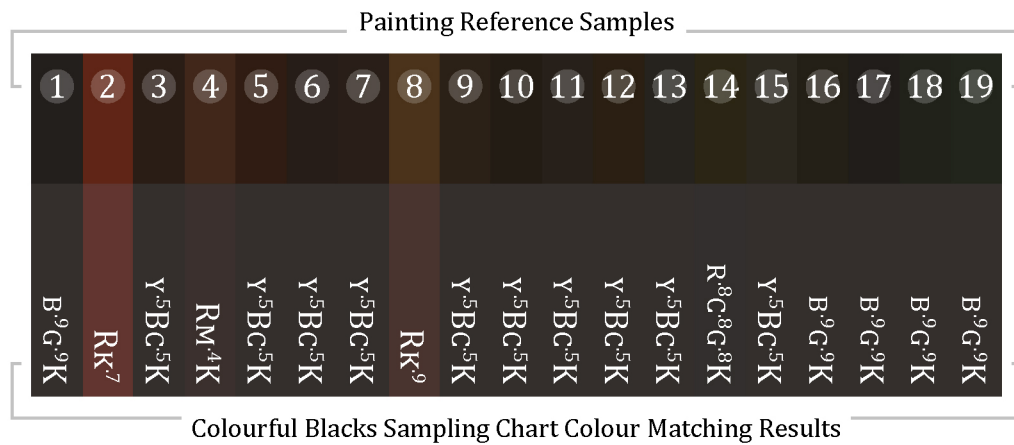


Figure 5.8. Solid colour patches representing the nineteen painting reference colours (top row) and the colour matching results from the Colourful Blacks Sampling Chart (bottom row). The fractional coverage for any colourant printed at less than 100% is specified following the small capital letter indicating the colourant.

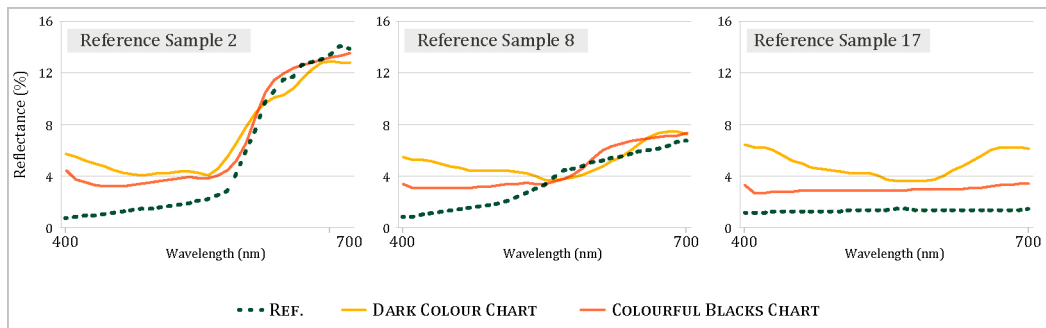


Figure 5.9. SRCs of painting reference samples 2, 8, and 17, plotted alongside the lowest RMS results from the DC/MP printed Dark Colour and Colourful Blacks Sampling Charts.

		RMS	% Change		RMS	% Change		RMS	% Change
Dark Colour	Ref. 1	0.0357	-58%	Ref. 2	0.0252	-33%	Ref. 3	0.0360	-56%
Colourful Blacks		0.0151			0.0168			0.0157	
Dark Colour	Ref. 4	0.0250	-54%	Ref. 5	0.0344	-58%	Ref. 6	0.0361	-57%
Colourful Blacks		0.0115			0.0143			0.0156	
Dark Colour	Ref. 7	0.0352	-58%	Ref. 8	0.0232	-44%	Ref. 9	0.0328	-62%
Colourful Blacks		0.0146			0.0129			0.0126	
Dark Colour	Ref. 10	0.0381	-54%	Ref. 11	0.0349	-59%	Ref. 12	0.0358	-58%
Colourful Blacks		0.0174			0.0143			0.0151	
Dark Colour	Ref. 13	0.0337	-62%	Ref. 14	0.0354	-60%	Ref. 15	0.0311	-68%
Colourful Blacks		0.0128			0.0141			0.0099	
Dark Colour	Ref. 16	0.0382	-55%	Ref. 17	0.0377	-55%	Ref. 18	0.0362	-57%
Colourful Blacks		0.0173			0.0171			0.0154	
Dark Colour	Ref. 19	0.0355	-59%						
Colourful Blacks		0.0145							


RMS 0

RMS 0.04

Table 5.2. Calculated RMS errors for the Dark Colour and Colourful Blacks Sampling Charts' best match results. The reductions in errors from the Dark Colour results to the Colourful Blacks results are shown as highlighted percentage changes.

It was known from previous analysis described in Chapter 4 (4.4.2) that the incorporation of black reduces the intensity of the colourant's hue as it darkens the printed colour, but the extent to which this would occur had yet to be tested. The results from the Colourful Black Sampling Chart established that even a fractional coverage of black ink, while showing improvements to the darkness of the printed colour, had a significant neutralising effect on the underlying colourants. With this, the results from this sampling chart continued to identify dark, yet fairly neutral patches as the closest match to the painting reference sample. The SR of the DC/MP printed patches measuring the lowest RMS error now appeared too neutral in comparison to the SRCs of the painting references. This indicates that the use of black ink may have over corrected for the chromatic colours in the Dark Colour Sampling Chart. With these results, the subtle hue differences present in the

painting continued to be unmatched using the DC/MP printing parameters established thus far in the experimentation.¹⁸

The inability to recreate the subtle differences in hue can also be identified through the limited diversity of colourant combinations calculated as the closest spectral match to the painting reference. While improving upon the Dark Colour Sampling Chart's duplicate colourant combinations, the Colourful Blacks Chart identified only six colourant combination assignments to reproduce all nineteen painting reference samples. This result can be attributed to two possible explanations. One explanation is that while the Colourful Blacks Sampling Chart expanded upon the possible colourant combinations from the Dark Colour Sampling Chart, it still only transitioned the total coverage in 10% increments, so not every possible colour variance was included in the sampling of dark printable colour. However, this can only be attributed to instances where the same colourant combination was selected for reference colours already similar in hue, such as the multiple yellow hues in the darker regions of the cloth draped over the table.

The second possible explanation for the Colourful Black Sampling chart producing duplicate results follows an observation made of the Dark Colour Sampling Chart's results. There a large portion of the results identified the darkest colour from the printed sampling chart to match the dark painting references.¹⁹ Due to the significant differences in reflectance values between the printed patches' SRCs and the SRCs of the nineteen painting references, the printed patch with the lowest overall reflectance consistently measured the smallest RMS to the reference, without consideration to the dominant wavelengths of the reference. Therefore, in order to truly test the capabilities of the DC/MP printing method's ability to improve accuracy in reproducing

¹⁸ Despite the easily recognised colour differences between the painting references and the Sampling Chart's results, a subset of these results were found to outperform ICC colour managed output (Olen and Padfield, 2015).

¹⁹ The CRGB-B80 combination from the dark colour sampling chart measured the lowest average reflectance at 0.0489.

dark colours, improvements need to be made to the attainable darkness levels in the printed output.

5.5. Advanced Testing Parameters for Colour Matching

Building on the early reproduction experimentation I began to explore various means of darkening the DC/MP printed colours. While it has been determined that printing multiple layers of colour increases the overall density, and can produce colours darker than those produced in a single pass print, the question remained: to what extent was this possible? The experiment presented in this section coincided with the development of the MAX colour chart presented in Chapter 4 (4.4.5).

In assessing the optimal parameters for surveying the darkest printable colours achievable with DC/MP methods, I returned to the earliest print tests I produced. This included the initial Colour Bar Test, which, in addition to multiple layers of the CMYRGB colourants, also included multiple layers of black (4.4.1). Re-examination of this print test, specifically of the black region, identified a previously unidentified limitation to the sampling charts' ability to achieve darker colours by increasing print density. As greater quantities of black ink were applied to the paper, the perceived darkness of the black did not appear to increase. In fact, depending on the viewing angle, the area with three printed layers appeared lighter than the area with only two printed layers. This was attributed to a surface reflectance differential caused by over inking the paper surface. While the ink applied in the first two layers was absorbed into the paper and coating layer, a portion of the final ink layer was likely sitting on the surface of the coating. This resulted in the surface characteristic being that of just the ink, instead of a paper/coating/ink combination.²⁰ The increased reflectiveness of the over

²⁰ This has been a problem experienced previously in the market. To combat the surface differential, which occurred in prints on glossy media, HP has included a 'gloss enhancer' in the inkset of the DesignJet z3200 printer. The gloss enhancer is printed in image areas where no other colour inks are printed in order to create a uniform gloss over the entire printed surface (Ma et al., 2011).

inked surface causes the black to appear lighter or darker than the two layer black, depending on the illumination and viewing angle.

The increased reflectiveness of the over inked black also effected the measurements taken with the X-Rite i1 Pro spectrophotometer. Due to the fixed angle of illumination, the SR of the three layers of black measured a similar reflectance to the two layer black print.²¹ As this surface reflectance differential presented itself as an inaccurately measured, yet observable print defect, it was considered necessary to correct for its occurrence.

5.5.1. Enhancing the Inkjet Printed Output with Varnish Coatings

Rationale for the Added Varnish Coating

It has been established through the refining of research parameters that using a highly absorbent paper is crucial to this research. As explained in Chapter 4 (4.3.4), the Somerset Enhanced paper was chosen specifically because it could handle the ink volume applied over multiple layers. However, I also recognised that gloss surfaces can produce a perceptually darker colour than is achieved with a matte surface as light is reflected back to the observer quite differently from a gloss print than from a matte print. This is caused by light reflecting off the glossy surface at a particular angle, which is typically not the angle of viewing (Pauler, 2012, p. 131). In order to obtain the benefits of both the high absorbency and the gloss surface reflectance, I conducted a series of tests using varnishes to create a reflective surface over the matte print. The use of a varnish surface coating was also intended to correct for the surface characteristic differential of the higher quantities of ink by creating a uniform surface over the entire print.

²¹ At the same time, measurements taken with the X-Rite i1Pro spectrophotometer of a controlled white source presented a problem with the device's repeatability. Therefore the progression of this research became dependent on the acquisition of a more stable device. The Konica Minolta FD-7 spectroradiometer was recognised for its ability to meet all of the requirements for this research.

For the coatings, I found Magic Inkjet's ClearJet Series FA to be the most appropriate for my experimentation.²² These clear coat varnishes are specifically designed for fine art inkjet printing applications, with significant consideration given to maintaining colour information without any shifts in hue (Clearstar Coatings Corp., 2002). I tested each of the three finishes available in the FA series as aerosol sprays: gloss, semi-gloss, and low gloss. More variations were not included in this experimentation as the use of varnish was considered only to develop a proof of concept for the DC/MP printing method's application in fine art reproduction, and as a secondary aspect to my research it did not necessitate a higher level of experimentation. The coatings were applied by hand, following the manufacturer's instructions for angle of application, distance from paper, and wait time between coatings. Care was taken to ensure consistency in the coating process. Each of the three varnishes were applied in three coating layers, and the gloss and semi gloss were additionally applied in six layers, to gauge an optimal coating thickness.

Analysis of Coating Appearance and Measureable Properties

Evaluations of the coated DC/MP prints were undertaken using both qualitative and quantitative methods. This mixed method evaluation was essential, as neither visual nor computational analysis alone could identify a definitive choice of the optimal coating. Initial evaluation, conducted purely through visual analysis of the coated surfaces, was necessary to determine if the surface differential was corrected for, as this could not be measured. These evaluations foremost confirmed that the coating was successful in providing a uniform surface reflectance over the printed output, eliminating the lighter appearance of the higher ink volumes at certain viewing angles. Additionally, the coating, particularly with the higher gloss, was noted to

²² Other varnishes and coatings were tested, but many required application by brush or roller. This application method caused the uppermost layers of ink to wipe away. A solvent UV printer was also tested to determine if a controlled and uniform varnish layer could be applied over the printed surface. However, the solvent gloss varnish reacted with a number of the ink colourants from the Canon printer resulting in warping and bubbles in some areas of the coated surface.

greatly enhance the perceived darkness of the printed colour while maintaining distinctions between the various hues.

Along with darkening the printed colour, the varnish coating simultaneously presented an adverse effect on the printed output. While the textured surface of the paper being used (Somerset Velvet Enhanced) is beneficial to my print methods, as the uncompressed paper fibres on the papers surface can absorb more ink, it became a distraction when emphasised by the gloss coating. The texture therefore became a visual deterrent when making visual judgements of the printed colour. It was reasoned that a smoother paper surface might be necessary for the forthcoming experimentation. To minimise the number of variables that accompany the introduction of a new substrate, I chose to use the Satin version of the Somerset Enhanced papers.²³ The same test chart was printed on the Somerset Satin Enhanced as was printed on the Velvet paper, and the same coating variables were applied with three varnish finishes.²⁴

With the initial observations made of the Somerset Satin Enhanced test prints matching those of the Velvet paper in relation to perceived darkness and maintained hue, I moved on to making quantitative assessments. A subset of test charts' patches was measured in order to substantiate the evaluations made on perceived darkness and hue. Measurements were taken of the patches with each single colourant overprinted with black, and the patches with 1, 2, and 3 layers of black ink using the Konica Minolta FD-7 spectrodensitometer. The SR of the measured colour patches for each paper and coating combination were then judged against measurements taken from the corresponding uncoated print.

²³ The production of the Somerset Satin Enhanced is nearly identical to that of the Velvet paper, with the only difference being the surface texture. The fibres in the Satin paper are pressed more in the manufacturing process in order to create a smoother surface. The coating make up and application then remain unchanged.

²⁴ With the introduction of the Satin paper, the characterisation process was undertaken following the same process that was previously carried out with the Velvet paper, including linearization and ink limit testing.

Evaluations made of the low-gloss varnish and the three coating layers of the semi-gloss and gloss varnishes corroborated the visual analysis. The coating did create a more uniform surface reflectance, correcting for the surface differential with the high volume of black ink. However, these three varnishes, with only 3 coating layers, did not fully correct for the difference between the darkness of the printed colour and the painting references. It was only the semi-gloss varnish, applied with 6 coating layers, which produced a suitable reflectance low enough to reproduce the darkest of the painting references.²⁵ The measurements taken of the one, two, and three layers of black with these varnish coatings are plotted in Figures 5.10 and 5.11 for the Somerset Velvet and Satin Enhanced paper. Here it can be observed that the reflectance of each printed black patch decreases in relation to the amount of ink layered in the print with the three layer black achieving the darkest colour for both the Satin and Velvet papers with each of the three varnishes.

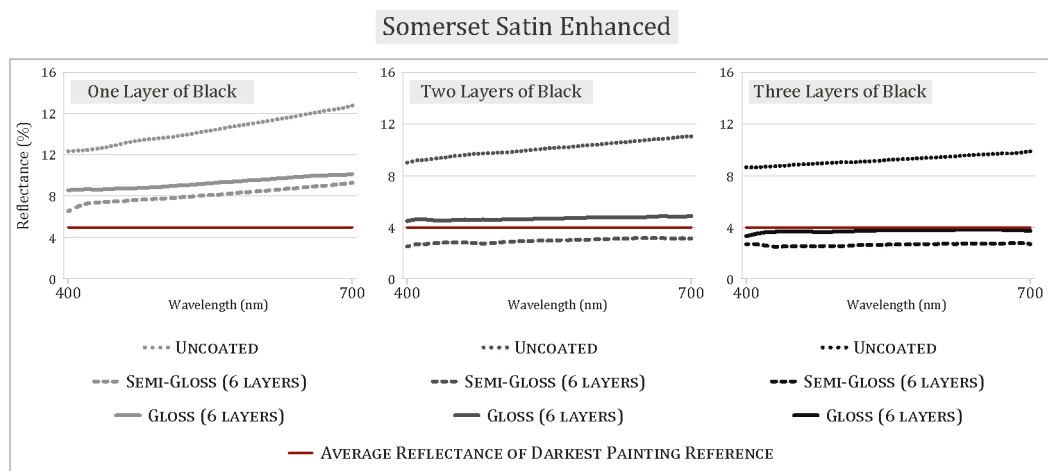


Figure 5.10. Plotted SRCs of the varnish coating trials using one, two, and three layers of black ink printed on Somerset Satin Enhanced paper.

²⁵ The average measured reflectance for the darkest painting reference, sample 10, was 1.24%. While four of the paper and varnish combinations were able to match, or fall below this reflectance value, only the six coatings of semi-gloss achieved this in the majority of the dark colour patches. This was considered an important attribute as it meant a greater number of variant hues could be reproduced at this darker level.

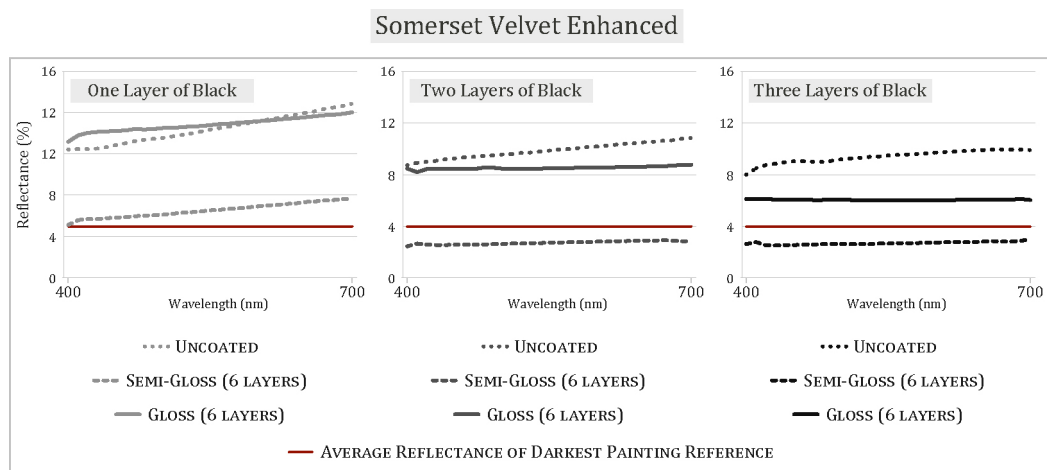


Figure 5.11. Plotted SRCs of the varnish coating trials using one, two, and three layers of black ink printed on Somerset Velvet Enhanced paper.

The evaluation of the colour measurements, coupled with the visual analysis, led to the decision to use six coating layers of semi-gloss on the Somerset Satin Enhanced paper for all forthcoming research on the colour reproduction of the painting references. This selection was informed as much by the visual judgements made on the coated prints as it was on the quantitative judgements. The Somerset Velvet Enhanced paper was inevitably eliminated due to the textured surface distracting from the printed colour. This was due to the high gloss reflecting greater amounts of light at the specular angle, resulting in only a reflected white appearance of the surface. The semi-gloss provided the necessary surface properties to scatter the light and make the printed colour appear darker without producing a distracting surface reflectance.

5.5.2. Colour Match Testing Using Coated Colour Charts

Rationale and Specifications for Testing Procedures

With the ability to lower the reflectance of the printed colour patches by coating the prints with a uniform semi-gloss varnish, I recognised that amendments to the colourant combinations used in the latest sampling chart may no longer be necessary. Specifically, the need for black ink to darken the colour may not be required to reproduce all the painting references. Instead, to achieve the final colour I could combine the layering of colourants to

produce the hue and rely on the varnish to darken its appearance. Therefore, in my final experimentation I reprinted both the Dark Colour and Colourful Black Sampling Charts to increase the variables in colourant combinations for the final sampling. Furthermore, I included the MAX colour chart, described in Chapter 4 (4.4.5), which had been developed at the same time as the varnish testing was undertaken.²⁶ All three charts were printed on Somerset Satin Enhanced paper and varnished with six layers of the Clearstar FA series Semi-Gloss coating.

As the premise of this experimentation was to investigate the DC/MP printing method's ability to outperform the current state of inkjet technology and practices, a further method of analysis was introduced. In addition to examining the varnish coating's improvement in reproducing a closer colour match to the painting reference, it was now also essential to consider how the colour matches compared to what could already be achieved through an ICC managed print workflow.²⁷ For this comparative analysis I produced a colour chart containing the nineteen painting reference colours.²⁸ This chart was printed using ICC managed workflows that replicated the working method of the National Gallery's Photographic Department, the National Gallery Company, and other recommended practices.²⁹

The chart was printed using Adobe Photoshop with the Canon printer driver, and also through the Caldera VisualRIP+ in CMYKRGB mode. For both the

²⁶ The MAX colour chart, as stated in the previous chapter (4.4.5) was designed in order to improve upon both the Dark Colour and Colourful Black charts to provide a more encompassing representation of the output colour that can be achieved using the DC/MP printing methods.

²⁷ This is the same testing setup as was used in the work presented in the paper *Reproducing the old masters: A study in replicating dark colours with inkjet printing* (Olen and Padfield, 2015).

²⁸ The SR of each painting reference was converted to Lab values using the Chromix ColorThink Pro software, version 3.0.3 set at the D50 illuminant, and the 2-degree observer (www.chromix.com). These were then entered into a raster image file in Adobe Photoshop. The document was assigned the Adobe(1998) colour space following the National Gallery Photographic Department Manual's specifications (2010).

²⁹ It was understood that the colour reproduced through this colorimetric workflow did not directly correlate to the spectral based RMS calculations. However, in the absence of an obtainable spectral workflow, I reverted to the colorimetric industry standard for colour reproduction.

driver and RIP output the chart was printed twice. The first version was printed using absolute colorimetric rendering, as recommended by Frey and Farnand for cultural heritage reproduction (Frey and Farnand, 2011). The second version was printed using the perceptual rendering intent, which is useful for images that require a remapping of the dynamic range in order to maintain detail information in the print (British Standards Institution, 2010). This rendering intent is used by the National Gallery Company's Print on Demand Service. To ensure consistency between the reproduction of the painting references and the DC/MP printed patches, these four colour managed prints were also coated with six layers of the semi-gloss varnish.³⁰

Examination of Colour Matching Results

Improvement in Spectral Reproduction

The colour patches contained in all three sampling charts were measured using the Konica Minolta FD-7 spectrodensitometer. In an identical manner as the earlier testing, the RMS error was calculated for each colour patch in order to identify the colourant combination that produced the closest spectral match to each of the nineteen painting reference samples. The results of these calculations can be seen in Figure 5.12, which illustrates the improvements in matching the SRCs for three of the painting references. Table 5.3 lists the calculated RMS of the final results alongside those of the earlier two experiments for all nineteen reference samples. The results of the coated colour charts reduced the RMS errors between 47 and 97% from the earlier results of the Colourful Blacks Sampling Chart, which did not include the varnish coating. The improved RMS errors, ranging from .0004 to .0069, also signified that the DC/MP printed colours were less distinguishable from the painting reference colours than the previous results.

³⁰ To correct for any shifts in hue or value resulting from the varnish, a custom ICC profile was made from a colour test chart that was also coated with the 6 layers of semi-gloss varnish.

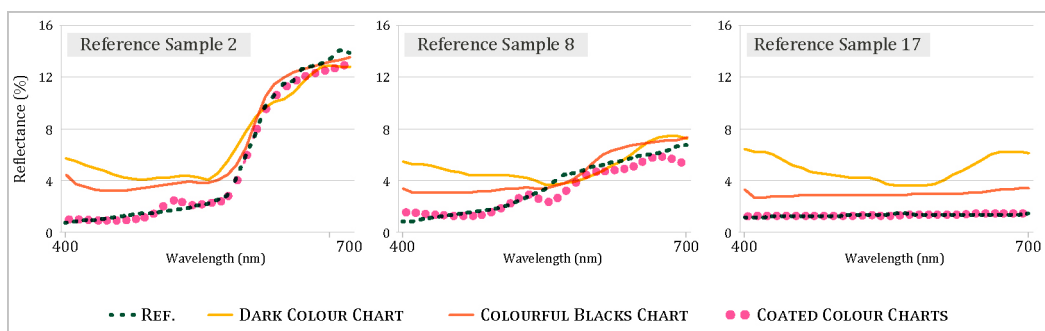


Figure 5.12. SRCs of painting reference samples 2, 8, and 17, plotted alongside the lowest RMS results from the DC/MP printed Dark Colour, Colourful Blacks, and all varnish coated Sampling Charts.

		dE2000	RMS		dE2000	RMS		dE2000	RMS
Dark Colour	Ref. 1	10.41	0.0357	Ref. 2	10.36	0.0252	Ref. 3	13.27	0.0360
Colourful Blacks		5.01	0.0151		6.99	0.0168		8.36	0.0157
Final COATED		0.28	0.0004		2.20	0.0049		0.83	0.0018
Dark Colour	Ref. 4	13.11	0.0250	Ref. 5	15.26	0.0344	Ref. 6	12.32	0.0361
Colourful Blacks		8.84	0.0115		10.55	0.0143		6.75	0.0156
Final COATED		1.09	0.0032		1.73	0.0021		2.00	0.0015
Dark Colour	Ref. 7	12.49	0.0352	Ref. 8	16.29	0.0232	Ref. 9	13.36	0.0328
Colourful Blacks		6.64	0.0146		9.88	0.0129		6.90	0.0126
Final COATED		1.88	0.0016		2.97	0.0069		2.03	0.0034
Dark Colour	Ref. 10	13.75	0.0381	Ref. 11	12.19	0.0349	Ref. 12	15.06	0.0358
Colourful Blacks		7.04	0.0174		5.93	0.0143		8.47	0.0151
Final COATED		1.06	0.0009		0.72	0.0016		3.18	0.0021
Dark Colour	Ref. 13	11.64	0.0337	Ref. 14	16.28	0.0354	Ref. 15	12.33	0.0311
Colourful Blacks		4.55	0.0128		7.87	0.0141		4.70	0.0099
Final COATED		0.71	0.0009		4.97	0.0034		5.09	0.0028
Dark Colour	Ref. 16	14.30	0.0382	Ref. 17	11.78	0.0377	Ref. 18	12.71	0.0362
Colourful Blacks		7.05	0.0173		5.75	0.0171		5.60	0.0154
Final COATED		1.32	0.0016		1.14	0.0006		0.52	0.0008
Dark Colour	Ref. 19	14.09	0.0355						
Colourful Blacks		7.24	0.0145						
Final COATED		2.01	0.0014						

RMS 0 RMS 0.04

Table 5.3. Calculated RMS and dE2000 errors for the coated colour charts' results.

The dE2000 colour difference was also calculated for each painting reference and DC/MP colour match (also in Table 5.2). Of the nineteen colour samples,

one fell within a just noticeable difference at less than 0.5. Fifteen of the colour matches found in the coated sampling charts measured a dE2000 less than 2.5. This indicates that the selected colour patches matched the painting reference sample to a small, yet discernible difference. This limited success in reproducing the painting references to within a just noticeable difference can be attributed, in part, to the incompleteness of colourant combinations present in the colour sampling charts. Expansion of the colourant variables to smaller increments, either printed and measured or mathematically predicted, could improve upon the results in this testing.

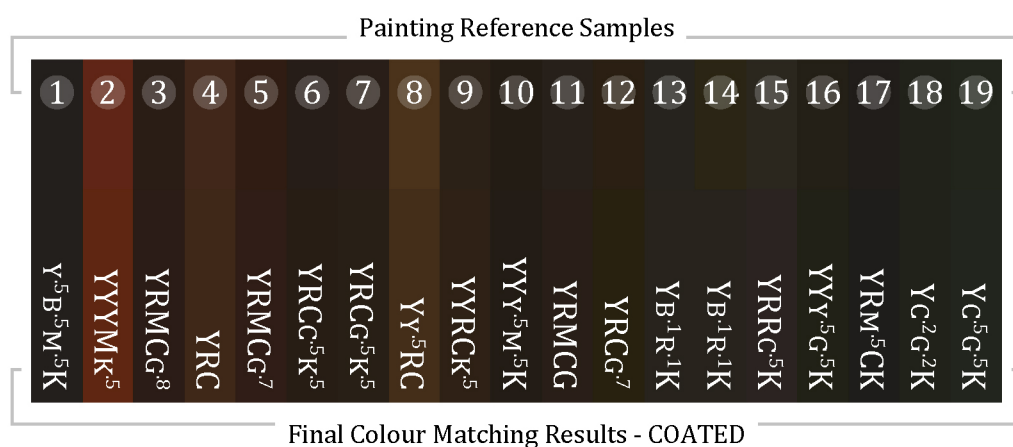


Figure 5.13. Solid colour patches representing the nineteen painting reference colours (top row) and the colour matching results from the coated colour sampling charts (bottom row). The fractional coverage for any colourant printed at less than 100% is specified following the small capital letter indicating the colourant.

A further improvement to earlier experimentation, where only one or two colourant combinations calculated the smallest RMS to all the references, was that the majority of the results from the coated sampling charts were unique. Only two painting references are recreated with the same colourant combination, suggesting that a variety of the subtle colour differences present in the original can be reproduced in print. To quantify this, of the eighteen unique colourant combinations, no two were within a dE2000 colour difference of less than 1.0 of each other. In fact, over 90% of the colour patches that achieved the lowest RMS error to the painting references measured a colour difference greater than 2.5 dE2000 from one another. Figure 5.13 provides a visual representation of this, with the colourant

combinations achieving the lowest RMS error presented alongside the corresponding painting references from the target painting.

Comparisons to ICC Colour Managed Reproduction Workflows

The printed and coated reproductions of the painting references were measured using the FD-7 spectrodensitometer. Replicating the computational analysis from the DC/MP colour sampling charts, RMS and dE2000 errors were calculated between the original painting reference and the reproductions. The results of the calculations are presented in Table 5.3. Here it can be seen that in the RMS results, the DC/MP printed colour outperforms the colour managed reproductions for every sample. Reference sample 17, shown in Figure 5.14, depicts one of these occurrences. Here it can be clearly seen that the SR of the DC/MP printed colour is a better fit to the SR of the painting reference than the colour managed reproductions. The DC/MP printing results reduced the error by more than 50% for 12 of the 19 painting reference samples when compared to the most accurate colour managed reproduction. For 18 samples, the most accurate colour managed reproduction was produced with the Caldera RIP using the absolute colorimetric rendering intent. The colours reproduced using absolute colorimetric rendering with Photoshop and the Canon printer driver produced the second closest RMS match to the painting reference samples. The fact that the colorimetric results outperformed those printed using perceptual rendering was to be expected due to the difference in the rendering intents' functions. The absolute rendering intent aims at reproducing colour as accurately as possible, mapping out of gamut colours to the closest in gamut colour. Alternatively the perceptual rendering will adjust any output colours as necessary in order to maintain the perceived relationship between the colours in the image. This results in changes to value, chroma, and possibly hue.

		dE 2000	RMS		dE 2000	RMS		dE 2000	RMS		
DC / MP Coated Result	Ref. Sample 1	0.28	0.0004		Ref. Sample 2	2.19	0.0049		Ref. Sample 3	0.82	0.0018
CM: Caldera Absolute		4.98	0.0068			3.18	0.0098			5.02	0.0051
CM: Caldera Perceptual		3.88	0.0121			5.12	0.0159			5.55	0.0129
CM: PS Absolute		2.75	0.0076			4.81	0.0122			4.45	0.0069
CM: PS Perceptual + BPC		6.01	0.0195			5.78	0.0169			6.70	0.0172
DC / MP Coated Result	Ref. Sample 4	1.09	0.0032		Ref. Sample 5	1.73	0.0021		Ref. Sample 6	2.01	0.0015
CM: Caldera Absolute		2.08	0.0034			5.58	0.0094			5.01	0.0039
CM: Caldera Perceptual		3.41	0.0105			5.96	0.0142			4.35	0.0107
CM: PS Absolute		2.66	0.0066			5.86	0.0119			4.16	0.0070
CM: PS Perceptual + BPC		5.89	0.0177			8.13	0.0226			7.13	0.0207
DC / MP Coated Result	Ref. Sample 7	1.88	0.0016		Ref. Sample 8	2.97	0.0069		Ref. Sample 9	2.03	0.0034
CM: Caldera Absolute		4.79	0.0033			2.46	0.0079			3.92	0.0054
CM: Caldera Perceptual		4.43	0.0108			2.54	0.0106			3.66	0.0099
CM: PS Absolute		3.44	0.0052			3.99	0.0120			3.73	0.0058
CM: PS Perceptual + BPC		6.50	0.0187			6.49	0.0223			6.42	0.0194
DC / MP Coated Result	Ref. Sample 10	1.06	0.0009		Ref. Sample 11	0.72	0.0016		Ref. Sample 12	3.18	0.0021
CM: Caldera Absolute		5.23	0.0041			4.80	0.0046			5.15	0.0073
CM: Caldera Perceptual		3.07	0.0084			5.50	0.0144			3.92	0.0089
CM: PS Absolute		4.27	0.0062			3.52	0.0057			4.77	0.0066
CM: PS Perceptual + BPC		6.91	0.0203			7.36	0.0222			6.80	0.0188
DC / MP Coated Result	Ref. Sample 13	0.71	0.0009		Ref. Sample 14	4.97	0.0034		Ref. Sample 15	5.09	0.0028
CM: Caldera Absolute		4.99	0.0057			2.65	0.0040			4.27	0.0048
CM: Caldera Perceptual		2.39	0.0087			2.83	0.0111			3.12	0.0116
CM: PS Absolute		4.55	0.0139			4.57	0.0091			2.48	0.0080
CM: PS Perceptual + BPC		6.35	0.0221			5.61	0.0197			4.92	0.0175
DC / MP Coated Result	Ref. Sample 16	1.31	0.0016		Ref. Sample 17	1.14	0.0006		Ref. Sample 18	0.52	0.0008
CM: Caldera Absolute		5.65	0.0029			4.77	0.0077			4.10	0.0047
CM: Caldera Perceptual		4.55	0.0142			4.78	0.0143			3.37	0.0108
CM: PS Absolute		4.57	0.0092			4.08	0.0112			3.39	0.0090
CM: PS Perceptual + BPC		6.93	0.0217			7.17	0.0229			6.52	0.0218
DC / MP Coated Result	Ref. Sample 19	2.02	0.0014								
CM: Caldera Absolute		4.16	0.0067								
CM: Caldera Perceptual		4.49	0.0143								
CM: PS Absolute		3.46	0.0068								
CM: PS Perceptual + BPC		7.13	0.0235								



Table 5.4. Calculated RMS and dE2000 errors for the coated colour charts' results, compared with ICC colour managed (CM) reproductions of each painting reference. The colour managed reproduction were output using the Caldera VisualRIP+ and Adobe Photoshop (PS) with both absolute colorimetric and perceptual rendering intents. The PS perceptual rendering also included black point compensation (BPC).

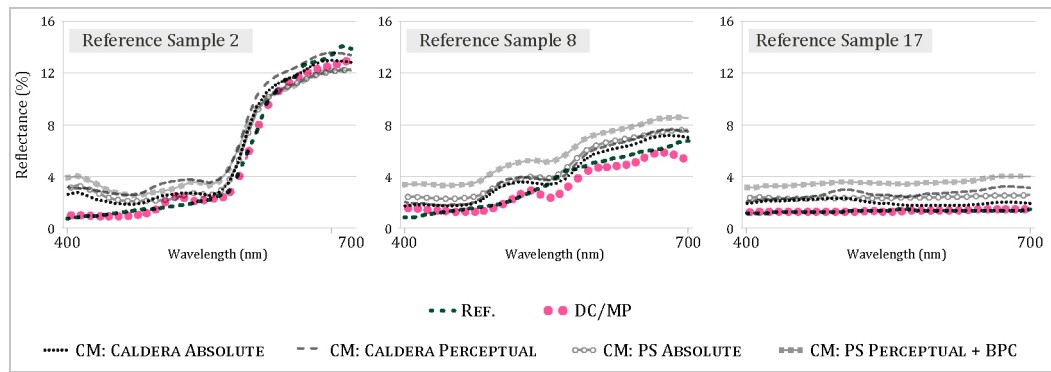


Figure 5.14. SRCs of painting reference samples 2, 8, and 17, plotted alongside the lowest RMS results from the varnish coated DC/MP printed Sampling Charts and the SRCs of the colour managed reproductions.

Although absolute colorimetric rendering intends to accurately reproduce the original colour, a colorimetric workflow is not designed to reproduce the most accurate spectral match to the painting reference colours. Therefore the RMS calculations alone were not considered a definitive indicator of improved colour reproduction. The dE2000 calculations account for the human visual sensitivities and lighting conditions used in the colour rendering for the colour managed reproductions. Here 16 out of the 18 DC/MP printed colours achieved the closest match to the painting reference samples. Of these 16, the DC/MP results improved the dE2000 error between 19% and 90%, with a 60% average. In the remaining three samples, two or more colour managed reproduction methods outperformed the DC/MP results. Such was the case in reference sample eight, where the DC/MP result was outperformed by both the Caldera RIP and Photoshop print driver when using absolute colorimetric rendering, despite it being the closest spectral match (Figure 5.14). The DC/MP colour in sample 15 was further found to be the worst match when using the dE2000 metric, despite superior results by the RMS metric (Figure 5.15). This occurrence highlights the need to consider both metrics at this stage of the research, as the appropriate metric will be dependent on the direction for future studies in regards to the reproduction application.

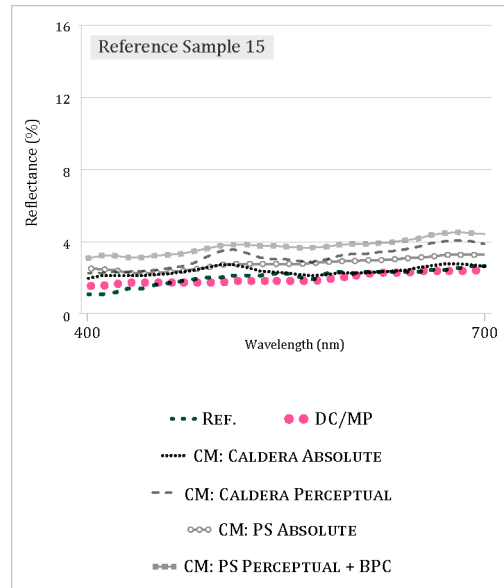


Figure 5.15. SRCs of painting reference sample 15, plotted alongside the lowest RMS results from the varnish coated DC/MP printed Sampling Charts and the SRCs of the colour managed reproductions.

5.6 Appraisal of Experimental Outcomes

The experimentation described in this chapter tested the hypothesis that DC/MP printing methods developed in the earlier aspects of my research could improve upon the colour reproduction achievable through standard ICC print workflows. The hypothesis was based on the DC/MP method's ability to maintain a greater appearance of hue in darker colours, increasing their likeness to the original. In practice my experimentation required a number of iterations to compensate and adapt to unexpected and inconclusive findings. This included the finding that dark colours printed without black were in fact more chromatic than the painting reference colours. Additionally, even with the addition of black, the appearance of the patches demonstrating the maximum ink density achievable still appeared too light. Yet, through the process of retesting my original hypothesis through empirically based modifications, I can conclude that the DC/MP printing methods can improve the printed reproduction of dark colours.

The success of this printing method is attributed to the ability to apply a varnish coating to the surface of the print in order to darken the appearance

of the colour. As previously mentioned, the necessary surface reflectance may also have been achieved through the selection of an alternative paper, but would have come with a trade off in absorbency. The application of the varnish after printing allows for the utilisation of a highly absorbent paper that can handle the increased ink volume accompanying the colourant mixtures contained in the developed sampling charts. This means a compromise does not have to be made between the paper's absorbency and its surface reflectance. Whereas the paper and varnish coating are both readily available consumer items, this aspect of the print production could be applied easily in practice.

All the printing and coating methods described in this chapter use available materials and technologies combined into a singular methodological approach. Therefore the ability to reproduce dark colours through selective colourant combinations and use of the multiple pass layering process, as described, can be easily replicated. This lends the process to improving the reproduction of the dark range of colours in the National Gallery's Collection. However, the current research is limited to the reproduction of singular colours found within the painted surface. More on the additional research required to integrate this research into an image reproduction workflow is discussed as an area for further research in Chapter 7. First, Chapter 6 will cover the immediately available implementation of the DC/MP printing methods into the creation of original works.

6 Demonstration of Findings through Creative Practice

6.1. Rationale for Chapter

In previous chapters I have explained the rationale and methodology for implementing bespoke inkjet printing methods to achieve a wider colour gamut and special effects in printed output. This was executed through a combination of both qualitative and quantitative analysis of a series of constructed colour charts. While the analysis effectively demonstrated the ability to create previously unachievable colour hues and chroma by implementing my printing methods, I identified that a limited amount of impact was achieved through printing colour patches alone. This realisation came primarily from discussions with peers in the CP7.0 project group, who, from a scientific standpoint, neither saw the significance in the numbers, nor comprehended why the ability to achieve additional colours would benefit the art and design community. This chapter focuses on the work I undertook to position myself more definitively in the art and design context.

6.2. Chapter Overview

In this chapter I will describe the transition of my printing methods into a creative workflow. First I account the early research undertaken which

highlighted the need for additional enquiry and influenced the latter research. This initially involved the creation of a pre-visualisation template file in Adobe Illustrator. Subsequently, I used the template to develop a series of original designs that specifically demonstrated the capabilities of my printing methods. The designs were then printed using the methods and procedures I had constructed and compared to the on screen appearance using the pre-visualisation template. Additionally, reproductions were printed using an ICC colour management workflow with a custom profile. The reproductions served the purpose of demonstrating the maximum potential of current industry practices and comparatively highlighting the capabilities of my printing methods when it came to colour and detail. These prints were prepared as demonstrative material from which qualitative evaluations could be made.

6.3. Early Exploration of Special Effects in Print

As part of a project for XL Recordings, a London based record label, I collaborated with Paul Laidler, a Research Fellow at the CFPR, through his print editions practice. For the project we discussed the opportunity to integrate some of the special effects achieved in my research into a print using the supplied text 'Pay Close Attention' (a song lyric from the British band *The Prodigy*). The goal was to create a play on the text itself, where the text would be indecipherable at one viewing angle, and begin to appear as the angle changed. The initial idea was inspired by the Glossmark™ technology developed by Xerox, where they exploited the different effects obtained with toner when controlling its deposition onto paper. Here, higher densities of toner create a shimmering effect when viewed at an acute angle to light, which is not prevalent in lower print densities. The implementation of two different halftone patterns allowed for the creation of an image that appears uniform in colour and density at one viewing angle, while integrating a selective spot gloss effect under another (Fan et al., 2008). Although the integration of gloss effects is not new to the security printing market, it is

worth noting that this technology creates the effect without the use of specialty inks or an additional printing pass or process.

My work implemented the concept behind the Glossmark™ technology, adapting it to be reliant on colourant selection instead of the halftoning process. I hypothesised that two colour samples, containing different ink colourant combinations, could create the same colour appearance under diffuse lighting conditions, yet produce different specular reflections under direct illumination due to the density differential (Laidler, 2013). I had previously applied this theory to my 2012 Miniature Print Edition.¹ In this design the image of a gnome was printed against a solid background printed with black ink. The gnome itself was printed with a combination of magenta, yellow, green, and blue ink colourants (Figure 6.1). This colourant combination was chosen as it matched the black ink colorimetrically within a just noticeable difference, and caused the gnome to blend into the background when directly viewed under normal lighting conditions. However, since the density of the ink was greater in the case of the multicolour black, it reflected light differently when viewed at an angle, thus making the gnome appear and disappear depending on the angle from which it was viewed (Figure 6.2).

¹ The Miniature Print Edition is an annual printmaking project organized by the Centre for Fine Print Research in collaboration with MA Multi-Disciplinary Printmaking students and the Print Centre staff at the University of the West of England. Each year 30 participants are invited to produce a print edition of 60 prints using any method of analogue or digital printmaking techniques they employ in their practice.

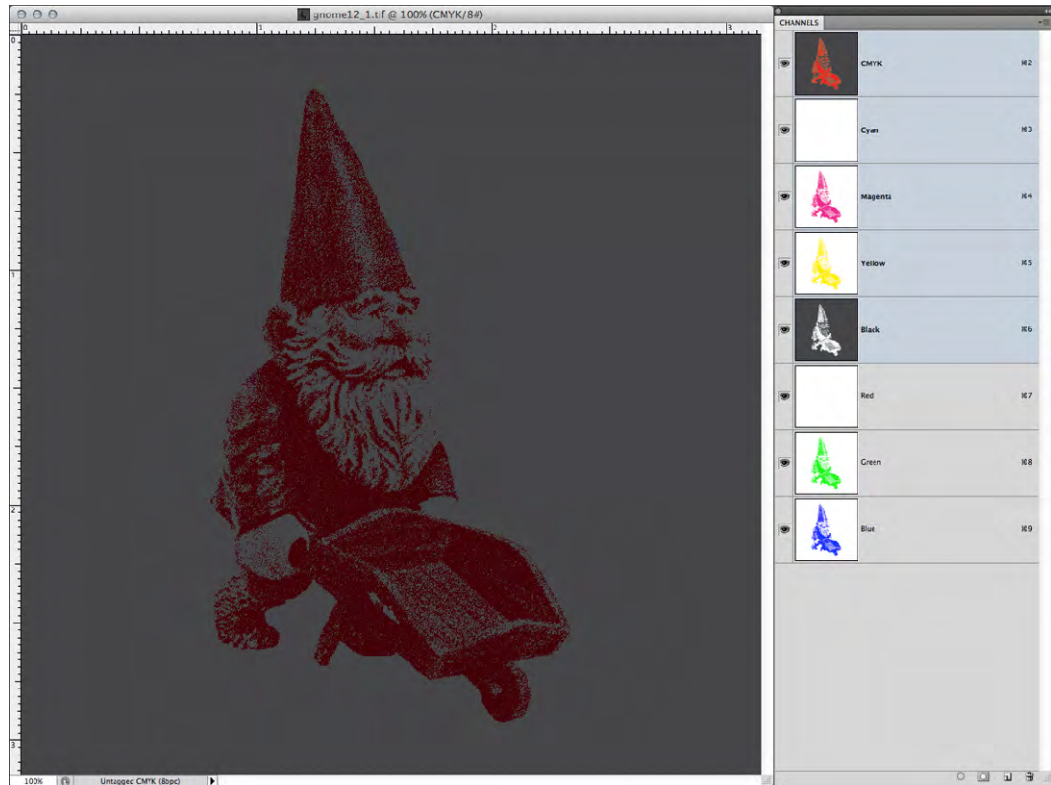


Figure 6.1. Screen capture of image file for the 'gnome' design. The channels palette on the right shows each of the colourants used to make the foreground and background colours.



Figure 6.2. Two photographs of the 'gnome' print, each illuminated from a different angle.

The same concept was applied to the print tests for XL recordings. Now, however, the colour matching tests from the gnome print were duplicated and expanded to incorporate the bronzing effects achieved in other areas of

my research. Instead of finding a colourant combination to match the solid black background, I began by selecting one of the known colourant combinations that produced a bronzing effect. For this print I chose to work with the blue colourant, which when printed over a solid layer of black produced a gold metallic effect under direct illumination. While under diffuse illumination the printed colour appeared as a cool black, which matched the background colour. Following a series of tests, the final image was produced as a two-pass print. The first layer consisted of full coverage black ink over the entire image area with 100% blue ink combined in the background area. The second print pass contained the blue colourant at 50% output value, half total coverage, for the text (Figure 6.3). Since the blue colourant in the background was printed at the same time as the black ink, the two inks mixed together in the act of printing and therefore did not produce a bronzing effect. It was only in the text region, where the blue colourant was applied as a second layer to the print, on top of the dry black ink, that the effect occurred (Figure 6.4).

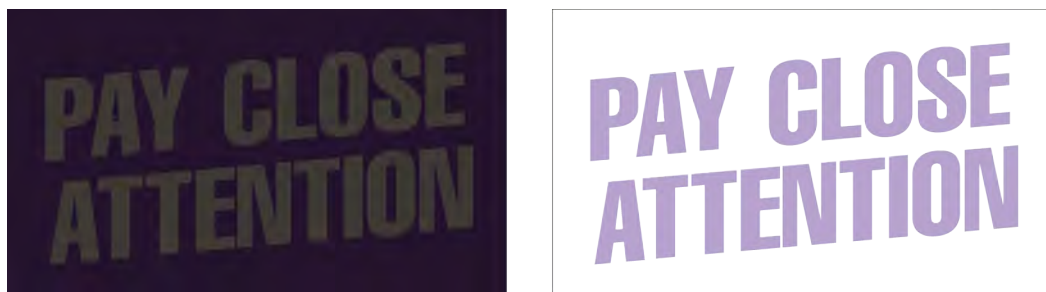


Figure 6.3. Two layers of the “Pay Close Attention” print file. The first layer (left) consists of 100% black and blue ink for the background colour, and 100% black ink only for the text. The second print layer (right) contained the text only, printed with the blue ink colourant at 50% coverage.



Figure 6.4. Photograph of the “Pay Close Attention” print showing the bronzing effect and its appearance change as a result of illumination angle.

This print, which confirmed my original hypothesis, was presented as part of the exhibition and study group on Visual Illusions and Effects at the 12th International Congress of the International Colour Society (AIC) (Olen and Laidler, 2013). This venue provided me the opportunity to advocate for the implementation of a previously defined print defect to be effectively implemented into the art making process. Moreover, I identified that further consideration was needed before the process could be integrated into a final art print for production. The font style and size were two major factors, as the large block style lettering made it difficult for the effect to work due to the well-defined edges being quickly recognisable. What’s more, I concluded that further development was needed to better integrate and demonstrate the achievable outcomes of my research with more impact.

6.4. Development of a Standardised Design Template

A design template was created in Adobe Illustrator for use as a pre-visualisation tool. This was intended to allow me to more easily design and construct test files for printing. Furthermore, it aimed to mimic the direct channel and multiple pass (DC/MP) printing effects in a pre-established template with which artists and designers could later work.

The construction of this template allowed for the generation of colour elements and arrangements through an additive, yet editable process. I chose to work with Illustrator for this template, as the software application works with vector paths, allowing for well-defined edges, infinitely adjustable size and shape, and the ability to quickly assign colour. Furthermore, Illustrator allowed for the design file to be saved as an editable PDF, meaning the design and print files could be one and the same. This is possible due to the PDF format being one of the requisite formats for Caldera's *Direct NColor* workflow.

To begin with, an A4 size document was created in CMYK mode. To further ensure the file was properly set up to communicate with the Caldera RIP, a particular set of colour swatches was required. Subsequently, all the default colour swatches in the software were deleted from the file and a custom colour swatch set was added, which directly corresponded to each of the colour channels in Caldera's CMYKRGB printing mode. The set included cyan, magenta, yellow, and black process colour swatches and red, green, and blue spot colour swatches. Instead of setting each swatch to the colour value of 100% of the named colour, each was assigned a colour value that correlates more perceptually to the ink colourants of the Canon iPF8000 series printer. For this the Lab colour values, which were measured from the direct channel colour chart test patches, were used as the values for the custom swatches. This created a soft proofing, virtual environment specific to the iPF8000 series printer. As mentioned in Chapter 4, each of the ink colourants are proprietary to the printer manufacturer, so the exact colours of the inks vary from machine to machine, none of which match the named colour swatches

that pre-exist in the software. As can be seen in Figure 6.5, the colour appearance resulting from this change allowed the swatches to more accurately match the colour that would appear in the printed output from each channel. While this template is thus specific to the IPF8000 printer used in my research, the assigned values of the swatches can be adjusted to match any other manufacturer or model's inkset.

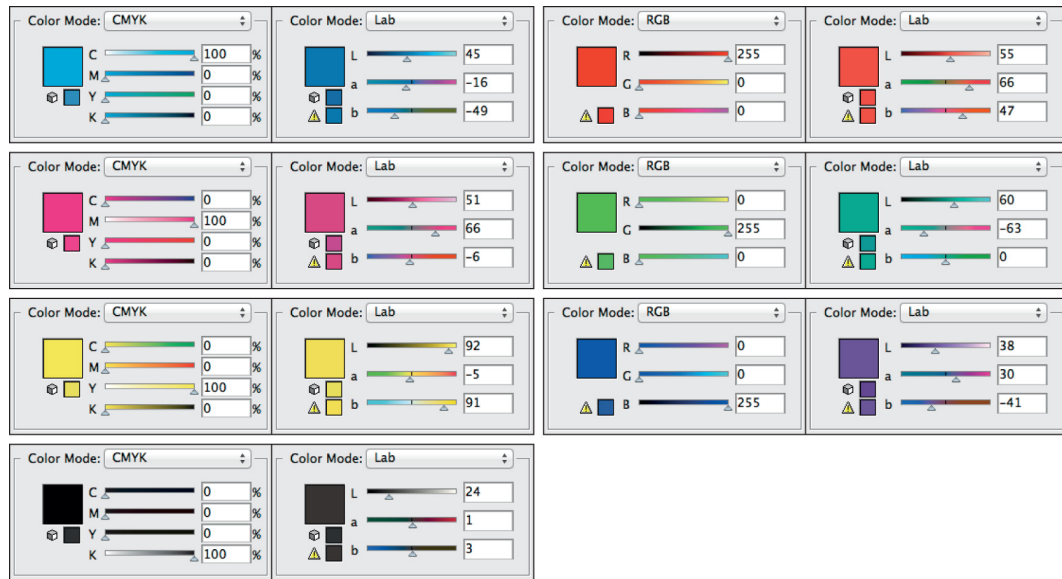


Figure 6.5. Screen captures of the CMYK and RGB values compared to the custom Lab values used in template document. The custom Lab values (right side of each pair) achieve a more perceptual match to the ink colourants in the Canon iPF8000 printer.

The file further consisted of a number of layers, each one corresponding with a separate printing pass. The challenge in designing this layering system was in trying to mimic the effects of mixing and layering colour on screen to match the effects of colour mixing through the layering of ink on paper in the printing process. For example, if two blue objects, drawn from paths, are placed on the first layer, both full strength in colour and overlapped, the objects would have to appear as one since the density of any single print layer could not exceed 100% (Figure 6.6). However, if one of the two objects were to be moved to a second layer, representing that it would be printed in a second pass, the layering effect has to be perceived. Here the colour density of the objects would have to increase where any overlap occurred (Figure 6.7). This effect was made visible on screen by changing the blending mode

(an appearance setting) for each object and layer. All individual paths, which make up the objects, were set to *darken* (Figure 6.8 left), allowing for objects of different colours or lighter values to be “mixed” when overlapped, but not exceed 100% coverage of any one colourant. Additionally, the layers were set to *multiply* (Figure 6.8 right), allowing both colour and density to change and increase when overlapping objects were placed on additional layers. The essential difference between the blending mode assignments for the paths and the layers is that the multiply setting allows for the layering effect to simulate an increase in density above 100% coverage when using multiple layers. With these customised settings the layers in the design template began to mimic the effects of DC/MP printing. The next step was then to test the effectiveness of this template in regards to colour predictability.

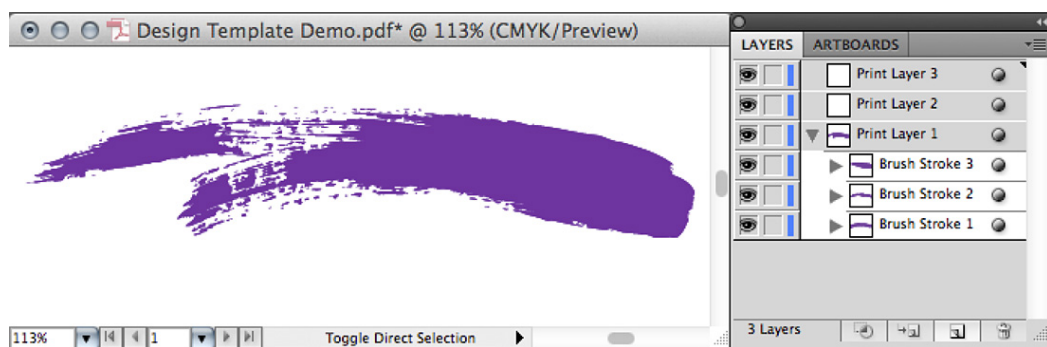


Figure 6.6. Screen capture of design template document. Here all three “brush strokes” are placed on a single layer. Since each individual stroke is already at 100% opacity, the opacity, or density appearance, cannot increase and no definition between strokes can be seen.

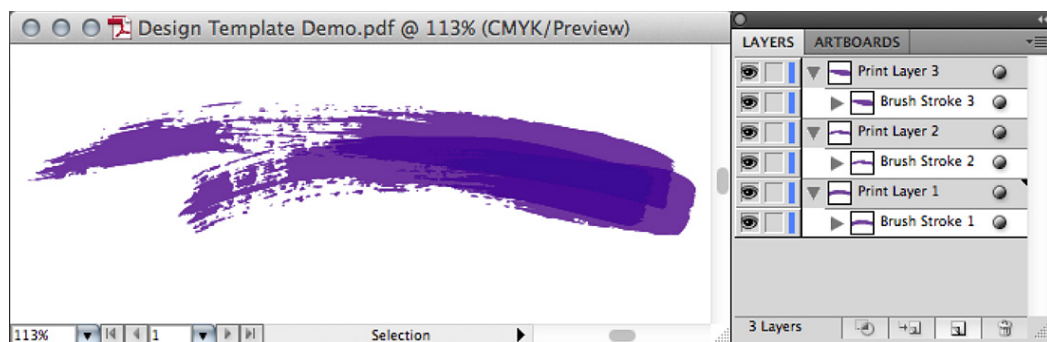


Figure 6.7. Screen capture of design template document. Here all three “brush strokes” are placed on separate layers. Because each layer relates to a new print pass the density can increase beyond 100% and the overlapping of the strokes can be seen.

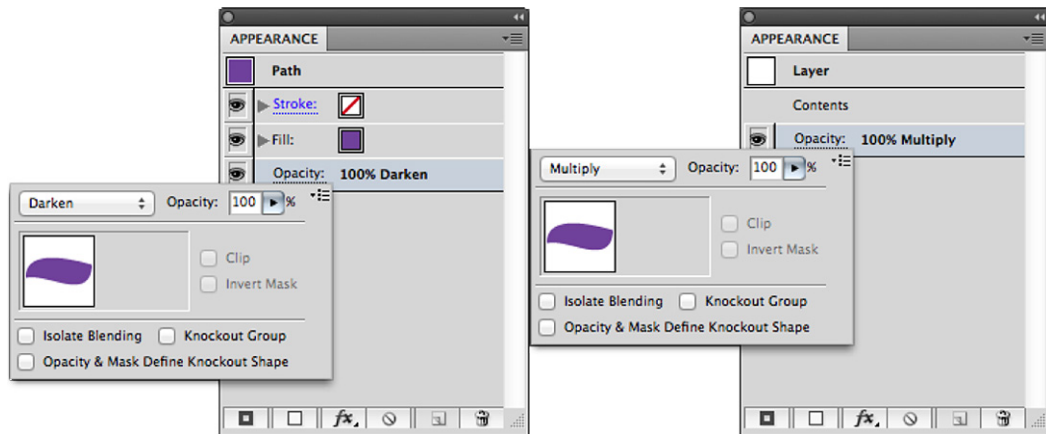


Figure 6.8. Screen capture of the blending mode settings. The paths, or objects, are set to darken (left), capping the density of any single colour at 100%. The layer the objects sit on is set to multiply (right), allowing density to increase beyond 100% with each new layer.

6.5. Creation of Original Prints Implementing a Custom Design Template and Direct Channel / Multiple Pass Print Methods

As a means of testing and evaluating both the design template and the opportunities related to DC/MP printing, original works have been designed with particular consideration to the process. The first was designed with a distorted repeat pattern intended to replicate ocean waves. For this several vector elements were drawn and arranged in an overlapping pattern, each placed on a separate printing layer. Each of these elements was assigned only cyan for colour, allowing the colour density and contour to be a product of the DC/MP printing process. To enhance the appearance of a receding horizon, a gradient of colour was added to the background in a mixture of green, yellow, and blue colourants. This allowed for the lower, foreground region of the image to have greater colour density than the lighter regions above, which contained only the cyan waves. The third, and final, part of the design was an elliptical frame. Created by a series of thin, horizontal lines in green and black, its intention was to overlay a dark, transparent boundary with fine detail. These darker regions on the design are intended to test the limits in printing barely discernible colour, which I have identified as a constant challenge with standard inkjet printing methods. Additionally I

included the areas of detail and sharp edges into the design as a testing parameter. The final design is illustrated in Figure 6.9.

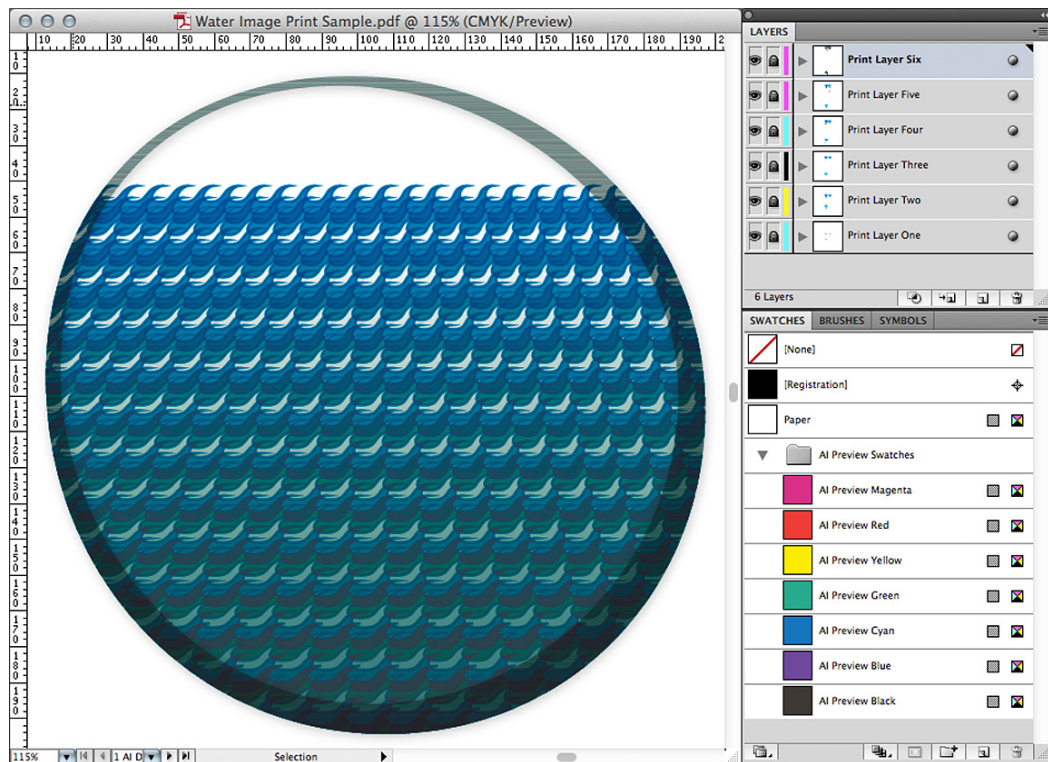


Figure 6.9. Screen capture of wave design file. This design was made to evaluate the capabilities of my design temple and the DC/MP printing methods.

The second design (Figure 6.10) was created with further emphasis on the use of dark colour. Here I used gradated layers of the black, blue, and green colourants to create a dark coloured background with subtle colour variation away from neutral dark greys. Building up dark base layers allowed me to integrate some of the bronzing effects experienced in earlier testing (4.4.1 & 4.4.3) by printing a pattern with lighter ink colourants on top of this base. This pattern consisted of wheat stalks, undulating in shape and size over the image area. The pattern is made up of two separate layers, one a larger scale version of the other. The small and large versions appear over three printing layers. The first has the two patterns grouped together which were assigned both red and green colourants. This was to control the final printed hue and increase the print density, which would underlay the following layers. I then repeated the small and large variations of the wheat pattern, each on a separate layer. Both were assigned to print with only yellow ink, which was

intended to affect both the hue of the colour, and also the bronzing. The bronzing effect was anticipated to appear in areas with a greater dark ink density underneath the pattern.

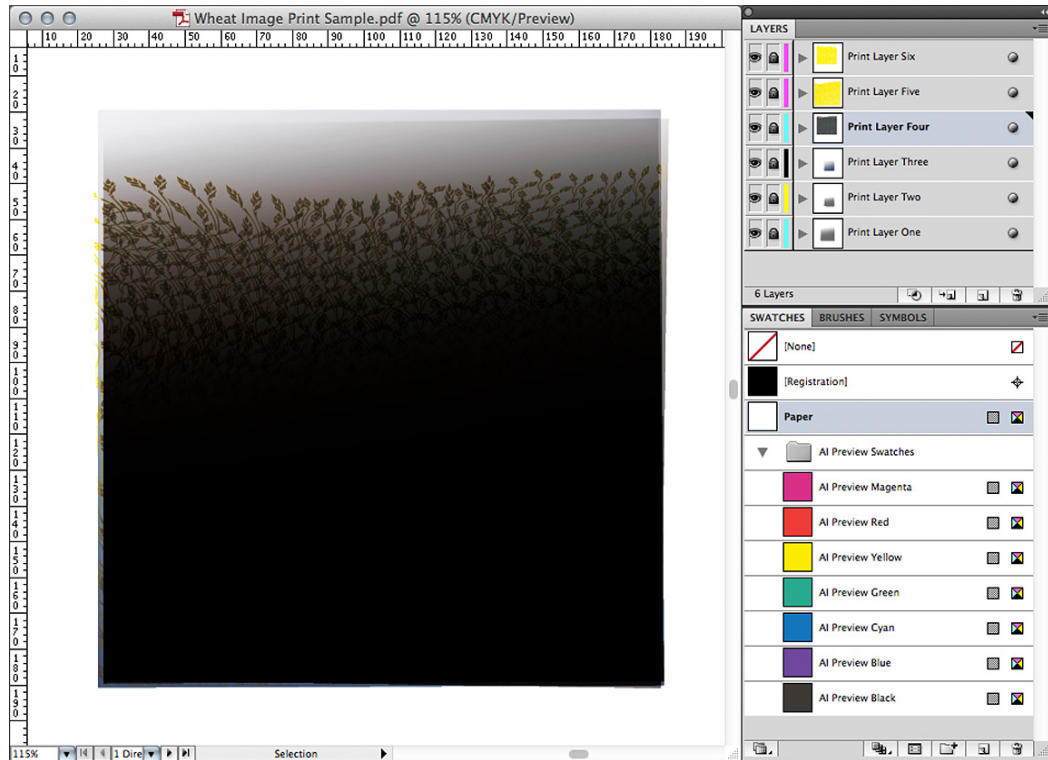


Figure 6.10. Screen capture of wheat design file. This design was the second file made to evaluate the capabilities of my design template and the DC/MP printing methods.

To prepare the design files for print, I first reassigned the colour swatches from their custom Lab values back to their pure CMYK and RGB values. This was necessary in order for Caldera to recognise them as individual colourant channels required for *Direct NColor* printing. I next separated the design file into multiple document pages, one for each print layer. The resulting multiple page PDF could then be imported into Caldera and sent to the printer one page at a time. As each layer was printed I reloaded the paper back into the printer maintaining proper registration. Figure 6.11 shows the multiple pass printing process, where one layer is printed over of the previous print layer. In total, for these designs, six layers were printed, the order of which are indicated in Figures 6.12 and 6.13.

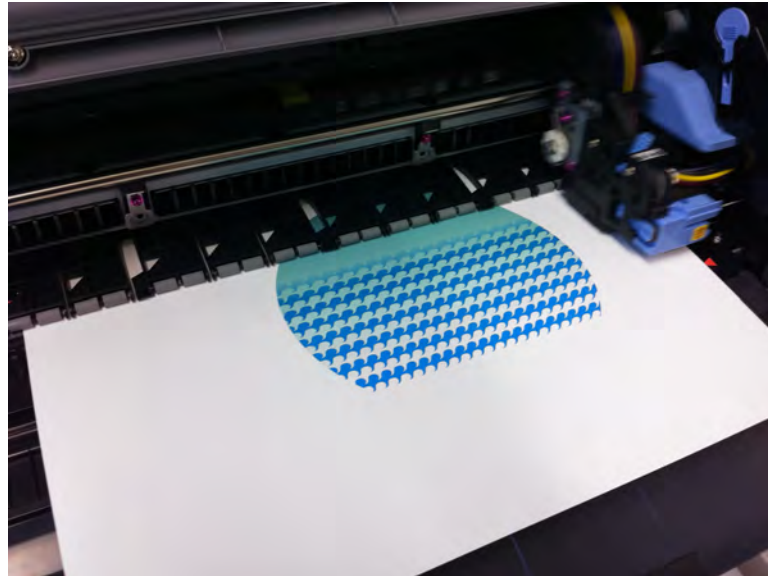


Figure 6.11. Photograph of the Canon iPF8000 printer in action. Here the printer is printing the second layer of the wave design over the top of print layer one.

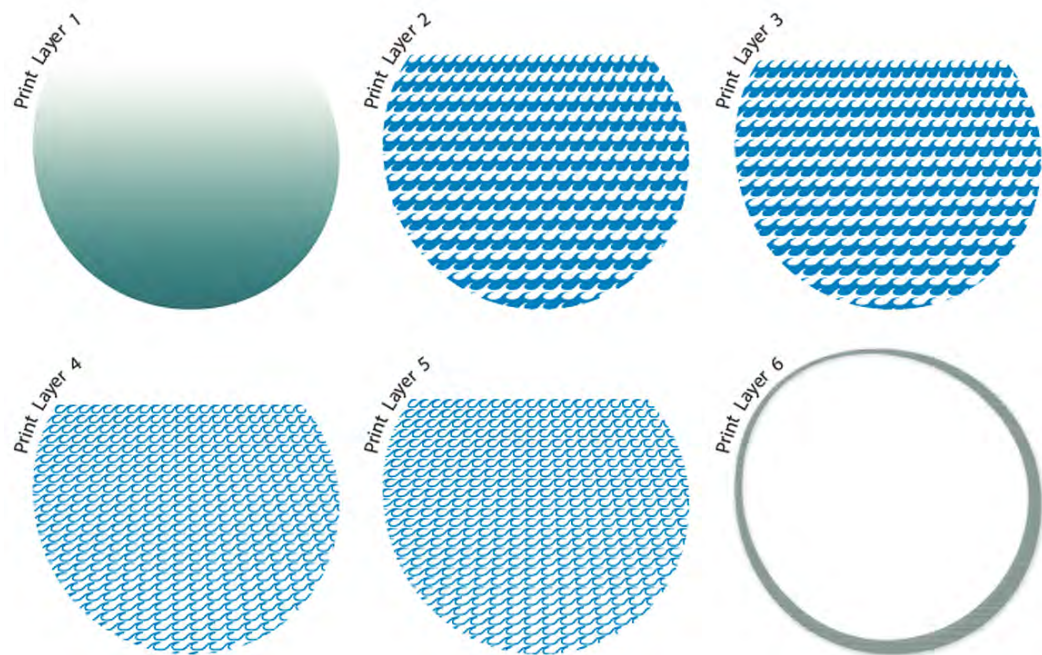


Figure 6.12. Individual layers of wave design. Each of the six layers is labelled to show the print order.

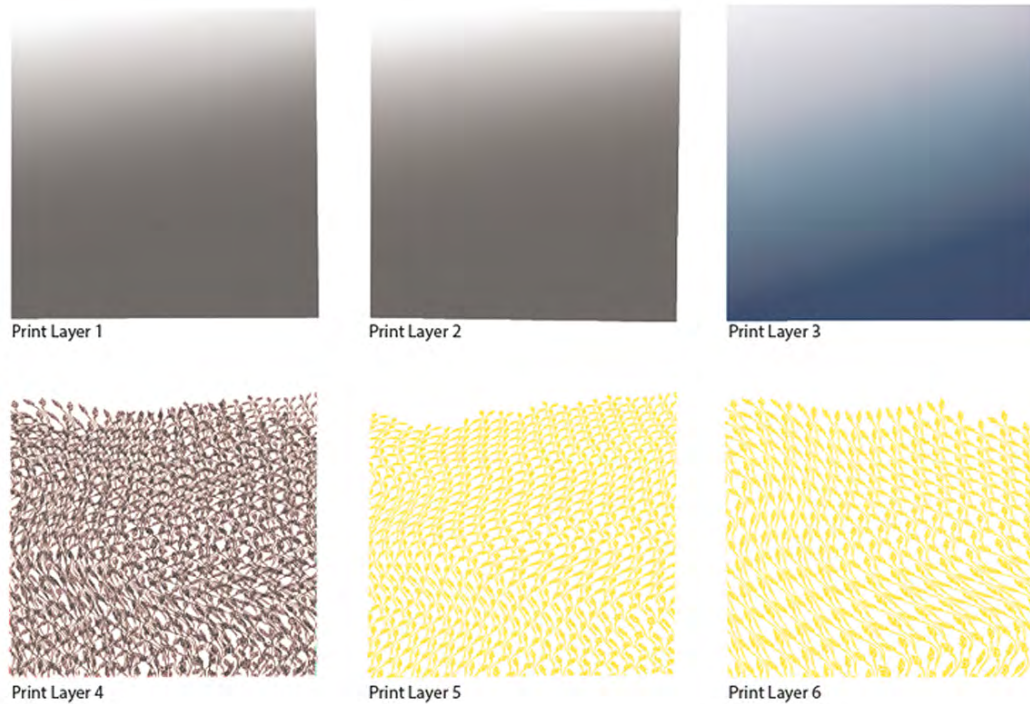


Figure 6.13. Individual layers of wheat design. Each of the six layers is labelled to show the print order.

The use of DC/MP printing for the creation of these prints allowed for the total ink coverage values of up to 390% for a single colourant, which specifically occurred in the overlapping areas of the waves. This far exceeds the 100% that would be possible with standard one pass printing. Furthermore, in the darker regions total ink coverage exceeded 700% as a result of the cumulative densities over all six layers. The observable results from printing with these increased densities were darker colours that maintained their hue, as a controlled amount of black was used in the designs and additional quantities were not needed in printing to achieve dark colours. Sharp detail was also maintained in these darker regions, especially in the ellipse frame. Without any effects from over inking, these fine lines were able to print without bleeding into one another. The printed results of the two design files can be seen in Figure 6.14 and 6.15.

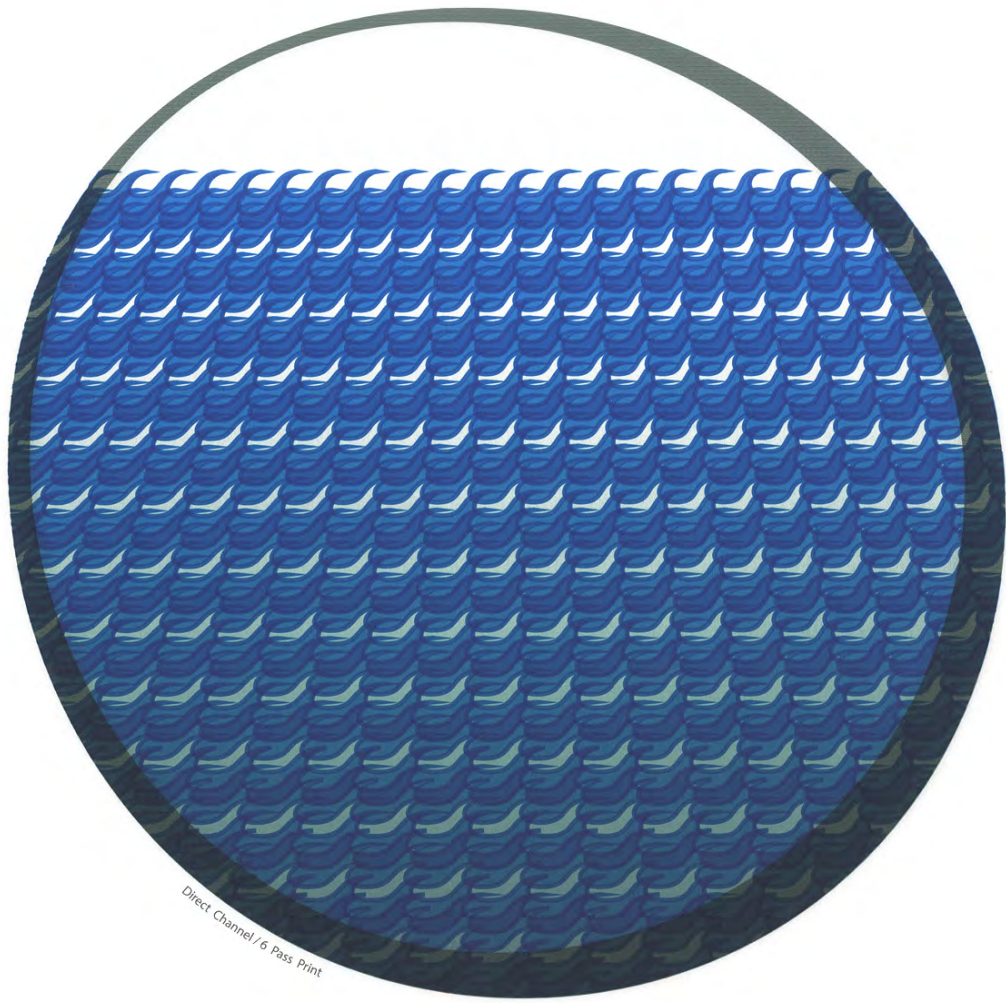
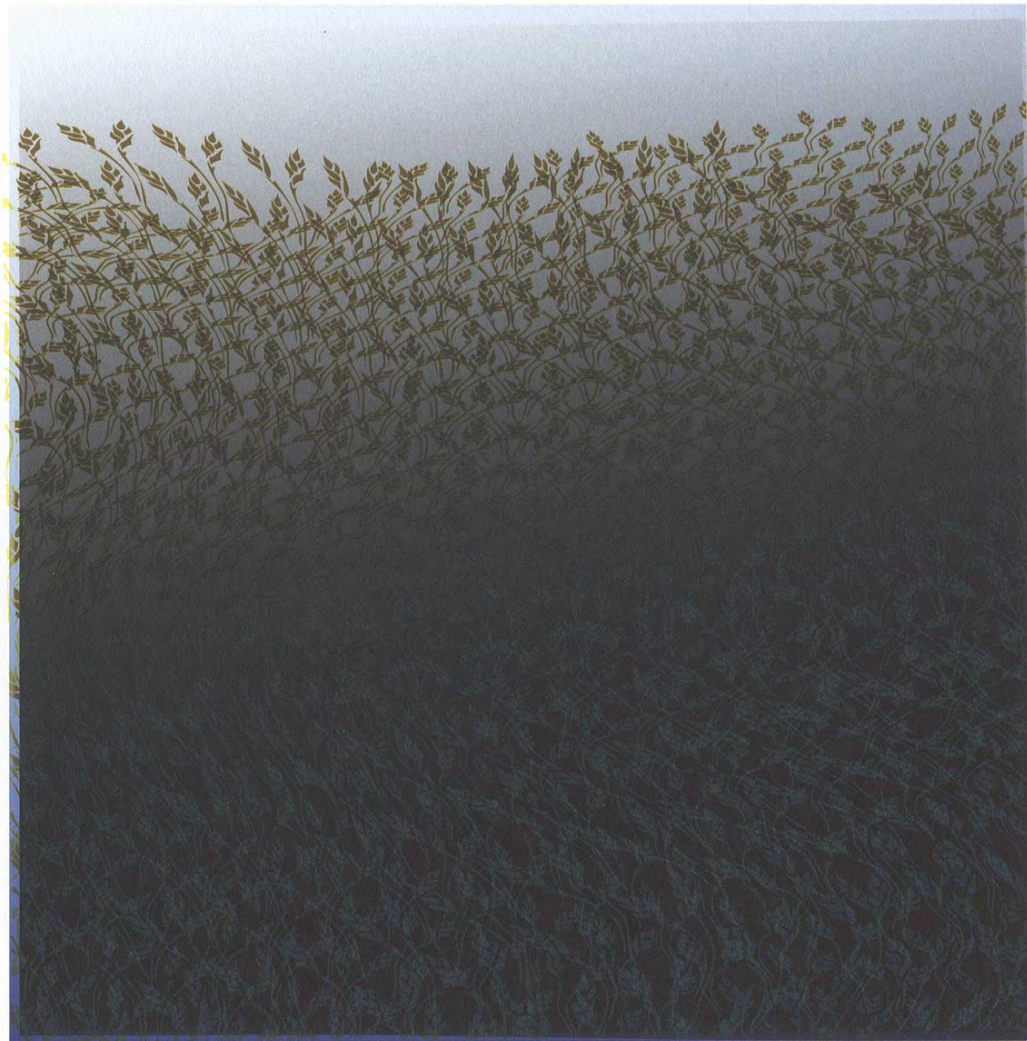


Figure 6.14. Scan of wave design print. This print was created using DC/MP printing methods.



Direct Channel / 6 Pass Print

Figure 6.15. Scan of wheat design print. This print was created using DC/MP printing methods.

While some effects of DC/MP printing can be seen on the computer screen, such as density increases and basic colour mixing effects, others are not as easily observed. Earlier research presented in Chapter 4 (4.4.1) described the variation in printed colour depending upon the sequence in which the colour layers were printed. This subtlety cannot be replicated in the design document due to limited capabilities of the software. The software can not be programmed to understand the variety of reactions caused by ink mixing on paper, as it is simply designed for mixing colour on screen. However, the template did successfully imitate the key aspects of DC/MP printing by providing close approximations to hue and density. Ultimately, the template

can be used as an aide in conjunction with the actual printing process. It allows the template to become an editable tool with which an artist can make alterations in response to what is observed in print. While the document allows you to maintain the graphic structure of the artwork and begin to see the effects of colour mixing, full exploration of the effects on colour created through DC/MP printing can only be obtained through the act of printing itself.

The need for integrating print testing into the design process, instead of a design first, print later approach, was particularly evident in printing the wheat design. While I was able to deduce the appearance of bronzing effects in the design based on prior results achieved in my research, the design file itself did not show any indication that this phenomenon would occur in print. Due to the inconsistency between on screen and printed appearance, I found it necessary to print several iterations of the design before settling on colourant choices and density assignments. This method of trial and error is similar to the process described by Richard Benson in his account of making reproductions of photographs for the book "Photographs from the Collection of the Gilman Paper Company" (Jardine, 2006). Here Benson describes his and Thomas Palmer's approach to printing as intuitive mark making, correcting and adjusting colour as layers are applied to the paper, as opposed to completing a final proof before starting production. Benson carried his method of printmaking forward into his later digital printing processes, migrating the techniques of working intrinsically with the offset device and mixing his own coloured inks into his digital workflow. Here his workflow similarly extends beyond merely reproducing the image that appeared on screen. However, Benson only accounts his workflow as additive, meaning he corrects as he prints and doesn't make mention of discarding new print layers (Benson, 2006). The implementation of the structured design file and printing process I have devised allows for the process to be editable, and also repeatable, making it more accessible to other practitioners.

6.6. Comparative Evaluation of Direct Channel / Multiple Pass Prints and Colour Managed Print Reproductions

For comparative analysis, I also prepared the design file for printing through a typical colour managed workflow. No longer employing direct channel printing, each colour swatch was converted to a process colour. The new values assigned to the swatches were the result of a series of print tests outputting colour swatches to identify the input values that would produce a close perceptual colour match to the pure ink colourants. As shown in Figure 6.16, not all direct channel colourants could be matched identically when printing with colour management. This is due to the direct channel colourants lying outside of the printer's colour gamut, as described in Chapter 4 (4.4.2). These adjustments allowed the colour appearance to be reproduced accurately wherever possible, such as in the background gradients, where total ink colourant combinations did not all exceed full area coverage. Alternatively, in areas where colours overlapped to create greater densities, it was known that the printing system would have to use an alternative approach to generating darker hues. With a fully colour managed workflow in place the designs were printed in a single pass through the printer.

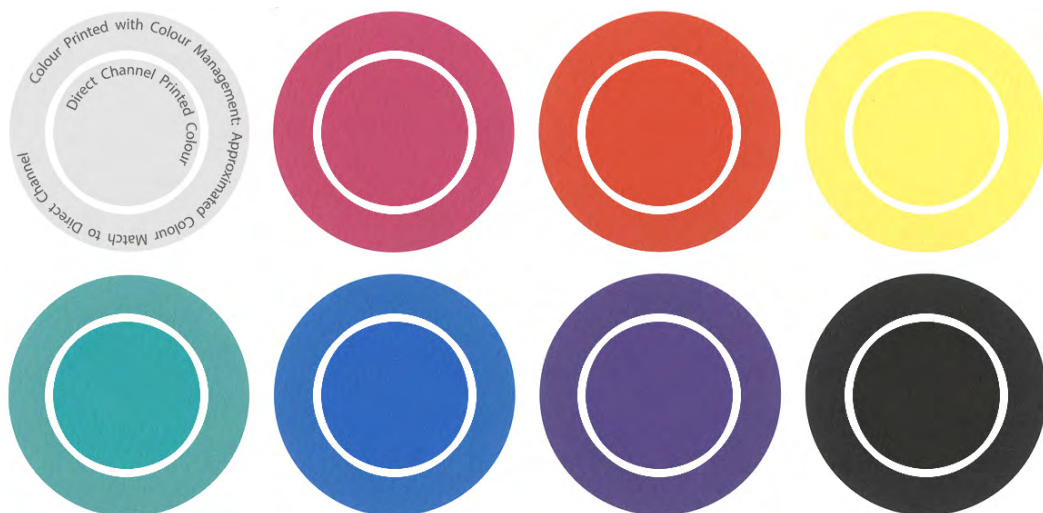


Figure 6.16. Scan of printed colour swatches for each of the seven ink colourants. The interior circles are each printed using direct channel capabilities. The outer circle shows the closest perceptual match that could be achieved using a colour-managed workflow.

The resulting print of the wave design achieved some colours similar to the DC/MP print, however the differences were more significant. Near the 'horizon' of the waves the colour maintained a close colour appearance compared to the pure cyan used in the DC/MP print, but in the regions where the density increased from a second layer of waves in the file, magenta and black began to appear in order to best match the darker cyan (Figure 6.17). The darker hues toward the bottom region of the print also appeared to use more black in the generation of darker hues. This resulted in not only a significant colour difference, but also noticeably less discernable colour variations. Furthermore, detail and sharpness of line appeared to be lost, especially where the ellipse frame overlapped the waves along the edge, as the larger quantities of ink applied to the paper all at once bled together slightly before drying (Figure 6.18).

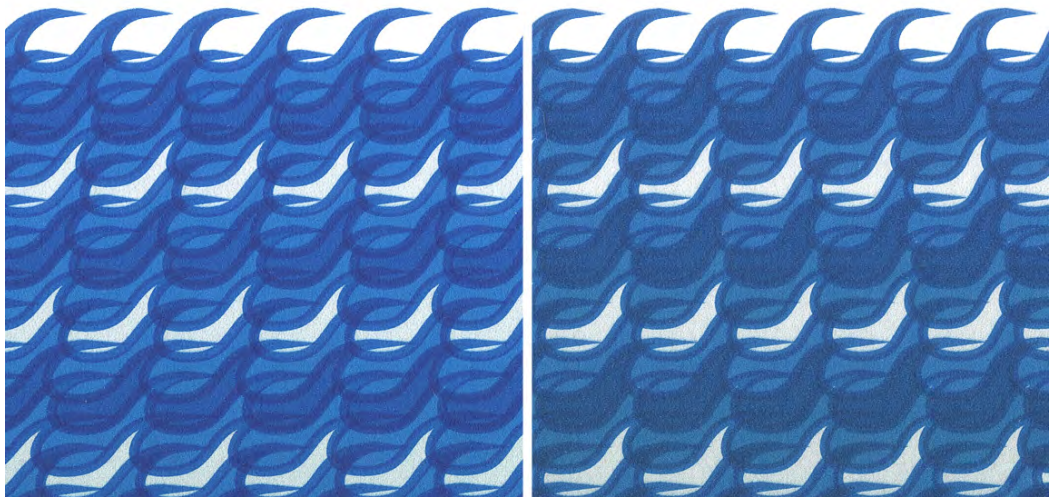


Figure 6.17. Detail of wave print scans showing the topmost portion of wave pattern. The DC/MP print (left) shows more highly chromatic colours in the design when compared to the colour managed print (right), which required the use of additional colourants to increase colour density in the darker regions.

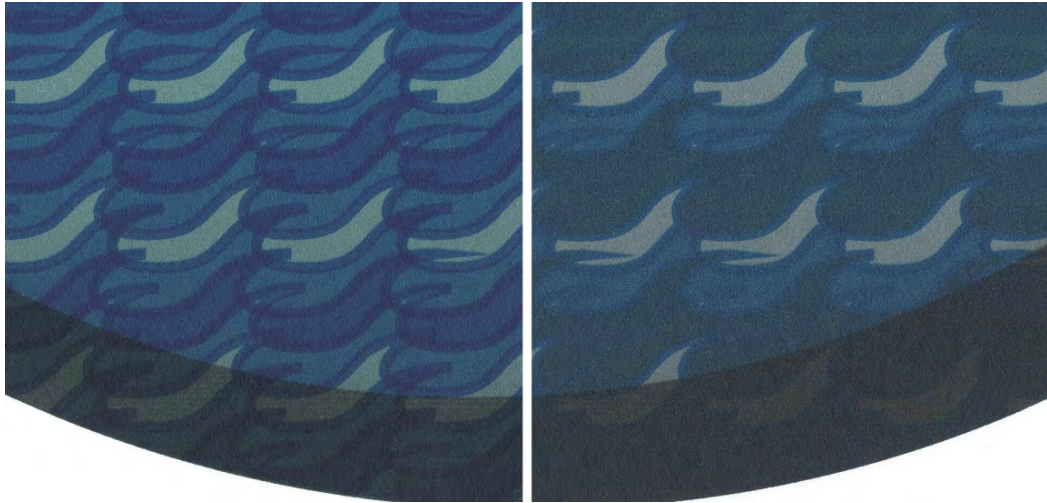
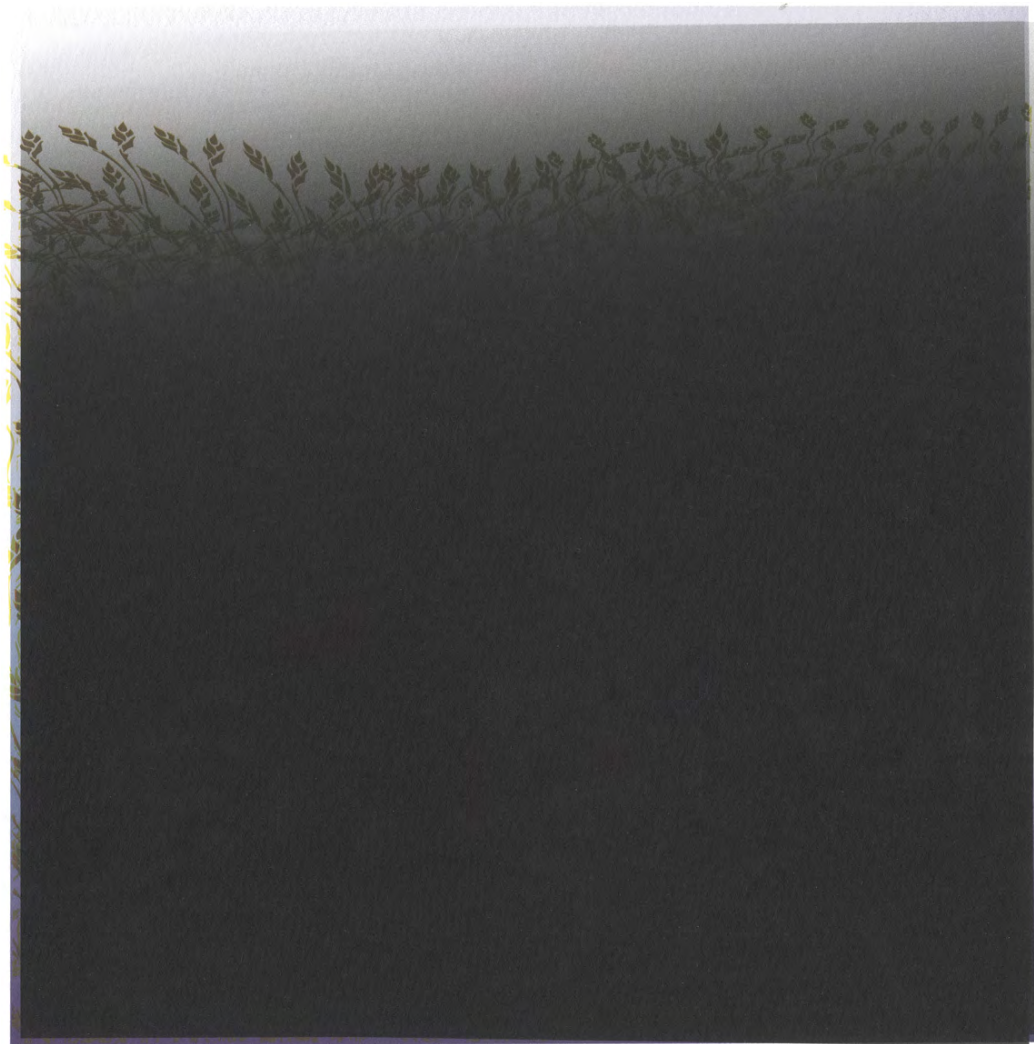


Figure 6.18. Detail of the wave print scans showing the bottom portion of the design. This dark portion of the print maintained hue, chroma and edge detail when printed with DC/MP methods (left). The colour-managed print (right) was unable to achieve the same colours due to larger quantities of ink, particularly black, being used to darken the hues. The undefined edges are also owing to the large quantities of ink, as they bled together on the paper.

The differences between the DC/MP print and the colour-managed reproduction were even more significant in the wheat design. The result of layering greater densities of black in the design resulted in the majority of the colour-managed reproduction having no discernable colour information (Figure 6.19). Although the black gradients do not all equal 100% opacity throughout the image, the blackness in the print resulted from all of ink colourants being applied at once during the printing process. This causes the inks to bleed together before drying on the paper surface, creating a dark mixture that appears as one combined colour. This is an obvious difference compared to the results of the DC/MP print, which maintains the colour hue in the background layers over the majority of the image. Even in the darkest areas, the background colour is not as black as in the colour managed reproduction. More significantly, the wheat pattern is visible over the entire image area. In the upper half of the image this is a result of the lighter background, which allows the pattern to stand out. In the lower portions of the image the wheat pattern is visible as a result of bronzing. The transition between these two ways of seeing the pattern varies according to the angle from which the print is illuminated. The wheat in the middle portion of the

print can be seen as bronzing against a dark background at one angle, and dark against a lighter background at another (Figure 6.20).



Colour Managed, Single Pass Print

Figure 6.19. Scan of wheat design printed as a colour managed reproduction. Due to high quantities of coloured and black inks the majority of pattern information does not appear in the print.

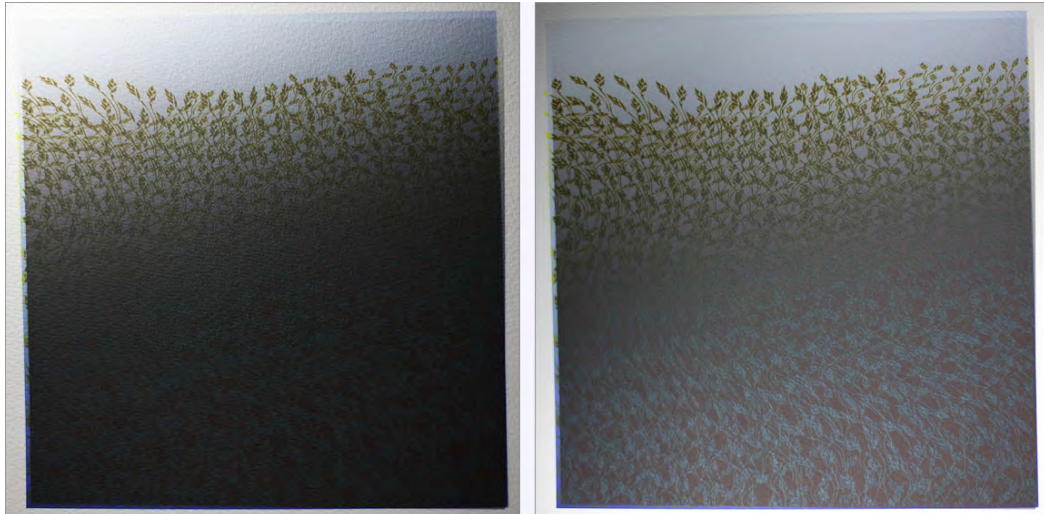


Figure 6.20. Two photographs of the DC/MP 'wheat' print, each illuminated from a different angle.

6.7. Appraisal of Impact of the Printed Designs on Demonstrating Research Outcomes

The printed imagery effectively demonstrated the ability to implement my methods into practice. The prints show that the DC/MP print methods can enable artists and designers to overcome some of the limitations encountered in inkjet printing, specifically concerning the making of colour. The prints demonstrate that by building up the design elements in layers, similar to analogue printmaking processes or painting, there exists more potential to control colour and detail in the final print. Where colour subtlety tended to be lost in the colour managed reproductions, definition of colour and shape was maintained in the original DC/MP prints. Furthermore, the required print tests during the design process, in order to witness the physical changes that result from image editing, allows for a dynamic relationship between the artist and printer. The design process extends beyond mere virtual representation on screen, to an interactive process between design and making.

By demonstrating the abilities of my printing methods through this series of prints, I subsequently devised a means of presentation that better enabled my research to expand beyond purely quantifiable results. The designs and prints discussed here have been used as illustrative material in a series of

presentations to academic communities in both the arts and sciences, and in discussions with industry.² These visual aides were found to effectively demonstrate the achievements of my printing methods and acted as a solid platform from which to better discuss the quantifiable analysis of my research.

² The wave and wheat designs were originally produced in preparation for a presentation given at The Image Conference in Berlin, Germany on 30 Oct. 2014. The prints were also used as example material for several informal presentations and discussions about my research. The first event was a poster presentation held during a training event at Océ Print Logic Technologies SA in France on 24 Oct. 2014. The presentation was part of an 'open house' event in which all the CP7.0 ESRs prepared posters describing their research and presented them to the invited employees at Océ. The subsequent two occurred during a research trip to Rochester, NY, funded by the UWE Santander PhD Student Travel Bursary. During this trip I discussed my research with students in the College of Imaging Arts and Sciences at the Rochester Institute of Technology, highlighting the creative approach to producing art prints. The second discussion was had with members of the product development team from Canson Infinity, discussing my paper requirements and the potential impacts of my research on the fine art printing community.

7

Conclusion

7.1. Chapter Overview

In the preceding chapters of this thesis I have outlined the rationale behind my research, presenting an historical overview of colour theories, explaining how colour managed inkjet systems function, and illustrating the difference between how the creation of colour is considered in the arts and sciences. This information provided the baseline to create a series of experiments conducted at the CFPR and the National Gallery, which explored how utilising an arts practitioner approach to managing colour in an inkjet workflow allowed for greater control in variant print qualities, including gamut expansion and maintaining fine detail. This conclusion will serve to synthesise the key points presented throughout the thesis, which evidence a clear contribution to knowledge.

7.2. Meeting Research Objectives

7.2.1. Identification of Limitations in Inkjet Printing Colour Management

As stated in Chapter 3, current standardised inkjet colour management systems are designed to predictably translate colour information from source files to printed output. While these standardisations are well meaning, with

the intent of making the printing process significantly easier for the end user, they remove the practitioner from the colour making process. Certain functions of colour management, specifically the use of black ink colourants to darken hues, adversely restrict colour gamuts, and limit the possibilities for what a practitioner can create.

7.2.2. Impact of Contemporary Digital Print Practitioners on Developed Methodology

Arts practitioners continue to grapple with the seeming divide between iterative processes of traditional image making and the prescribed process of inkjet printing. By rejecting various premises of colour managed inkjet workflows, artists are able to work beyond the defined parameters of printers. Artists such as Benson and Laird successfully altered the inkjet printing process in ways that aligned with their intuitive processes of making, ultimately creating prints that would have not been possible through current workflows, as discussed in greater detail in Chapter 3.

7.2.3. Development of Direct Channel and Multiple Pass Printing Methods

Inspired by the methodologies of the artists mentioned above, I developed my own unique printing workflow to test various hypotheses, as outlined in Chapters 4, 5, and 6. This method employed both direct channel printing and multiple pass printing in order to expand colour gamuts and preserve fine detail in imagery. Employing direct channel printing allowed for absolute control of how ink colourants were mixed to produce colour by eliminating transforms applied by printer drivers and RIP software. The utilization of multiple pass printing allowed me to further investigate the optical effects of colour mixing in prints, with my experiments showing that variant ordering of colour layers produced significantly different spectral results from physically congruent materials. These methods were refined through a series of test charts, as well as through production and reproduction experiments.

7.2.4. Testing Print Method's Ability to Reproduce Colour from an Old Master Painting

The research described in Chapter 5 was directed at examining the direct channel and multiple pass printing method's ability to reproduce the dark colours found in an Old Master painting while maintaining the distinct hues present in the original. A limitation found in both the Dark Colour and Colourful Blacks Sampling Charts was the inability for the ink and paper combination to produce a colour dark enough to match the original. Both of these charts relied on the total amount of ink coverage to assist in producing printed colour that achieved a low lightness value while preserving the colour's hue. With little success in matching the Dark Colour Sampling Chart to the reference colours from the painting, the Colourful Blacks Sampling Chart reintroduced black ink to help darken the achievable colour. However, this approach still failed in accurately reproducing the painting reference colours. The additional process of adding a semi-gloss varnish coating to the surface of the printed output proved necessary to reproduce a reflectance as low as the painting references. Once the surface reflectance was corrected for, the colour matching greatly improved.

However, the implementation of DC/MP printing into a full reproduction workflow requires significant further development. While this experimentation was able to demonstrate an ability to closely match a large portion of the painting reference colours, this was only tested as colour patches. Given the limitations of my secondment at the National Gallery, my experiments served as a proof of concept requiring further investigation, which will be discussed later in this chapter.

7.2.5. Demonstrating Increased Colour Control in Fine Art Design and Print Applications

In Chapter 6 I presented how my DC/MP method could be applied to creative practice. A series of images were designed specifically to illustrate the expanded control inherent in the DC/MP method in how colour and detail are respectively formed and maintained. These illustrations also served to

exemplify common deficiencies that result from standard colour managed inkjet workflows. With further development the DC/MP method could be employed by a wider group of creative practitioners, greatly expanding both how and what they produce with inkjet technology.

7.3. Appraisal of Findings

The results of the experimentation presented in Chapter 4 evidenced a proven expansion of an inkjet printer's achievable gamut through the implementation of the DC/MP method. This research focused primarily on the possible expansion of dark areas of colour gamuts, with experiments further revealing the expansion of the lightest, most chromatic printable colours in this particular printing system.

While successful in recreating highly chromatic dark colours, the DC/MP method was not fully implemented into a reproduction workflow. My experiments focused directly on the accurate recreation of specific colours from a target painting, requiring further work to develop a method to incorporate my DC/MP method in a way that considers the entire source image of the target.

The DC/MP method is admittedly laborious and requires significantly more involvement by the practitioner in order to be utilised. This involvement spans the amount of time devoted to creating and testing source imagery, to the expense of additional software and training.

7.4. Impact of Research

My research can be greatly utilised in the field of spectral printing. While spectral printing has exploited the increased colourant combinations available in multi-channel ink sets by eliminating subgamut division, my research investigated colour printing from even greater variance from standard workflows by combining direct channel and multiple pass printing. The possibility for the success of achieving a spectral reproduction lies in the fact that the change in colour appearance caused by controlling the order in

which the ink is laid down exponentially increases the number of colours, and each associated spectral reflectance, the printer can produce. With a spectral match in colour printing, colour consistency can be maintained between the reproduction and an original reference under multiple lighting conditions.

7.5. Contribution to Knowledge

My research has resulted in a clear contribution to knowledge by directly illustrating how practitioner based approaches to creating colour can increase an available gamut without altering the physical or mechanical nature of the printer, inks, or paper. The practitioner based approaches, specifically, utilise traditional methods of creating colour such as employing the use of complementary colours to neutralise and darken a hue, and layering colour in such a way that the underlying colourants alter the appearance of the surface colour. Available gamuts are increased by minimising or eliminating the use of black ink colourants for many darkening purposes, resulting in a greater number of highly chromatic dark colours. By employing pre-existing, commercially available software that allows for this method of printing, no modification is required of the print heads responsible for ink deposition, the pigments used in the creation of the inks, or the substrate and coating combination of paper.

7.6. Areas for Further Research

The success of my research has laid the groundwork for significant areas of further research. A natural extension would be exploring how my DC/MP method would effect the creation of highly chromatic light colours. Certain colour sequences were eliminated in my quantitative tests on account of bronzing, providing for more practical experiments into how this effect may be controlled and utilised for alternate means.

Additionally there are many opportunities to apply the results of my research to the purely scientific aspects of inkjet printing, such as developing a look up

table that could distinguish and separate print passes. Likewise, given the difficulties that would arise from pixel by pixel rendering from an image capture, vector segmentation could be explored as a means of mapping colour data from near identical pixels.

7.7. Concluding Remarks

This thesis has established the historical baseline that led to my research topic and formed my approach to the developed experimentation. I have clearly presented experiments that produce data supportive of my hypothesis, which are repeatable and verifiable by others. Further, I have produced applied results of my data in order to illustrate how my research could be utilised in real world applications, and as the groundwork for additional study.

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Appendix



Glossary of Key Terms

A.1. Terms Defined

Artefact, Print: An area on the surface of a print of compromised quality, directly resulting from the combination of specified print parameters, image data, ink composition and deposition, and paper.

Bronzing: A visually discernable type of print artefact that results in areas of extremely dark colours appearing as a reflective bronze at a standard viewing angle.

Chroma (as defined by Munsell (2.2.1)): The strength of a colour.

Colour Manage(d): The process of controlling how output colour is generated from source colour data, involving the creation of a lookup table which maps source colour data to a particular combination of ink colourants for a specified substrate.

Colour Transform: The computational change colour information goes through when converting from one colour space to another. For example, a CIE XYZ value would go through a transform when it is converted to RGB, or the CMYK values in a file would go through a transformation into the ink percentages needed to output the colour in print.

Colourant: A substance that colours something. In this thesis the term ink colourant is used to differentiate the named colour of the ink from the printed colour it creates in output.

Direct Channel: Direct channel printing refers to printing from each ink channel on demand. For example, telling the printer to make green using only the named green ink, rather than a combination of yellow and cyan. This only works when colour management is deactivated, as the ICC profile used to colour manage a print may use any number of combinations of cyan, yellow, and green inks to create the requested 'green'.

Printer Gamut: The discrete range of colours achievable with a particular printer/ink/paper combination in consideration to specified settings in the print driver or RIP.

Hue (as defined by Musell (2.2.1)): The name of a colour.

Multi-Channel: An industry term given to any printing device containing more than the standard set of CMYK inks. The channel refers to the physical tubing that carries ink from an ink tank to the print head.

Multiple Pass: The physical act of loading a single sheet of paper into the printer multiple times. Each time the paper is loaded into the printer a new image is printed onto the paper over the top of the previously printed image(s).

Raster Image Processor (RIP): Specialised software utilised in replacement of an inkjet printer's driver, which allows for advanced control of printing parameters.

Screen Angles: The angles at which halftone patterns are oriented on each colour plate in lithographic processes, which prevent interference patterns created by variant inks printing out of register.

Spectral Locus: The resulting form of all spectral wavelengths being mapped around Maxwell's RGB colour triangle.

Spectrophotometer: A colour measurement device, that when calibrated, can be placed in contact with a surface to record the spectral power distribution of a colour sample, illuminating it with an internal light source at a fixed geometry.

Spectroradiometer: A colour measurement device that measures the amount of spectral radiation emanating from a surface from a fixed point in space. For an illuminant independent colour measurement, corrections must be calculated using a white calibration tile with a known surface reflectance.

Total Area Coverage: The range from 0-100% that any single colourant can attain in a single print pass.

Total Ink Coverage: The amount of ink coverage referenced by the input densities in the design file.

Tristimulus values (as defined by Hunt and Pointer (2.3.2)): The amounts of three matching stimuli, expressed in units adopted for them.

Value (as defined by Munsell (2.2.1)): The light of a colour.

Appendix

B

Comparison of Canon iPF8400 and HP z3200 Printer Capabilities

B.1. Transferability of Print Methods from the Canon to HP Printer

The Hewlett Packard DesignJet z3200 (HP z3200) is comparable to the Canon imagePROGRAF8400 in that it contains the RGB ink colourants in addition to the standard CMYK. It also contains a range of light ink colourants, which were not utilised in this evaluation to maintain consistency with the research carried out on the Canon printer, with the exception of light cyan. The HP z3200 printer's inkset does not include an alternative, full strength cyan, and therefore the light cyan was utilised in its absence.

The Caldera RIP offers the same CMYKRGB driver for the HP z3200 as was used for printing with the iPF8400. This allowed the characterisation processes and printing methods to be replicated. For this evaluation the same Somerset Velvet Enhanced paper that was used in the primary research of the Canon was characterised on the HP printer. Custom linearization curves were applied, as is required for every printer and paper combination in order to optimally limit each ink colourant. The Permutation Test described in Chapter 4 (4.4.4) was replicated on the HP z3200, and the same colourant order of YBRMCG was found to consistently darken with the addition of each new colourant layer and to be free of bronzing. The YBRMCG

colourant sequence is shown in Figure B.1 to the right of the CRYMGB and GRCMBY samples, as was shown in Chapter 4, Figure 4.17 (4.4.4).

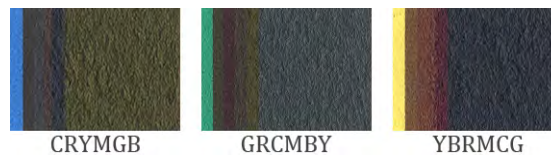


Figure B.1. Scanned samples from the colourant Permutations Test printed with the HP z3200. The first two samples (left and middle) show bronzing and an inconsistent transition from light to dark as the layers increase. The YBRMCG sequence on the right was identified as the optimal colourant sequence.

B.2. Comparison of Printable Hue and Chroma Range Using Dark Colour Sample Set

The Dark Colour Sampling Chart, presented in Chapter 5 (5.4.1) was printed on both the Canon and HP printers as DC/MP prints. Through both quantitative and qualitative analyses, I found that while the DC/MP methods could be transferred to the HP in regards to gaining direct channel control of the printer and successfully reloading printed sheets in register for multiple pass printing, the colour and print quality achieved with the Canon was unmatched by the HP z3200. Figures B.2 and B.3 illustrate the gamut differences of the Dark Colour Sampling Chart achieved with each printer. While both gamuts extend to similar chromatic strengths of green and red, the yellow and blue regions are quite dissimilar.



Figure B.2. Illustration of the Dark Colour Sampling Chart's colour gamut from the Canon iPF8400 printer.

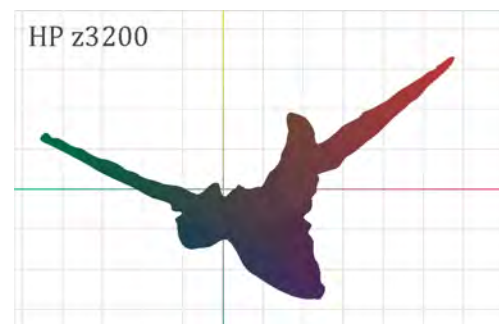


Figure B.3. Illustration of the Dark Colour Sampling Chart's colour gamut from the HP z3200 printer.

For the HP, there is an extension into the red/blue region that exceeds what is achievable by the Canon. But for the Canon, the gamut covers a large

portion of both the blue and yellow regions that are unmatched by the HP. To quantify these gamuts the minimum, median, and maximum values were calculated from the CIELAB and LCH colour spaces. The results of these calculations are listed in Tables B.1 and B.2. These calculations show that both printers achieved the same relative minimum and maximum lightness values, with only a 1% difference in range between the two. The two printers also reach near identical red (a^*) values. However, this is where the similarities stop.

Canon 8400 - Dark Colour Sampling Chart						
	Lab - L*	Lab - a*	Lab - b*	Lab - a*b*	LCH - Chroma	LCH - Hue
MIN	23.23	-40.14	-30.66	-	0.44	0.15
MEDIAN	27.12	8.94	-0.28	4.14	12.11	188.50
MAX	46.59	56.62	39.92	-	69.18	360.00

Table B.1. Colour data collected from the Canon iPF8400 printed Dark Colour Sampling Chart.

HP 3200 - Dark Colour Sampling Chart						
	Lab - L*	Lab - a*	Lab - b*	Lab - a*b*	LCH - Chroma	LCH - Hue
MIN	23.01	-44.47	-26.66	-	1.24	0.00
MEDIAN	25.88	1.74	-4.90	-1.63	10.79	262.37
MAX	45.24	56.84	32.21	-	65.33	359.89

Table B.2. Colour data collected from the HP z3200 printed Dark Colour Sampling Chart.

While the HP surpassed the Canon with a larger extension on the green ($-a^*$) axis, the Canon more than compensated with its coverage on the blue and yellow axes ($-b^*$, b^*), as was noted above. While the information presented does indicate the HP colour patches were more centred near the neutral axis, it was the limited chroma and hue ranges which inevitably led to the HP's exclusion from my further research. The Canon printer achieved a greater range in chroma with the given data set, exceeding both the minimum and maximum values from the HP. But the most significant result was the median hue, which fell just beyond the 180° mark (Figure B.4). This indicates that equal quantities of the printed hues fell on both halves of the hue circle. This

was considered ideal, given that the patch set incorporates all ink colorants with the aim of sampling the broadest range of hues. As is indicated by the mark at 262° in Figure B.4, the hues resulting from the same colour patch set were far from equally dispersed when printed with the HP printer. Here it can be observed that the dominance of the HP's gamut in the purple region is the result of not just a large coverage area, but also a higher concentration of colour patches.

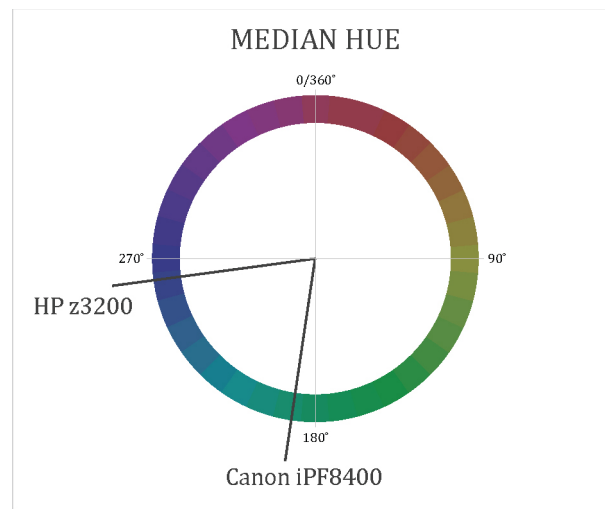


Figure B.4. Median hues from the HP and Canon printed Dark Colour Sampling Chart indicating at the corresponding hue angle on an illustrated hue circle.

The following pages depict the scanned Dark Colour Sampling Chart's printed pages from both the HP z3200 and Canon iPF8400 printers (Figures B.5 to B.10). The overall presence of dominantly dark, relatively blue hues can be seen in the scanned HP prints, particularly in rows 131-136 (Figure B.10). Given that the blue and cyan ink colourants are eliminated in rows 131 and 132, respectively, it starts to become apparent that the green ink, which is applied in the final printing layer, has significantly more dominance over the underlying layers when printing with the HP, as opposed to the Canon. Another section of the test chart that demonstrates the overt dominance of the green ink is in the MYRG combination in rows 23-26 (Figure B.6). While the Canon print (Figure B.5) maintains the dominant red hues, all HP patches appear green until the green colourant is removed.

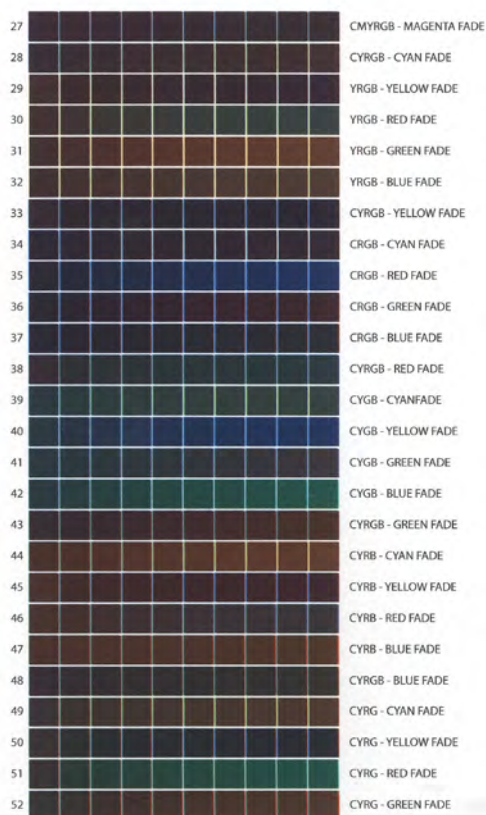
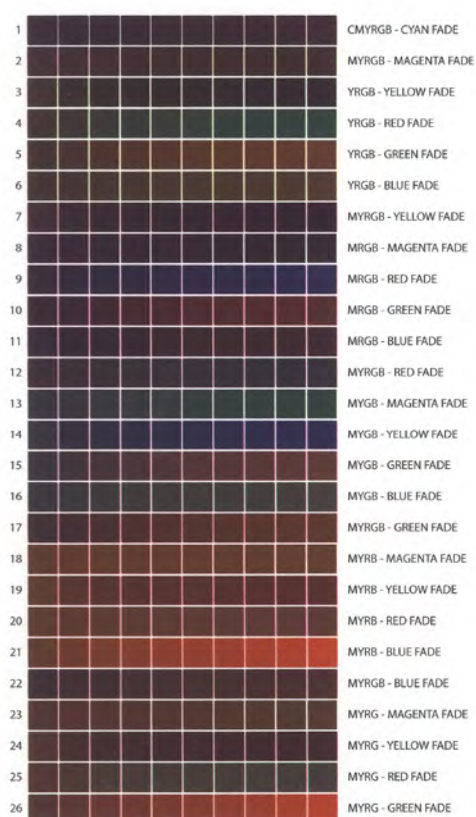


Figure B.5. Scanned DC/MP printed Dark Colour Sampling Chart, rows 1-52 from the Canon iPF8400.

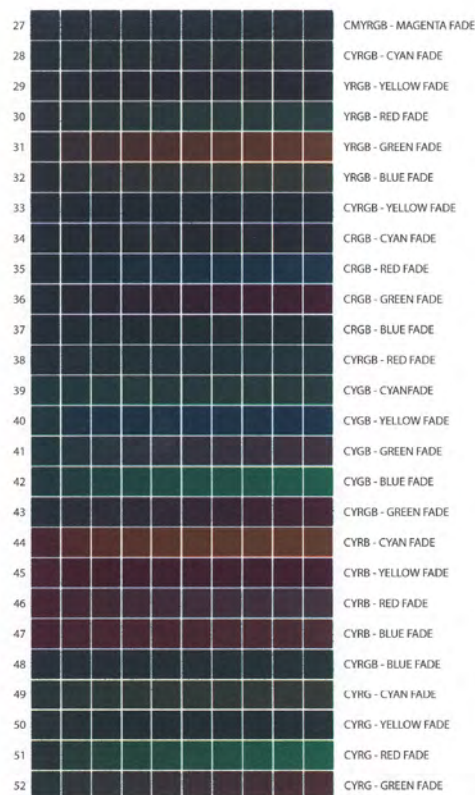
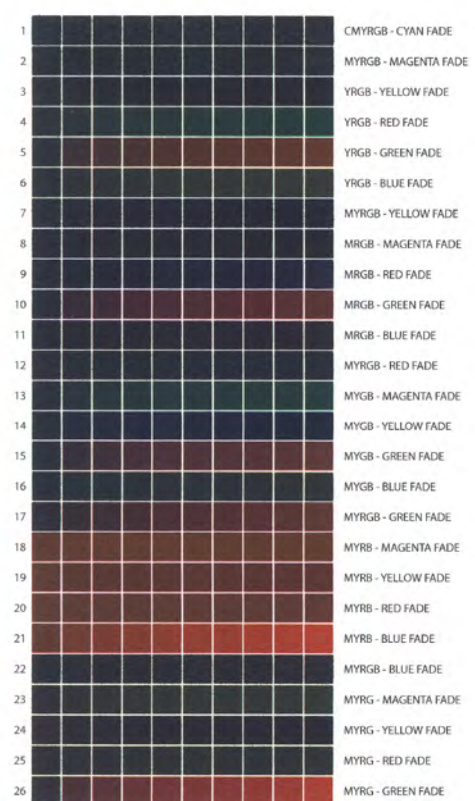


Figure B.6. Scanned DC/MP printed Dark Colour Sampling Chart, rows 1-52 from the HP z3200.

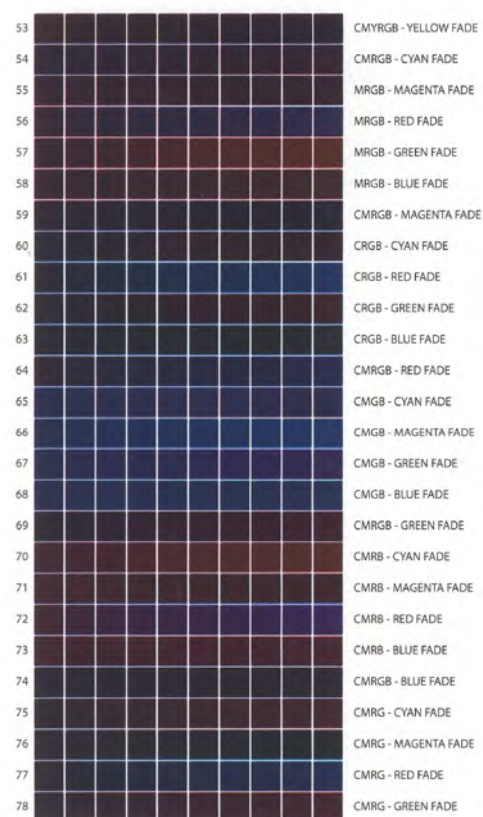


Figure B.7. Scanned DC/MP printed Dark Colour Sampling Chart, rows 53-104 from the Canon iPF8400.

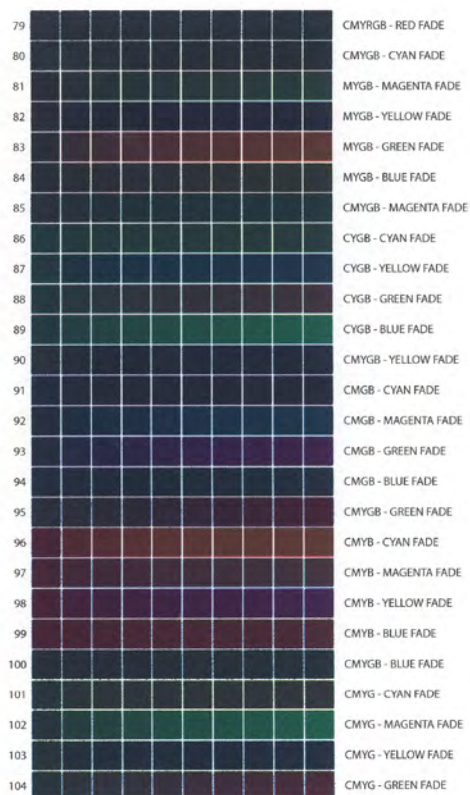
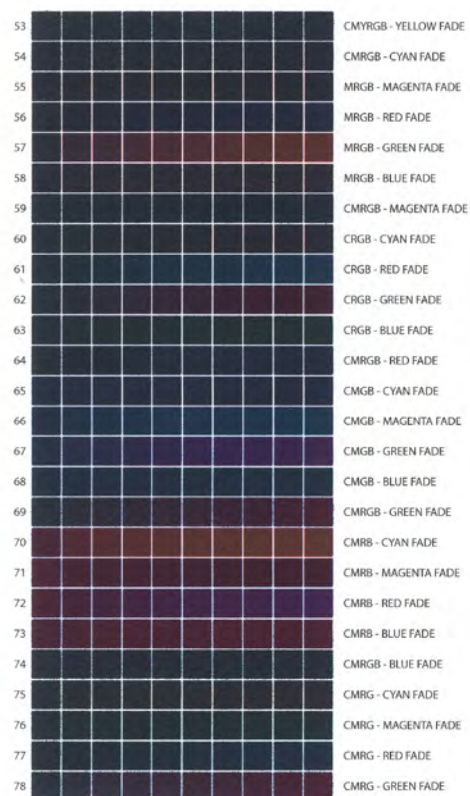


Figure B.8. Scanned DC/MP printed Dark Colour Sampling Chart, rows 53-104 from the HP z3200.

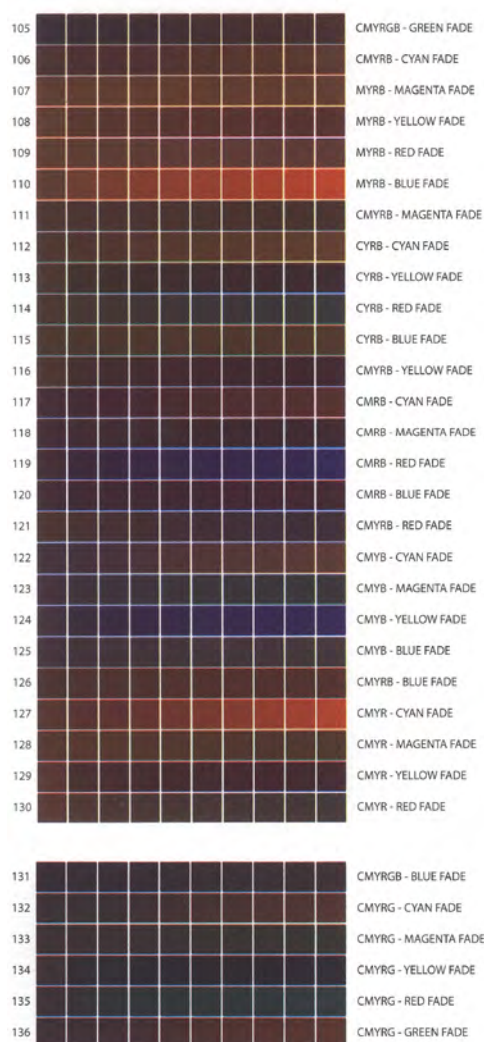


Figure B.9. Scanned DC/MP printed Dark Colour Sampling Chart, rows 105-136 from the Canon iPF8400.

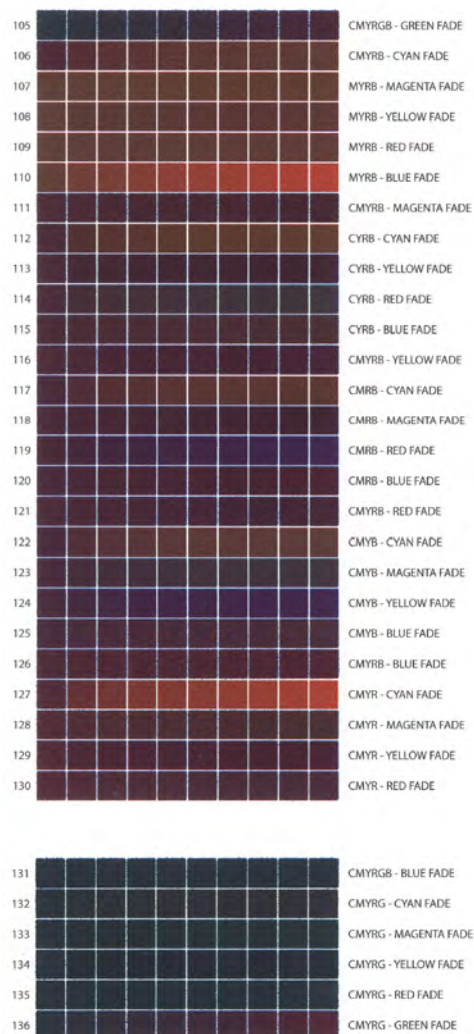


Figure B.10. Scanned DC/MP printed Dark Colour Sampling Chart, rows 105-136 from the HP z3200.

Appendix



Specification for Test Chart Compositions

C.1. Design of the Colour Bar Chart (as appears in 4.4.1)

The design of the Colour Bar test chart is illustrated in Figure C.1, where the separate print layers appear in succession, followed by a representation of their combined appearance.



Figure C.1. Illustration of the Colour Bar Chart's layered design. From left to right: print layer one, print layer two, print layer three, composite of all three print layers superimposed in registration.

The vertical bars on the first layer are made up of seven parallel rectangles, each designated to correspond with a different ink colourant. At the bottom appear seven thin horizontal lines, each intersecting with all of the vertical bars. These lines were included to evaluate the appearance of the two colour combinations at each intersection when printed in a single pass, and to

compare against similar colourant combinations created by layering colourants through multiple pass printing. The second and third layers each consisted of horizontal lines, again with each corresponding to one of the seven ink colourants. The bars on each of these two pages were positioned to overlap the bars on layer one, as well as each other, while being offset slightly. This arrangement allowed for each colour to be printed as one or two layers on top of any other one colourant. Additionally, a grey stroke was placed around the perimeter of each layer, allowing for registration to be evaluated by ensuring the stroke printed in the same position as it did in the printing pass that preceded it.

C.2. Design of the Three Layer / Six Colourant Colour Circle Chart (as appears in 4.4.2)

The refinement of parameters presented for the Colour Circle Chart result in 258 colour combinations to be represented as individual colour patches. These were comprised of every combination and permutation of the six colourants in combinations comprised of one, two, or three colourants, where colourants were allowed to repeat. These include each of the ink colourants, printed through direct channel printing, along with all colourant combinations in all possible sequences of two- and three-colour mixtures, in up to three print layers. This allows for the analysis of output colour of each individual colourant in increments of up to three layers (e.g. R, RR, RRR), and for colour generated by layering each of the two ink colourants in alternating orders (e.g. RY, YR). Furthermore, the patches include all colour variables and sequences for up to three layers, including where one ink colour is applied to the paper twice in conjunction with a layer of an additional ink colour (e.g. YYR, YRY, RYY, RRY, RYR, YRR, and CYR, RCY, RYC, YCR, YRC, CRY). Diagrams of the combinations listed as examples are presented in Figure C.2 as cross sections showing each patch's colourant sequence. For comparison, the 35 two- and three-colour in-line (printed together in a single pass) combinations were also included (indicated by the "-XX-" format, e.g. -RY- and -CRY-). This brought the total number of patches to 293. These

variations were constructed in a print file, resulting in a two-page chart demonstrating all combinations and permutations of colour for the CMYRGB colourants.

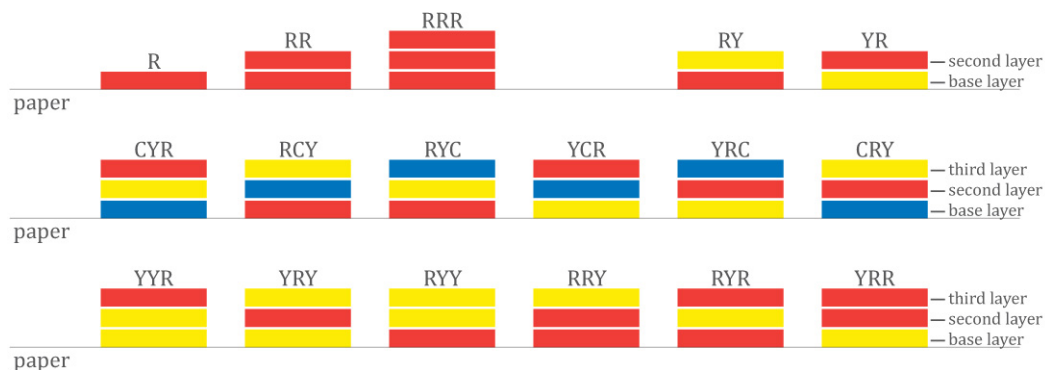


Figure C2. Cross section diagrams of the example colour combinations and sequences from the Circle Colour Chart.

The patches were arranged in a pattern that allowed for qualitative visual judgements of the colour differences in neighbouring hues. The configuration was achieved after printing each patch and subjectively arranging them to group similar colours. The design of the Colour Circle Chart is illustrated in Figure C.3, where the separate print layers appear in succession, followed by a representation of their combined appearance. The patches were printed as circles, 9mm in diameter, to allow for printed area coverage large enough to be measured with a the X-Rite i1Pro spectrophotometer (and subsequently the Konica Minolta FD-7 device). This allowed the chart to also be analysed quantitatively.

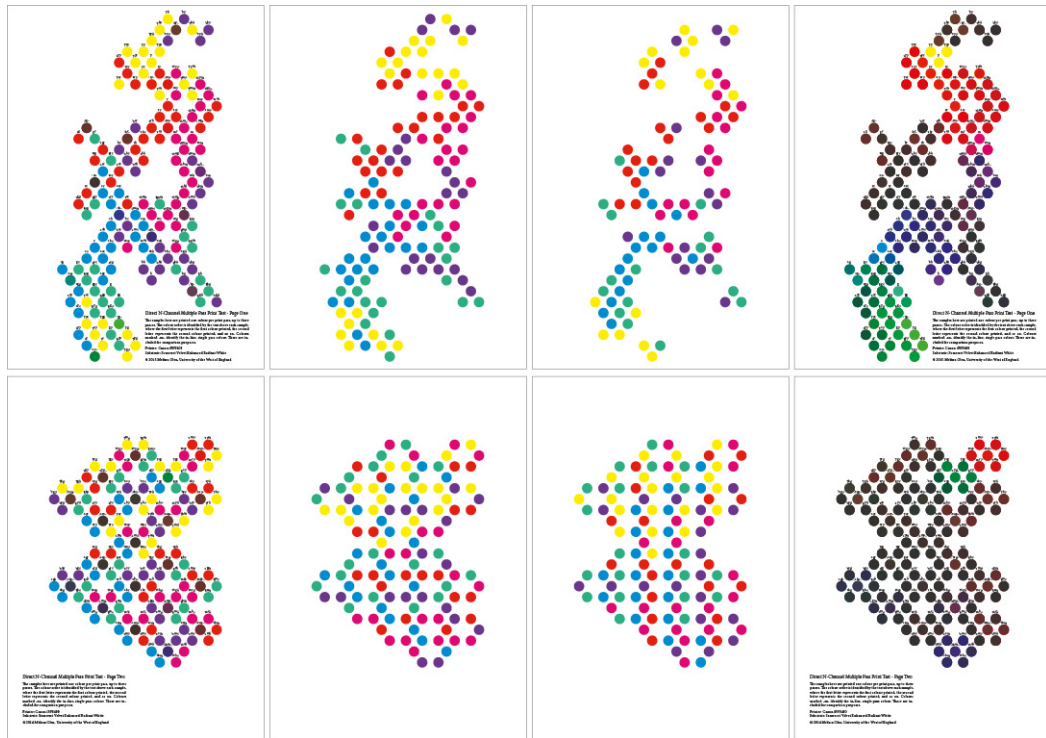


Figure C.3. Illustration of the two page Colour Circle Chart's layered design. Page one appears on the top row, and page two on the bottom. From left to right: print layer one, print layer two, print layer three, composite of all three print layers superimposed in registration.

C.3. Design of the Ink Limit Chart (as appears in 4.4.3)

For the seven-colourant Ink Limit Chart the total coverage range is extended from the simple chart's 400% total area coverage (TAC) to 700% TAC. The overall increase in TAC is achieved in two ways. The first method is to add one colourant at a time for each 100% increment of TAC. Therefore only one colourant is present from 10-100%, a second ink colourant is then added for 110-200%, and so forth (Figure C.4). The final colourant is then applied in 10% increments to total 700% TAC.

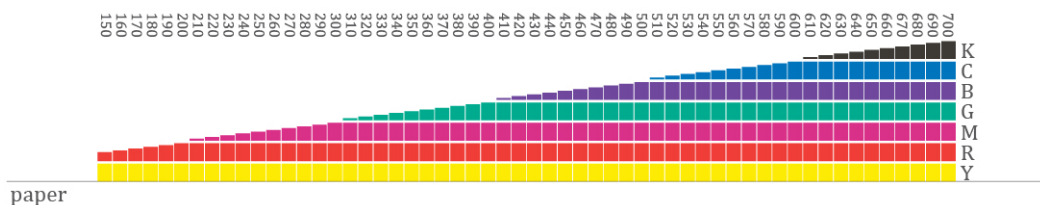


Figure C.4. Illustration of colourant layer sequence, adding one new colourant at a time to increase the total ink coverage.

The second arrangement uses two ink colourants in equal values to achieve each 200% increment up to 600% TAC. For example, 50% of both cyan and magenta would achieve 100% TAC, or 100% of both yellow and black, plus 50% of both magenta and green would total 300% TAC (Figure C.5). Again, the final colourant is then applied in 10% increments to total 700% TAC.

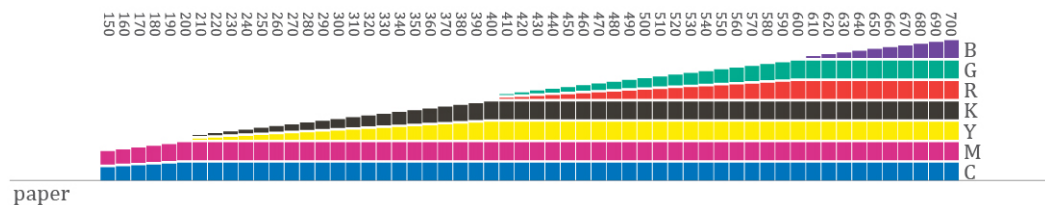


Figure C.5. Illustration of colourant layer sequence, using equal amounts of two colourants to increase the total ink coverage for each 200% interval, up to 600% TAC.

These two arrangements were used to form a set of nine rows. This set of rows with an organised colourant order change allowed the simple CMYK ink limit chart¹ to incorporate every possible permutation of CMY, with the addition of black included in the third or fourth layer. This rearrangement of colourants accounts for the fact that certain ink combinations cause adverse print artefacts, such as ink bleeding and pooling, before others. Figure C.6 illustrates the colourant orders for this set of nine rows. It can be observed that the first four layers contain every possible permutation of the CMY colourants.

¹ The simple CMYK ink limit chart is the chart referenced for this design. See Chapter 4 (4.4.3) for more details.

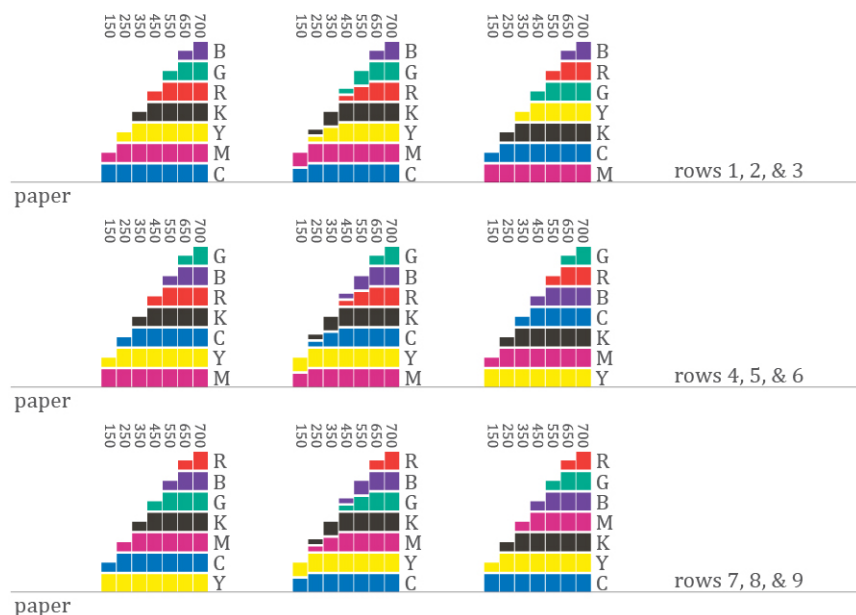


Figure C.6. Illustration of the colourant layer sequence for the set of nine rows using different colourant permutations.

As the number of colourant permutations extends greatly when working with a colour set beyond CMYK, the set of nine rows from the simplified target was not enough to address the increased colourant set. This is particularly visible in the first set of nine rows, where the red, green, and blue colourants all appear only in the higher maximum above 400% TAC. Therefore I deemed it necessary to repeat this set of nine rows multiple times, where the sequence of colourants is altered each time. This was done in order to cover a wider range of possible colour permutations at any given TAC. Although not every possible permutation could be covered due to size and feasibility,² the increase would still allow for a more informed determination of the TAC capabilities. Eleven additional sets (of nine rows each) were incorporated into the design, each with a colourant sequence determined using a random list generator.³ In some instances the first three colourants were found to repeat, however this was not considered to restrict the sampling, as the subsequent colourant sequences differed.

² The decision to randomly sample a subset of possible colourant permutations followed the identification of 10,000+ unique rows.

³ The list randomising application used can be found at random.org/lists.

The final three rows across the bottom of the custom ink limit chart are a replication of the simplified chart. These rows address coverage increases using equal amounts of the six CMYRGB colourants, with three different methods of including black. These rows are illustrated in Figure C.7. The first row contains only the six CMYRGB colourants, in equal proportions, to generate the ink coverage up to 600%, with black being included for 610% to 700% TAC. The second row uses equal amounts of all seven ink colourants, including black, in equal proportions to generate each increment of ink coverage. The final row contains 100% black coverage over the entire range, leaving equal amounts of the CMYRGB colourants to achieve the remaining percentage ink coverage, still in equal amounts.

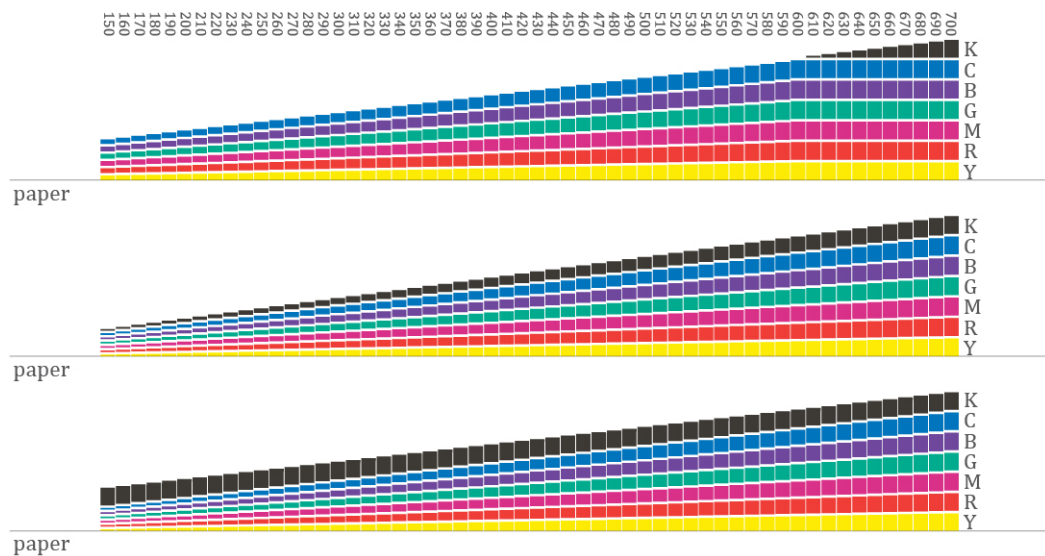


Figure C.7. Illustration of the final three rows of the custom ink limit chart. These rows were generated using equal amounts of the CMYRGB colourants, with three different methods of including the black colourant.

In total, the Ink Limit Chart contained 111 rows of varying colourant sequences and 56 columns, each representing a 10% increase in TAC from 150% to 700%. The chart was designed with a 4mm by 4mm patch size. Since this colour chart was only to be visually inspected the minimum size did not need to be determined by the requirements of a spectrophotometer. The size reduction further allowed more patches to fit on a single sheet of A2 paper. This is a comparatively small size when reviewing other ink limit charts, as larger patches produce less bleeding due to a larger pooling area.

However, ink pooling in the centre of a patch is as problematic as ink bleeding outside of the patch, as neither present a smooth, uniform surface. The smaller patches further seem to better reflect the edge detail maintained in smaller print regions of artworks with no compromise to the larger, flat colour areas.

To prepare the file for DC/MP printing, the layers were divided onto separate pages, each corresponding to a separate printing layer, to then be printed over seven passes. The colourant sequences were set to the randomised arrangements used in the design of chart. The multiple layers of the chart are shown in Figure C.8, illustrating these various permutations in colourant layers. The illustration depicts the twelve sets (of nine rows) each having the same colourant sequence, even if the first colourant is not printed in the first layer, as is the case for rows three through seven (see Figure C.6). In these instances the gaps will be filled in when printing the second or third layer.

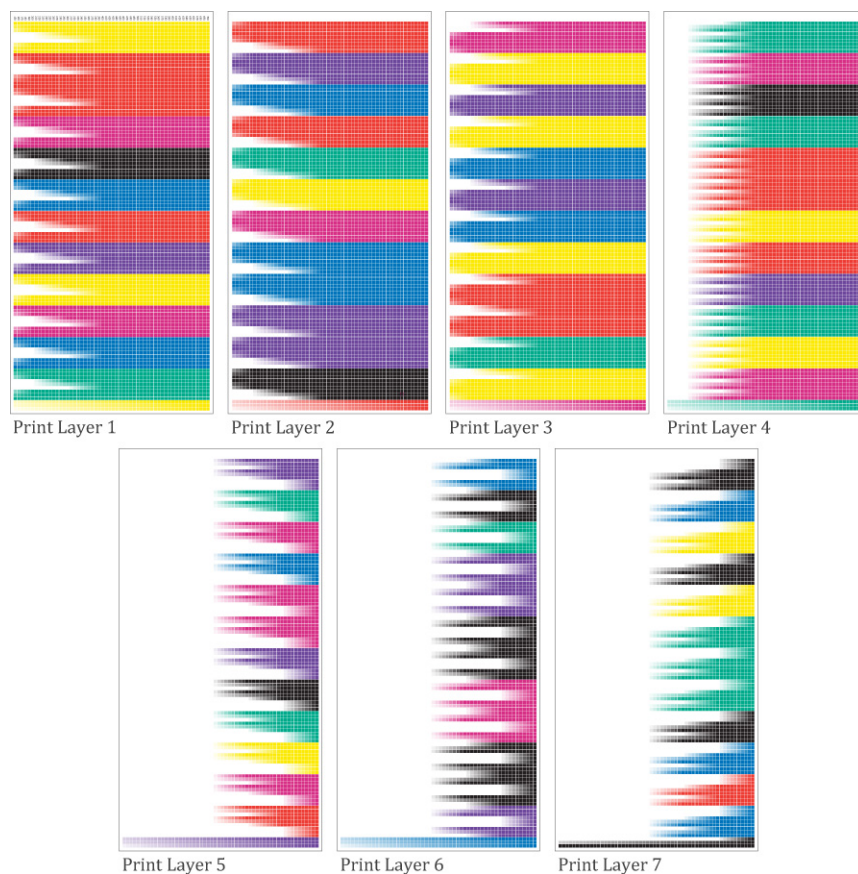


Figure C.8. Illustration of the seven print layers making up the DC/MP Custom Ink Limit Chart.

C.4. Design of a Permutation Test Chart (as appears in 4.4.4)

The test chart consisted of a simple design of overlapping rectangles decreasing in width, as illustrated by the side elevation and print preview view in Figure C.9. Each permutation was printed with a patch size of 15mm x 11.5mm for the base layer colourant. While the 11.5mm height was maintained for all subsequent layers, the width tapered by 1mm for each additional layer. The width of the top layer's colour patch measured 10mm.



Figure C.9. Illustration of the print layers for the Six Colourant Permutation test. The illustration on the left depicts the colourant layers, each slightly narrower than the ones below. To the right is a screen capture of the layered print file.

The reduction in width for each consecutive print layer was incorporated for two purposes. The first was to ensure bronzing did not occur at an intermittent layer only to be hidden by printing the next pass. Secondly, it allowed for a visual assessment of the perceived lightness as each colourant layer was applied. From observations made of the Colour Bars Test (4.4.4), I was aware that the printing of a yellow layer on top of particular colourants resulted in the final printed colour appearing lighter. To avoid unexpected shifts in lightness values when printing with a multiple pass approach, the colourant sequence to be used in further testing required that the printed colours darken proportionately to the increase in TAC.

After the identification of the optimal YBRMCG colourant sequence based on the Permutation Test Chart described above (4.4.4), the following print tests were designed to confirm the results. The first of these two tests consisted of three rows of a similar design to the patch illustrated in Figure C.9. Each row was printed at 120mm x 15mm, with 20mm reduction in width between each layer in the first variation (Figure C.10). The following two rows were modified to gradate the TAC. The first gradient test was a step wedge that included a solid base layer of yellow, with each additional colourant layer

being a gradient from 0 to 100% TAC (Figure C.11). The second variation was a single gradient from 0 to 100% coverage of each colourant from edge to edge (Figure C.12).



Figure C.10. Illustration of the print layers and screen capture of the layered print file from YBRMCG colourant sequence step wedge test.



Figure C.11. Illustration of the print layers and screen capture of the layered print file from YBRMCG colourant sequence step wedge test with gradated transitions.



Figure C.12. Illustration of the print layers and screen capture of the layered print file from YBRMCG colourant sequence test with 0 to 100% coverage gradation.

The final confirmation test consisted of a colour hexagon with 100% coverage of all colourants in the centre, and each of the colourants fading from 100 to 40% out in one direction (Figure C.13). On each edge of the hexagon one colourant was represented by a letter, indicating the edge where it would be printed with 100% TAC. The TAC would then fade, starting at the fifth row down to 40%.

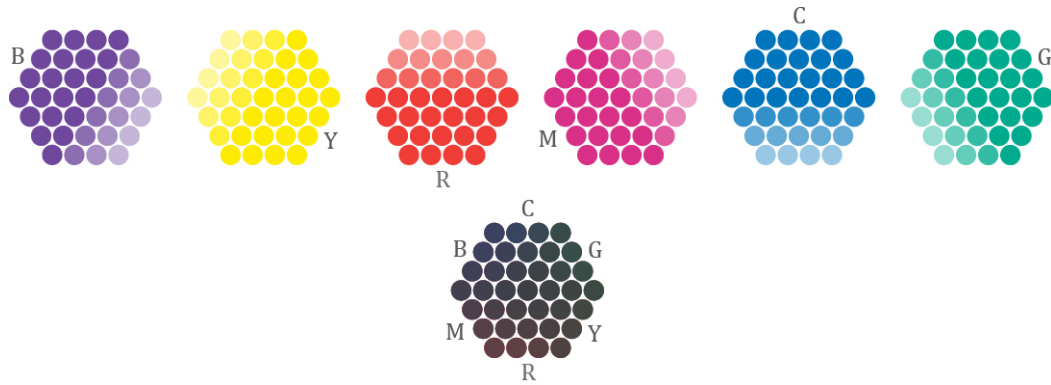


Figure C.13. Illustration of the print layers for the YBRMCG colourant sequence hexagon test. The top row depicts the colourant layers. On the bottom is a screen capture of the layered print file.

C.5. Design of the Maximum Variable “MAX” Colour Chart (as appears in 4.4.5)

For the selection of colourant combinations and layering sequences used in the MAX colour chart I began by determining a number of colourant combinations that would span the entirety of the printer’s gamut, but would limit the patch count to an amount that could be reasonably printed at a size of 7mm x 7mm on a sheet of A2 paper. To begin I set the following parameters:

1. Only two increments in coverage, 50% and 100%, would be included for any single colourant. This would reduce the total patch count by 80% compared to the other test charts I had designed using 10% incremental coverages.⁴ While minimising subsampling, this simplification continues to sample from all relevant dark regions of the colour gamut.
2. All combinations of chromatic colourants were used to define two, three, and four layer patches where any single colourant could repeat up to three times.

⁴ Colour charts that include 10% incremental coverage transitions include the Ink Limit Chart, presented in Chapter 4 (4.4.3), and the Dark Colour Sampling and Colourful Blacks Sampling Charts presented in Chapter 5 (5.4.1 and 5.4.2).

3. Every patch defined by the above simplifications was to be printed two additional times, once with 50% black coverage, and once with 100% black TIC.

These three parameters resulted in the identification of 20,538 colour patches. In an effort to strategically reduce this number I experimented by illustrating a number of colour relationship diagrams influenced by my literature study into colour circles and subgamut divisions. In the end, it was the triangulated arrangement shown in Figure C.14 that was used to devise all the colourant combinations and layer sequences included in the MAX colour chart. My presentation of this colour arrangement is not intended to visually define the subsequent MAX colour chart, but is included here as a visual key to the more complex series of colourant specifications to follow.

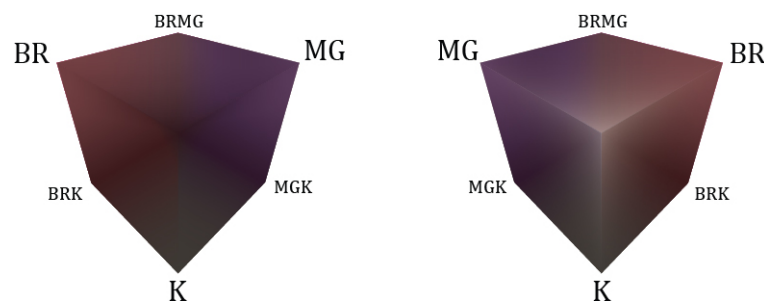


Figure C.14. Illustration of triangulated five colourant subgroup containing two colourant pairs and black. The BR and MG colourant pairs are representative of all possible colourant pairs integrated into the MAX Colour Chart's Design.

As stated in Chapter 4 (4.4.5), and in parameter 2 above, the MAX colour chart was to be limited to 500% TAC, comprising of four CMYRGB colourants, with the addition of black (K). In explaining the procedural development of the MAX colour chart I will use the colourant combination BRMGK, as shown in Figure C.14.

As will be seen in the following colour chart presented in accompaniment to Chapter 5, a series of 'fading' procedures were established to break down the five colourant BRMGK combination, in an effort to sample a small subset of the printer's gamut. The following operations for subsampling the five-colourant combination provide the framework for the entire MAX Colour

Chart. To begin, the first three operations were aimed at modifying the BRMGK combination with all colourants at 100% TIC. These directives are written and illustrated in Figure C.15. Figure C.16 illustrates the next seven operations, directed towards reducing specified colourants to 50% TIC (where the small capital letter indicates a 50% coverage reduction).

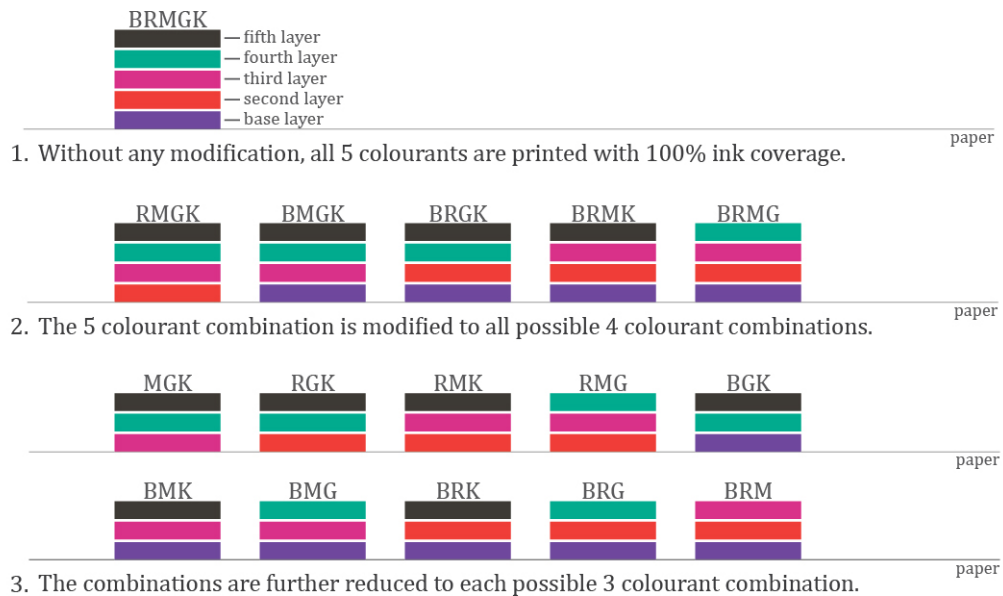


Figure C.15. Illustration of first three layer modifications deriving from the BRMGK colourant combination. The sixteen subsequent patches form a portion of the MAX Colour Chart.

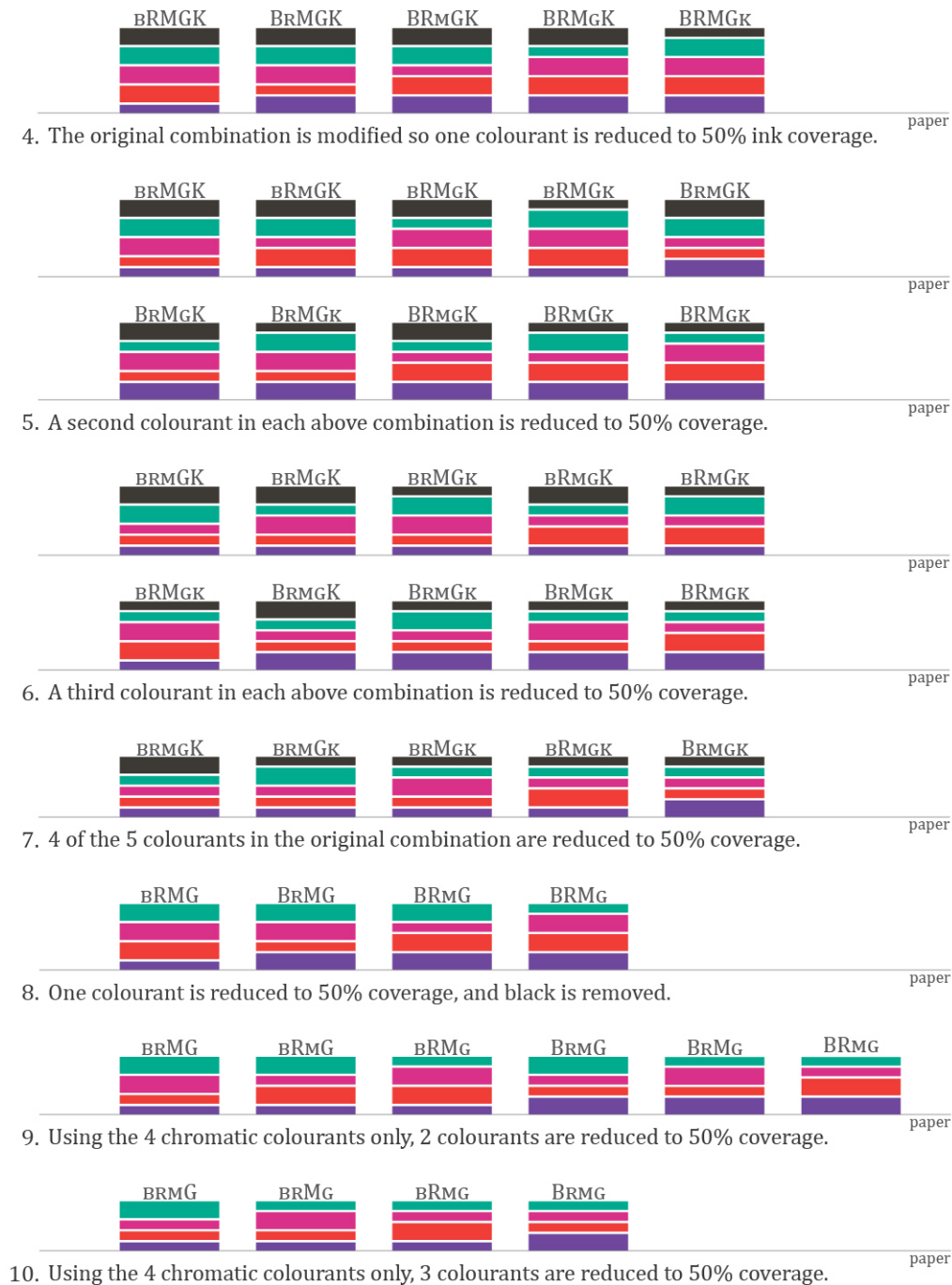


Figure C.16. Illustration of layer modifications 4 thru 7, derived from the BRMGK colourant combination. The forty-four subsequent patches form a portion of the MAX Colour Chart.

The ten commands presented in Figures C.15 & C.16 established 60 layer sequences for the BRMGK colourant combination. These sequences were organised into a single grouping. From here the same grouping could be duplicated and amended to accommodate each of the other possible four colourant CMYRGB combinations. In replacing the BRMG colourants from the

preceding examples, I reverted back to the triangulated colour arrangement in Figure C.14. By grouping the BR and MG colourants I found I could significantly reduce the final number of combinations that would be exchanged for the RMGB colourants. The colourant identification resulted from these two processes:

1. Observing the YBRMCG print sequence, the 21 two-colourant combinations, where any single colourant repeated twice, were identified.
2. Following the concept of the 'three-colourant' mixture from the triangulation in Figure C.14, two two-colourant combinations, in addition to black, could make up the five colourants inserted into each modified layer sequence group.

In combining the two-colourant combinations I chose not to include repeats, as this eliminated 21 combinations, or 1,260 layer sequences. From here I inserted the remaining 210 five-colourant (with black) combinations into my worksheet and applied the 60 modifications commands to each. This resulted in 12,600 layer sequences, a significant number of which were duplicates. This was predominantly a result of commands 2 and 3 (Figure C.15), which constructed patches containing combinations of three and four colourants at 100% coverage.⁵ Furthermore, some duplicates appeared within the group of 60 modifications using just one of the four-colourant combinations. For example, when rule 4 was applied to the YYYG combination, three of the five results contained two 100% coverage layers, plus a 50% coverage layer. Here three of the five colour patches contained a total of 250% Y coverage, along with 100% coverage of G and K, as can be seen in Figure C.17.

⁵ Command 2 and 3 resulted in five four-colourant and ten three-colourant combinations. When multiplied by 210 (for each five-colourant combination that would replace the RMGB variables) this generated 3,150 colour patches. Of these only 77 three-colourant, and 176 four-colourant combinations were unique.

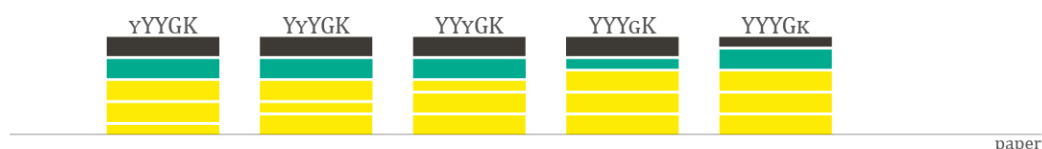


Figure C.17. Illustration of the five-colourant patch layers resulting from command four, modifying the YYYG colourant combination.

The repetition shown the YYYGK combination also highlights another occurrence found in a large number of colour patch combinations. When scanning through the listed combinations such repetitions as Yy and yY were found. Despite the change in layer order the final outcome for both combinations is 150% coverage of Y. Because the layer order will have no quantifiable result when printing with the same ink colourant, I chose to simplify the combinations to establish consistency and eliminate further duplication. The following simplifications were made to the 7,200 colourant combinations calculated for the MAX colour chart:

1. Two consecutive layers of the same colourant at 50% TIC were re-written as a single layer of 100% TIC (e.g. YyBMK became YBMK).
2. Two consecutive layers of the same colourant, one at 100%, one at 50% coverage were arranged to consistently print the 100% TIC layer before the 50% TIC layer (e.g. YyGGK became YyGGK), which helped in the identification of duplicates.

The last processing step for the selection of colour patches was to eliminate all duplicate values resulting from the rearrangements listed above.⁶ In total the MAX colour chart contains 2,840⁷ unique colourant combinations,

⁶ It was through the process of re-arranging the colourant sequences to correct for variation to the YBRMCG that it became evident that a simpler calculation could have been made to determine all four non-repetitive colourant combinations. This would have been to calculate all 126 possible four colourant combinations from the six CMYRGB colourants and then remove the 6 where any single colourant was repeated four times. However, it is under consideration that the two colourant pairings used in the method informed by the triangulation diagram may be beneficial to future research where alternating layer sequences are introduced (7.6).

⁷ In conducting the data analysis on the MAX Colour Chart it was found that 93 of the total 2,933 colour patches contained the incorrect colourant layer sequence. This has been attributed to errors in the file design process. All 93 erroneous colour patches were removed from the data analysis presented in this thesis. Furthermore, recalculation of the colourant

providing a far greater sampling when compared with the earlier Colour Circle Chart. This provides a more comprehensive patch set for the assessment of the DC/MP printing method's ability to expand the printer's gamut. These colour patch combinations were arranged as a grid in Adobe Illustrator, giving no particular attention to placement on the page. As was done for the Ink Limit Chart, two versions of the same chart design were created: the first with all colourant layers assigned to a single page and the second with each layer separated over five pages. Figure C.18 shows the composite file with all colourant layers on a single page.

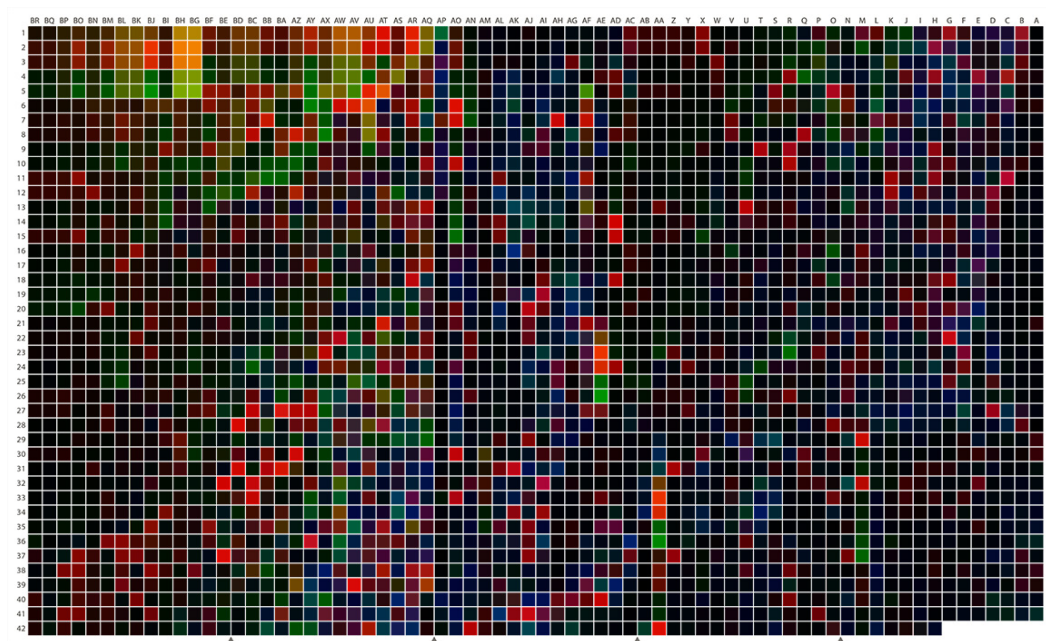


Figure C.18. Illustration of the MAX Colour Chart's layered design.

C.6. Design of the Dark Colour Test Chart (as appears in 5.4.1)

The Dark Colour Sampling Chart's patches totalled between 300% and 600% TAC to ensure enough ink was layered to produce the dark colours. The chart was designed with one hundred thirty-six rows and ten columns. Each row represented one of the possible 4, 5, and 6 colourant combinations from the CMYRGB inkset. The first column of each row contained 100% TIC for each

combinations and modified layer sequences, following a further simplification of the permutation model, identified that the MAX Colour Chart should contain 3,295 patches. Therefore the 2,840 colour patches included here are recognised to be a sampling of the greater patch count.

colourant in the combination, then, starting at the second column, one of the colourants in the combination began to decrease in coverage by 10%. The incremental decrease continued over the remaining columns until the specific colorant's coverage percentage was 10%. The design sequencing is exhibited in Figure C.19, depicting the first 7 rows of the Dark Colour Sampling Chart. The colourant that is reduced by 10% TIC increments for each row was referred to as a colourant 'fade'.

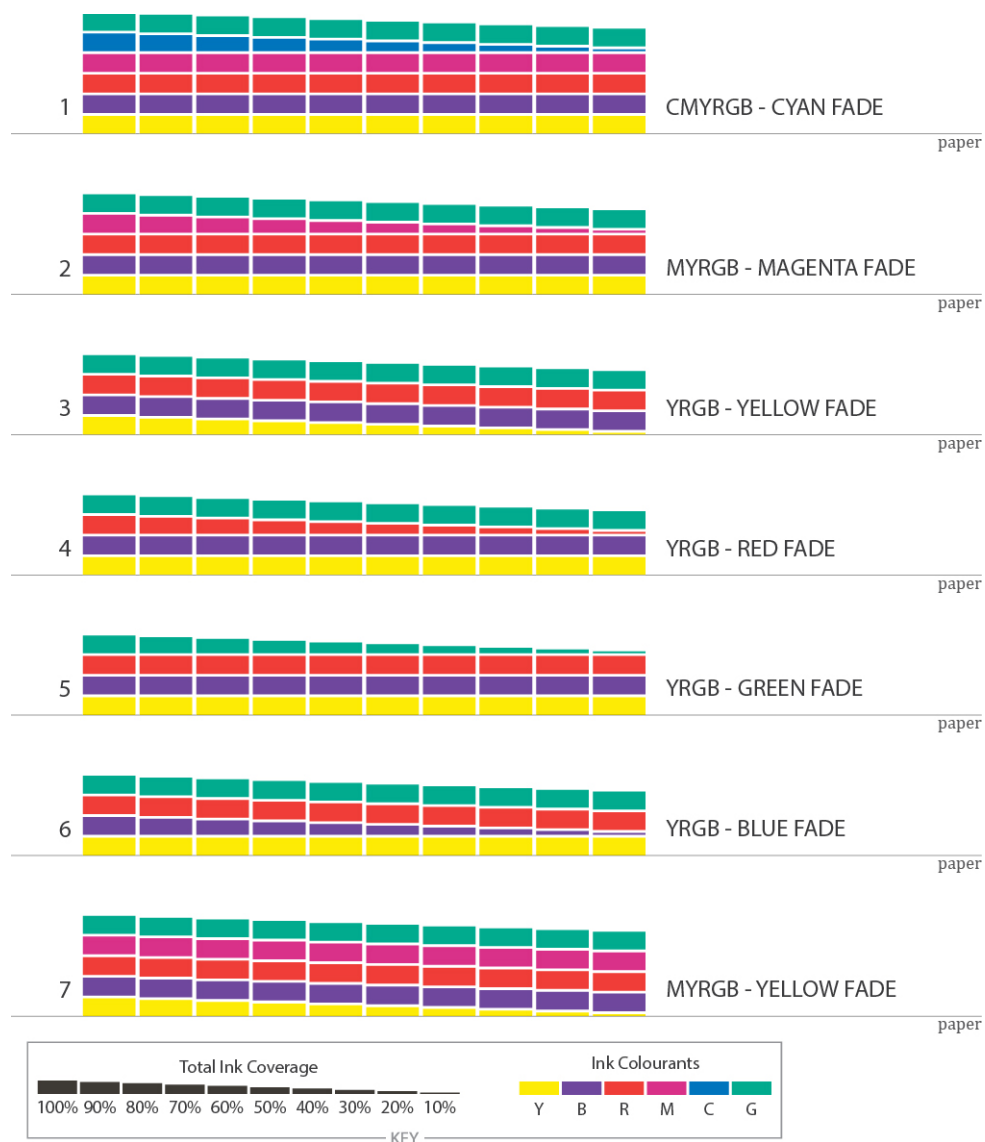


Figure C.19. Illustration of the colourant layer sequence for the set of nine rows of the Dark Colour Sampling Chart.

Each colourant in the Dark Colour Sampling Chart's patches was assigned to print as individual layers and output using DC/MP printing only. Of the 1,360

colour patches in the chart, 860 represented unique colourant combinations.⁸ The Dark Colour chart was printed on six A5 sheets of Somerset Velvet Enhanced paper. The six print layers for page 1 are shown in Figure C.20, followed by composite of the page layers in registration.

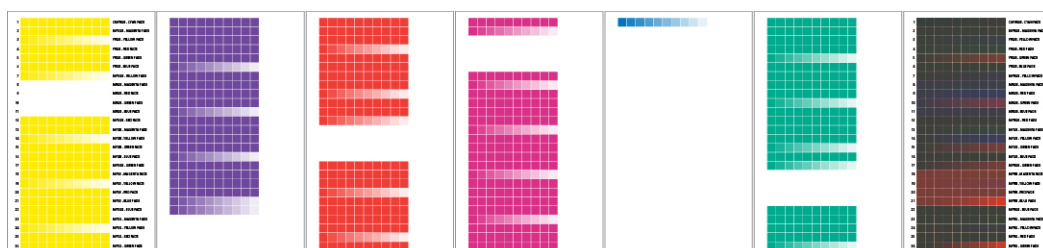


Figure C.20. Illustration of the Dark Colour Sampling Chart's layered design for page 1. From left to right: print layer one through six, followed by a composite of all six print layers superimposed in registration.

C.7. Design of the Colourful Blacks Test Chart (as appears in 5.4.2)

The Colourful Black Sampling Chart was designed in a similar fashion to the previous Dark Colour Chart (C.6). The chart included twenty four-colourant combinations containing three chromatic colourants in addition to black. It possesses 229 rows, each made up of ten columns, where one or more of the colourants in the row is assigned to 'fade'. The first, larger portion, of the chart contains each four-colourant combination assigned twenty 'fade' changes from 400% to 200% TAC. The first ten rows for the CMYK colourant combination are illustrated in Figure C.21. This pattern continues for the remainder of the CMYK combination through row 20. In row 20, equal amounts CMY fade together, toward black ink only.

⁸ Duplicate patches appeared in the first column of many rows due to the 'fading' colourant still being assigned to start at 100% coverage.

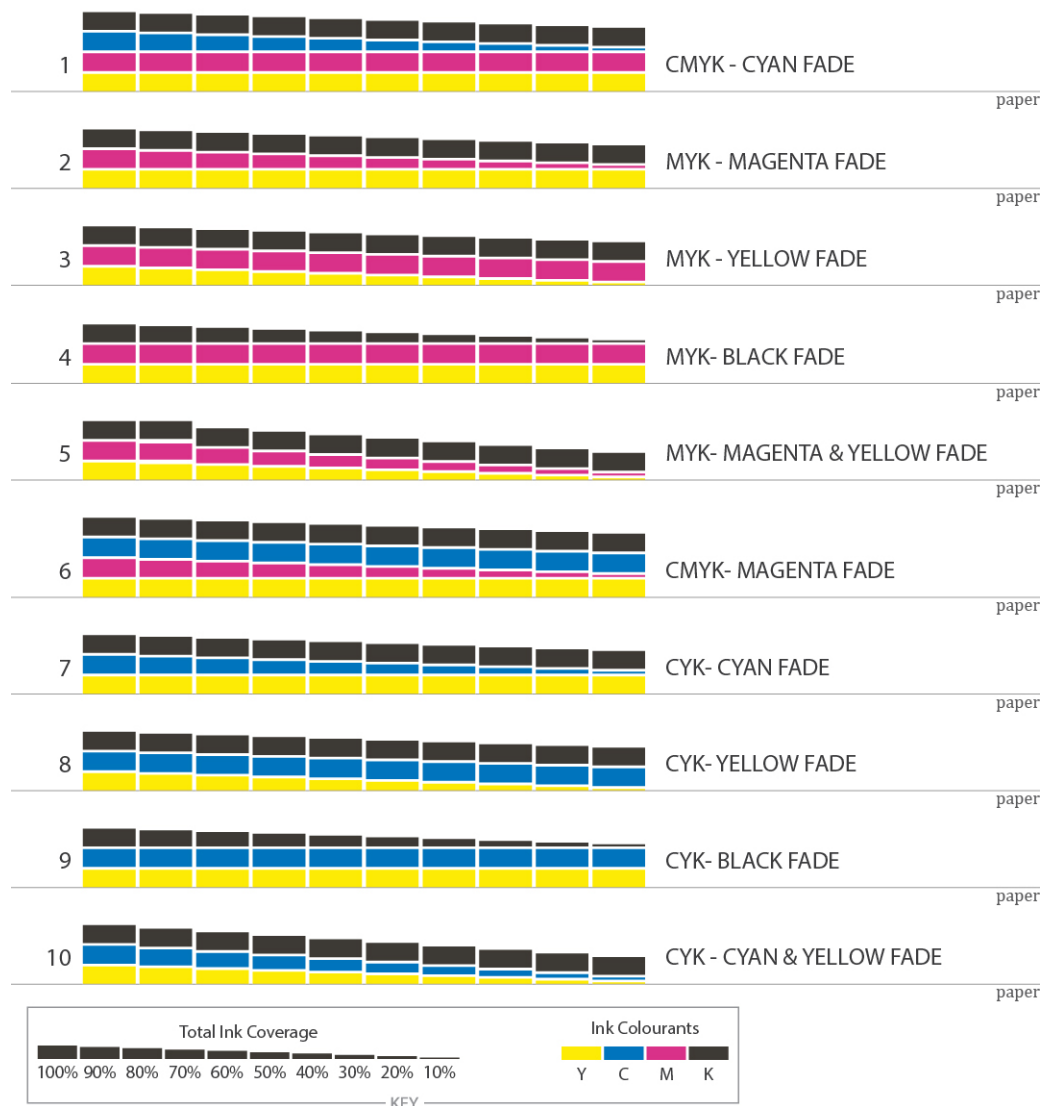


Figure C.21. Illustration of the colourant layer sequence for the set of nine rows of the Colourful Black Sampling Chart.

It was found that the fade assignments produced duplicate rows from one colourant combination to the next. For example once the cyan and red colourants were faded from the CMYK and MYRK, all subsequent rows would only include combination of MYK. After removing all duplicates, the sampling chart contained a total of 220 rows.

An additional nine rows were added at the end of the colour chart. These contained combinations of each chromatic colourant and black with variant coverage combinations. The colourant transitions first included 100% coverage of the chromatic colourant with incremental black coverage from

60-100%. Secondly, the black remained at 100% coverage while the chromatic colourant coverage ranged from 10-100% TAC. This transition is illustrated in Figure C.22, depicting rows 221 and 222.

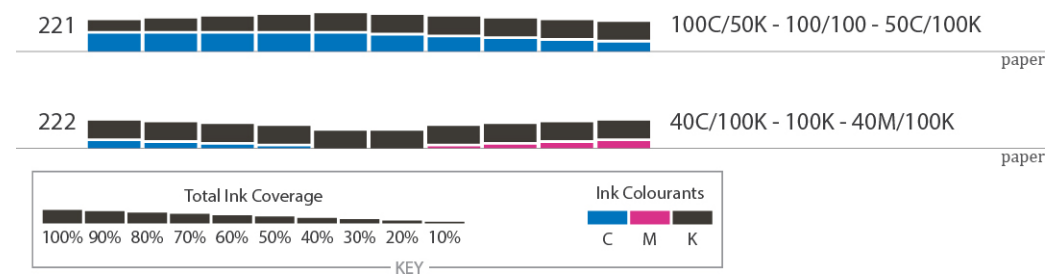


Figure C.22. Illustration of the colourant layer sequence for rows 221 and 222 of the Colourful Blacks Sampling Chart.

The page layout of the Colourful Blacks Sampling Chart was modified from the previous A5 format to consolidate all of the rows onto three A4 sheets of Somerset Velvet Enhanced paper. The sequential print layers for the first 26 rows are shown in Figure C.23, followed by a composite of the print layers in registration.

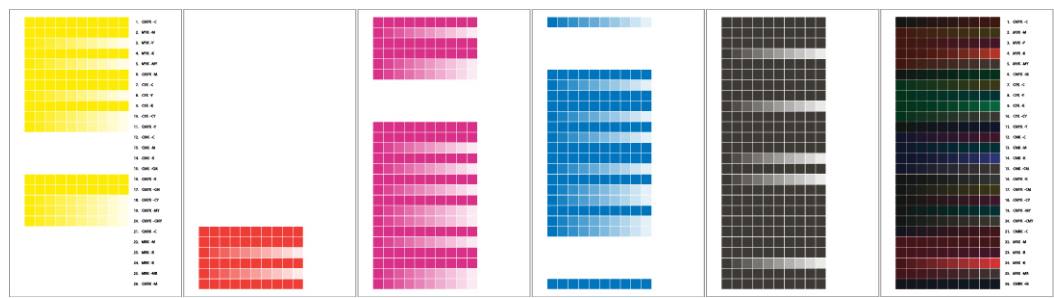


Figure C.23. Illustration of the Colourful Blacks Sampling Chart's layered design for the first 26 rows. From left to right: print layer one through five, followed by a composite of all five print layers superimposed in registration.

C.8. Design of the Varnish Coating Tests (as appears in 5.5.1)

In order to evaluate the effects of adding a varnish to the surface of the printed output, I designed a simple test chart that could be coated with a variety of vanishes after printing. This chart contained sixty-six patches of one or two chromatic colourant combinations, sequenced with up to three consecutive layers of black either on top or bottom of the chromatic colourants. It also replicated the one, two, and three layers of only black ink from the Colour Bar Test (4.4.1) specifically to evaluate the perceived

darkness of the black at increasing ink volumes after varnish was applied. The colourant combinations contained in this test chart are shown in Figure C.24.

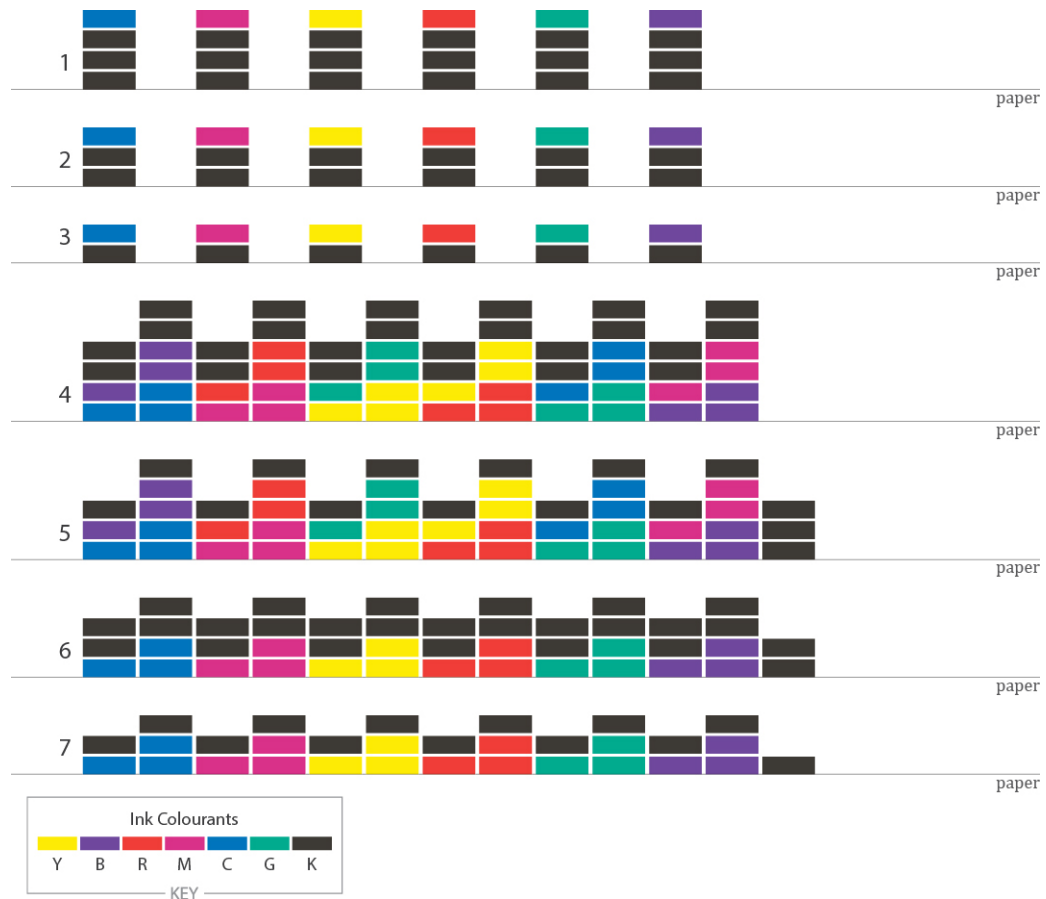


Figure C.24. Illustration of the colourant layer sequence for the varnish coating tests.

The patches for the varnish coating test analysed in Chapter 5 (5.5.1) measured 8.5mm x 8.4mm. An earlier version contained patches at 21mm x 19mm, allowing enough coverage area to ensure the varnish coating could be applied smoothly over the printed area.

Appendix

D Supplemental Colour Data for Select Experimental Outcomes

D.1. Colour Data for the Colour Circle Chart

Colourant combinations expressed as “-XX-” are colourant combinations printed as direct channel, single pass prints. The analysis made from this colour data is presented in Chapter 4 (4.4.2). These results are tabulated by total error.

Page One				
	dL'	dC'	dH'	dE2000
RRG & GGR	3.13	-11.75	34.66	30.24
MMG & GGM	5.43	-6.59	-36.54	27.39
MGM & GGM	3.82	3.08	-29.99	24.29
GR & RRG	-3.56	15.37	-24.62	22.79
BBY & YYB	12.86	27.08	17.29	22.53
RG & GGR	2.33	2.23	23.24	20.91
GMM & GGM	3.47	5.75	-25.81	20.81
CRR & RCC	-5.52	13.04	-21.17	20.49
MMG & GMG	1.96	-9.29	-24.42	20.44
BBG & GGB	9.04	-14.76	-26.68	19.78
RRC & CCR	-1.01	-21.80	16.33	19.62
RRC & CR	-0.46	-22.24	15.67	19.41
MG & GGM	2.65	-2.49	-27.31	19.34
CCY & YYC	12.28	18.01	-24.45	19.22
CCR & RCC	-4.60	17.20	-17.00	19.22
CR & RCC	-5.14	17.63	-16.07	18.88
RRG & GRR	2.51	-14.79	19.48	18.35
RCR & RCC	-5.70	10.47	-19.41	17.84
-RG- & RRG	-3.03	18.07	-16.80	17.65
CRR & RRC	0.08	17.46	-16.45	17.51
MGM & GMG	0.35	-0.48	-19.19	17.25
BGB & GGB	4.82	-2.48	-22.23	17.24
GBB & GGB	4.24	-1.36	-22.03	17.22
MMG & GM	5.29	-9.93	-18.87	16.77
YYM & MMY	-9.70	-7.98	-23.26	16.62
RGR & GGR	0.37	0.17	18.84	16.29
YB & BBY	-8.73	-18.18	-12.63	16.25
CYC & YYC	12.28	22.76	-13.97	16.25
MMC & CCM	2.29	2.06	-19.07	15.91
MMG & MGG	0.42	-9.29	-18.47	15.90
CRR & CRC	-2.31	7.31	-16.54	15.75
BG & GGB	4.90	-14.02	-20.39	15.31
CRC & CCR	1.38	-11.33	14.06	15.30
RRG & GRG	-1.60	-24.73	-4.51	15.29
-CM- & MMC	-2.21	-7.99	17.65	15.23
CCG & GGC	5.51	-0.81	-26.30	15.20
MMC & CM	2.94	4.78	-17.86	15.14
RRB & BBR	-7.82	-23.11	-11.15	15.14

-MG- & GGM	1.17	-0.67	-21.76	15.04
CR & CRC	-1.93	11.75	-13.34	14.99
YCC & YYC	11.79	17.84	-14.57	14.97
-CR- & RRC	1.07	23.75	-2.74	14.96
CGC & GGC	4.56	3.57	-25.38	14.88
RGG & GGR	4.96	11.77	12.54	14.86
-BG- & GGB	3.50	-12.72	-20.07	14.82
GGR & GRG	-4.73	-12.28	-11.89	14.59
RRG & RGG	-1.83	-24.22	-1.93	14.59
CCG & GCG	4.18	3.91	-26.42	14.57
GCG & CGC	-3.23	-8.22	25.50	14.51
-MG- & MMG	-4.26	4.88	16.63	14.50
RGR & RRG	-2.76	11.55	-15.77	14.43
RC & CCR	1.43	-10.33	13.26	14.42
YYM & MYM	-9.76	-3.50	-18.39	14.39
CRR & RC	-2.36	6.32	-15.02	14.38
GGY & YYG	11.18	11.33	-21.73	14.30
RG & GR	2.76	-1.58	15.54	14.26
-CR- & RCC	-4.53	19.13	-6.45	14.24
GBB & GBG	-1.24	4.85	-15.72	14.24
GYG & YYG	11.73	8.95	-20.37	14.22
RC & CR	1.98	-10.75	12.62	14.16
BY & YYB	7.01	19.24	10.88	14.10
GMM & GMG	0.00	2.07	-15.32	13.85
BGB & GBG	-0.67	3.76	-15.56	13.71
MMB & BBM	-7.65	4.89	-19.35	13.46
MGM & GM	3.68	-1.25	-14.22	13.27
-BY- & YYB	6.57	15.88	11.66	13.20
BBG & GBG	3.56	-7.56	-18.36	13.16
MGG & GGM	5.00	3.59	-17.58	13.13
YBB & YYB	10.05	16.67	7.37	13.04
CCY & YCY	8.24	15.12	-14.94	13.00
YYM & YMM	-8.96	-3.37	-16.33	13.00
RRC & CRC	-2.49	4.79	-14.23	12.92
RRC & RCR	0.10	-14.82	11.51	12.86
-CG- & CGC	-7.07	-12.57	19.64	12.84
-CG- & CCG	-8.02	-8.32	20.18	12.74
GBB & BGG	-2.22	5.02	-13.34	12.70
YYB & BYB	-9.94	-18.73	-3.80	12.69
GCC & GGC	4.32	4.46	-20.78	12.67
MGM & MGG	-1.18	-0.68	-13.86	12.67
YBY & BBY	-8.37	-9.82	-10.15	12.64
RRC & RCC	-5.60	-4.60	-16.48	12.61
CCY & YC	7.43	16.53	-14.49	12.60
YGG & YYG	10.46	6.66	-17.92	12.45
YYC & CY	-6.76	-2.49	20.19	12.34
GCC & GCG	2.99	9.13	-20.61	12.27
RRB & BR	-4.88	-11.38	-13.85	12.17
MMB & BM	-4.12	13.24	-17.94	12.13

BGB & BGG	-1.64	3.95	-13.11	12.12
GM & GGM	0.14	4.19	-16.78	12.09
YYR & RRY	-6.81	-7.63	-18.38	11.97
GC & CCG	-7.15	-4.15	19.44	11.94
GC & CGC	-6.21	-8.42	18.93	11.92
GGY & YG	9.84	16.27	-13.92	11.78
GYG & YG	10.39	13.89	-12.34	11.73
MG & GMG	-0.82	-5.34	-14.67	11.67
CGC & CGG	2.18	6.07	-20.48	11.57
-MG- & MGM	-2.65	-3.36	12.15	11.57
CCG & CGG	3.13	1.76	-21.10	11.53
RGR & GRG	-4.36	-11.96	-7.62	11.51
GR & GRG	-5.15	-8.41	-9.25	11.51
GB & GGB	1.10	-5.39	-15.64	11.37
YYB & BYY	-5.49	-19.46	-5.39	11.33
RCR & RC	-2.53	3.81	-12.33	11.32
GRR & GGR	0.63	3.25	13.05	11.30
BBG & BGG	2.58	-7.15	-15.62	11.29
GR & RGG	-5.39	-7.89	-9.16	11.28
-MB- & MMB	2.60	-12.64	16.97	11.26
-CY- & CCY	-6.53	-19.40	10.59	11.18
BBY & BYY	7.36	7.34	9.39	11.16
CYC & YCY	8.25	19.99	-5.31	11.12
-BY- & BBY	-6.29	-12.55	-7.64	11.05
YM & MMY	-6.67	-9.61	-15.14	11.02
-CM- & MCM	-1.38	-15.55	7.60	10.94
-CY- & YYC	5.75	-1.22	-18.56	10.92
MCM & CCM	1.47	9.64	-9.54	10.91
CYC & YC	7.44	21.39	-4.74	10.90
-YG- & GYG	-10.02	-13.74	9.01	10.90
-YG- & GGY	-9.47	-16.12	10.66	10.89
-CG- & GCC	-6.83	-13.49	14.47	10.88
GGB & BGG	-6.46	6.60	12.85	10.87
-CY- & CYC	-6.54	-24.24	0.85	10.81
-RG- & GGR	0.10	6.18	11.50	10.75
RGR & RGG	-4.59	-11.45	-6.54	10.73
-BR- & RRB	3.78	8.61	12.66	10.62
BBY & BYB	2.91	7.86	10.43	10.59
YBB & BBY	-2.81	-10.76	-9.44	10.59
GRR & GRG	-4.10	-8.87	-8.14	10.58
YR & RRY	-5.75	-9.22	-16.35	10.53
MCM & CM	2.11	12.35	-8.13	10.52
-CR- & CRC	-1.32	13.24	-4.44	10.47
GBB & BG	-0.66	11.98	-7.16	10.45
RG & GRR	1.71	-1.10	11.51	10.43
RB & BBR	-5.17	-18.45	-4.67	10.34
BBG & GB	7.94	-8.12	-11.64	10.33
YYM & MY	-4.41	-1.89	-16.24	10.26
YYC & CY	-6.56	-5.63	14.99	10.19

GMM & GM	3.33	1.28	-10.52	10.15
CG & CGC	-4.79	-10.66	15.66	10.11
CCY & CYY	5.72	12.54	-11.51	10.02
GRR & RGG	-4.34	-8.36	-7.56	10.01
-BG- & GBB	-0.74	-10.78	7.24	10.00
YMY & MMY	-6.98	-4.64	-12.51	9.98
YBY & YYB	4.49	17.19	5.51	9.98
YGG & YG	9.12	11.59	-9.64	9.95
GBB & GB	3.14	3.90	-9.84	9.88
GC & GCC	-5.96	-9.33	13.99	9.85
CG & CCG	-5.74	-6.41	15.97	9.84
MMC & CMC	0.57	5.98	-11.84	9.74
BGB & BG	-0.08	10.91	-6.74	9.70
-CR- & RC	-1.37	12.24	-3.65	9.70
CB & BBC	-5.59	-2.87	10.25	9.60
GMM & MGG	-1.53	1.83	-10.13	9.60
-RG- & RG	-2.23	4.02	-9.85	9.50
BGB & GB	3.71	2.84	-9.54	9.48
GYG & GY	8.77	10.75	-7.24	9.46
GGY & GY	8.22	13.13	-8.88	9.42
-BR- & BRB	-1.32	-12.08	9.43	9.39
CYC & CY	5.53	20.63	0.92	9.37
RRB & BRB	-5.11	-18.53	0.01	9.35
YCC & YCY	7.75	14.95	-5.09	9.33
-BG- & BGB	-1.32	-9.71	6.82	9.31
MMB & BMB	-3.93	-4.26	-13.71	9.30
RRB & RBB	-5.76	-15.82	-5.04	9.29
BR & BRB	-0.23	-9.52	10.30	9.29
GCC & CGG	1.94	6.97	-15.69	9.28
RRC & CRC	-2.39	-10.46	-9.57	9.27
MMG & MG	2.77	-3.26	-10.92	9.24
GBG & GGB	5.48	-6.46	-10.49	9.21
CCY & CY	5.52	15.72	-8.28	9.21
-MY- & MMY	-6.14	-9.21	-11.74	9.21
BY & BBY	-5.84	-8.54	-6.84	9.20
-YG- & YGG	-8.75	-11.44	6.24	9.18
GR & RGR	-0.80	3.49	-9.85	9.17
GGY & GYY	7.48	7.84	-11.93	9.17
MYY & YMY	3.83	3.62	14.39	9.16
GYG & GYY	8.03	5.46	-10.41	9.15
RBR & BBR	-4.19	-14.98	-5.38	9.06
MMC & MC	1.19	7.72	-10.67	9.03
CMM & MMC	-1.12	5.96	11.59	9.00
YCC & YC	6.94	16.36	-4.46	8.99
GMG & GGM	3.47	3.43	-11.87	8.96
-RY- & RRY	-5.57	-7.90	-12.90	8.89
-RG- & GRG	-4.63	-6.00	-6.99	8.87
-MG- & GMM	-2.30	-5.75	8.23	8.86
-BR- & BBR	-4.04	-16.73	-1.86	8.79

MYM & YM	6.73	5.13	9.87	8.77
-CY- & YCC	-6.04	-19.22	0.18	8.77
CCB & BBC	-5.61	5.63	10.53	8.76
CYC & CYY	5.73	17.49	-2.38	8.68
-CB- & BBC	-4.05	-7.33	8.62	8.61
RCR & CR	-0.56	-6.83	7.26	8.54
RG & GRG	-2.40	-10.09	-4.05	8.53
RB & BRB	-2.46	-13.75	6.61	8.51
RCR & CCR	-1.10	-6.41	7.40	8.46
-RG- & RGG	-4.86	-5.48	-6.48	8.38
MMB & MB	-0.72	8.58	-12.78	8.31
-BG- & BBG	-5.55	1.18	8.77	8.30
MCC & CCM	2.88	-3.12	-10.41	8.29
BRR & RRB	4.38	11.61	7.16	8.23
RRC & RC	-2.44	-11.45	-6.57	8.18
RG & RRG	-0.80	14.32	-3.54	8.17
YMY & MYM	-7.04	-0.16	-7.34	8.16
CG & GCC	-4.55	-11.57	10.61	8.13
BBG & BG	4.15	0.01	-8.72	8.07
MMB & MBB	-3.47	-2.98	-12.01	8.04
MMC & MCC	-0.59	5.30	-9.87	8.02
-MY- & YMY	3.56	-1.23	12.57	7.98
YYC & YC	-4.85	-1.61	12.61	7.96
YYR & RYR	-6.24	-3.27	-9.60	7.95
CG & GGC	-0.23	-7.39	-13.07	7.92
MG & GM	2.52	-5.99	-9.05	7.92
MYY & MMY	-5.87	-4.36	-9.20	7.85
GMM & MMG	-1.96	11.87	5.96	7.80
GGY & YGY	5.69	5.57	-11.91	7.79
YGG & GY	7.50	8.46	-4.49	7.77
MBM & BBM	-3.01	-0.22	-11.72	7.76
MMB & BMM	-5.05	4.44	-10.61	7.75
BRR & BBR	-3.45	-12.41	-4.84	7.75
MB & BBM	-6.93	-3.35	-8.37	7.73
RG & RGG	-2.63	-9.58	-2.45	7.69
GYG & YGY	6.24	3.19	-10.43	7.68
RG & RGR	1.96	2.00	8.44	7.65
CB & BCB	-2.00	-13.03	4.62	7.65
CM & MCC	-3.53	0.47	8.76	7.61
-CM- & CMM	-1.09	-13.48	3.66	7.60
-CB- & BCB	-0.45	-17.49	2.98	7.59
-CM- & MCC	-2.80	-2.69	8.14	7.54
CMM & CCM	1.17	7.64	-5.91	7.49
YB & BY	-2.89	-9.86	-5.94	7.47
RRB & RB	-2.65	-6.28	-8.84	7.46
YM & YMM	-5.94	-5.00	-7.76	7.46
MG & MGG	-2.35	-5.43	-8.52	7.42
YGG & GYY	6.76	3.16	-7.83	7.40
MC & CCM	1.10	-5.49	-10.16	7.36

YCC & CY	5.03	15.55	1.74	7.36
BBR & BRB	2.72	3.36	8.19	7.26
BR & BBR	-2.95	-13.89	-0.61	7.25
RRB & RBR	-3.63	-9.21	-6.97	7.22
-MY- & MYM	-6.20	-4.73	-6.35	7.19
-MG- & GMG	-2.30	-3.65	-9.06	7.17
YYC & YCY	-4.04	-3.02	11.53	7.17
CMM & CM	1.82	10.32	-4.33	7.16
GBB & BBG	-4.81	12.52	0.23	7.14
YB & BYB	-5.82	-9.86	0.68	7.06
CB & CBB	-1.73	-12.44	4.09	7.06
-CB- & CBB	-0.18	-16.91	2.40	7.04
BC & BCB	1.14	-19.28	1.05	7.02
BC & BBC	-2.45	-9.12	6.53	6.99
YYR & YRR	-5.60	-3.39	-8.18	6.98
MGM & MG	1.17	5.16	-7.03	6.95
MY & MMY	-5.29	-6.08	-7.75	6.95
YB & YYB	4.13	9.41	5.35	6.94
CG & GCG	-1.56	-2.58	-12.19	6.93
YMY & YMM	-6.25	-0.03	-5.31	6.93
YYM & YMY	-2.72	-3.33	-10.92	6.92
-BG- & GBG	-1.99	-6.09	-10.34	6.92
YRY & RRY	-5.48	-2.49	-8.04	6.86
MMB & MBM	-4.64	5.36	-8.82	6.80
-CR- & RCR	1.17	8.31	1.36	6.76
-CG- & GGC	-2.51	-9.33	-9.47	6.75
BG & GBG	-0.59	-7.28	-10.56	6.74
RBR & BRB	-1.47	-10.66	5.28	6.73
GR & GGR	-0.42	3.73	7.67	6.72
YCC & CYY	5.23	12.38	-1.91	6.67
BM & BMB	0.18	-16.44	0.49	6.62
MCM & CMC	-0.25	13.63	-2.53	6.58
MCM & MC	0.37	15.37	-1.31	6.58
YYG & YGY	-5.49	-5.77	9.80	6.56
BC & CBB	1.41	-18.70	0.45	6.55
YB & YBB	-5.92	-7.41	-2.46	6.54
RC & RCC	-3.17	6.86	-6.39	6.52
CM & MC	-1.74	2.85	8.45	6.52
-MB- & BMB	-1.34	-15.87	-0.34	6.49
BM & MBB	0.65	-15.45	2.88	6.48
RYR & YR	5.17	4.87	7.41	6.47
BMM & BBM	-2.60	0.61	-9.51	6.46
-CM- & MC	-1.01	-0.31	7.80	6.45
RYR & YYR	1.88	5.15	11.31	6.45
YYR & RY	-2.38	-2.41	-11.20	6.42
CMC & CCM	1.72	-3.79	-8.54	6.41
-BY- & YB	2.44	6.22	6.33	6.39
MCM & MMC	-0.83	8.10	7.51	6.30
MYR & MYM	-5.93	0.12	-3.91	6.29

GY & YYG	2.96	-1.80	-14.36	6.28
BGB & BBG	-4.23	11.39	0.82	6.25
MBM & BM	0.52	7.92	-9.06	6.20
-BY- & BYB	-3.37	-4.24	5.89	6.16
-MB- & MBB	-0.87	-14.86	2.02	6.15
RYR & RRY	-4.93	-2.48	-7.06	6.13
MB & BMB	-3.21	-12.03	-3.58	6.05
MBB & BBM	-4.19	7.33	-5.82	6.01
-MY- & YMM	-5.40	-4.60	-4.24	5.99
BRR & BRB	-0.73	-8.31	5.44	5.99
RY & RRY	-4.44	-5.22	-7.48	5.99
BBR & RBB	2.06	7.29	5.43	5.98
YYM & YM	-3.03	1.63	-9.02	5.97
-BR- & RBB	-1.98	-8.59	5.42	5.95
-CG- & GCG	-3.84	-4.51	-8.32	5.94
YGG & YGY	4.97	0.89	-7.89	5.94
GB & GBG	-4.38	0.79	-6.38	5.90
CCB & BCB	-2.01	-4.53	5.31	5.84
YRY & YRR	1.34	5.13	10.28	5.81
-MB- & MBM	-2.04	-7.31	8.04	5.76
BR & RBB	-0.89	-5.88	6.57	5.76
MBM & BMB	0.71	-9.06	-6.69	5.74
GC & GGC	-1.64	-5.08	-8.85	5.73
-CR- & CRR	0.99	5.84	3.06	5.71
-MB- & BBM	-5.06	-7.34	-4.90	5.70
RB & RBB	-3.11	-10.47	2.25	5.68
YRR & RRY	-1.21	-4.23	-10.24	5.67
CM & CMC	-2.36	1.14	6.81	5.66
MCM & MCC	-1.42	12.99	-0.82	5.64
YB & BYR	-1.36	-10.52	-0.88	5.61
-CM- & CMC	-1.63	-2.01	6.11	5.60
YR & YRR	-4.54	-4.99	-5.97	5.52
CB & BCC	-4.74	1.61	5.62	5.51
BCC & BCB	2.74	-14.66	-0.10	5.48
MYM & MY	5.35	1.60	2.34	5.47
CCY & YCC	0.49	0.04	-8.08	5.43
CCB & BCC	-4.75	10.09	6.39	5.43
-YG- & YYG	1.71	-4.78	-12.91	5.38
-BG- & BGG	-2.96	-5.72	-7.50	5.36
GYR & YYG	3.69	3.49	-10.17	5.36
GMM & MG	0.82	7.55	-3.21	5.35
-RY- & RYR	-4.99	-3.55	-3.91	5.32
BMM & BM	0.93	8.73	-6.63	5.29
BBM & BMB	3.72	-8.39	3.61	5.28
BY & BYB	-2.93	-0.47	5.45	5.27
-RG- & RGR	-0.27	5.91	-3.87	5.26
CCB & CBB	-1.75	-3.95	4.83	5.25
YCY & CY	-2.72	0.53	8.44	5.25
MYR & YMM	-5.13	0.25	-1.87	5.22

CCY & CYC	0.00	-5.38	-6.84	5.22
MMG & MGM	1.61	-9.35	-2.46	5.22
RYY & YR	0.81	6.74	9.16	5.18
CB & CBC	-3.81	1.11	5.65	5.18
-MG- & MG	-1.49	1.53	5.92	5.16
BCC & CBB	3.01	-14.08	-0.69	5.15
GB & BGG	-5.36	1.03	-3.68	5.14
GC & GCG	-2.98	-0.26	-7.73	5.13
CRR & CR	-0.38	-4.36	4.03	5.10
MB & MBB	-2.74	-10.96	-1.39	5.10
CBC & BCB	1.82	-14.15	-0.16	5.08
-CG- & CGG	-4.89	-6.67	-2.73	5.07
CRC & RCC	-3.22	5.86	-4.10	5.02
YR & RY	-1.31	-4.00	-9.01	5.02
-MB- & BMM	-2.45	-8.12	5.64	5.01
CCB & CBC	-3.83	9.58	6.41	5.01
BG & BGG	-1.56	-6.90	-7.70	5.00
CBB & BBC	-3.86	9.62	4.88	4.94
BR & RB	2.23	5.23	5.37	4.94
RBR & BR	-1.24	-1.87	-6.35	4.93
RMR & RMM	-2.73	-2.57	-7.49	4.87
RYR & RRY	-0.58	-4.35	-8.90	4.86
CRR & CCR	-0.93	-3.94	3.96	4.85
-MR- & MRM	-4.26	-6.15	-4.06	4.85
YBY & YBB	-5.56	0.82	-1.46	4.85
MRM & RMR	2.79	3.21	7.26	4.83
YBY & BYB	-5.45	-1.85	1.25	4.81
GM & GMG	-3.33	0.75	-5.11	4.81
-MR- & RMM	-4.19	-5.52	-4.28	4.80
YRY & RYR	-4.90	1.86	0.78	4.79
BCB & BBC	-3.60	10.20	4.29	4.73
CBC & CBB	2.08	-13.57	-0.74	4.73
BMM & BMB	1.12	-8.17	-4.80	4.73
BM & BBM	-3.53	-7.94	-3.97	4.72
CRR & RCR	0.18	2.46	-4.70	4.71
RRM & RMM	-2.33	-5.72	-7.21	4.67
BCC & BBC	-0.86	-4.49	4.99	4.67
-BY- & BYY	1.08	-4.86	4.38	4.66
RRM & MRM	-2.40	-6.36	-6.98	4.65
CBC & BBC	-1.78	-3.98	4.90	4.65
GMG & MGG	-1.53	-0.20	5.76	4.65
CMM & MC	0.08	13.27	2.86	4.62
YRY & YR	0.27	6.73	8.12	4.61
YG & YGY	-4.15	-10.70	1.14	4.61
RGR & GRR	-0.25	-3.01	4.63	4.58
-BY- & YBY	2.08	-2.33	4.80	4.57
BC & CCB	3.16	-14.71	-5.45	4.56
CG & CGG	-2.61	-4.75	-6.64	4.56
CY & YC	1.91	0.88	-7.70	4.56

GR & GRR	-1.05	0.47	-4.93	4.54
MY & YMM	-4.55	-1.47	-0.27	4.54
YM & MY	-1.38	-3.53	-7.57	4.53
MBM & MBB	1.17	-7.93	-4.65	4.52
MB & BM	-3.39	4.69	-5.14	4.49
-RY- & YRR	-4.36	-3.67	-2.49	4.48
CGG & GGC	2.38	-2.64	-6.34	4.46
BY & YBY	2.52	1.45	4.47	4.44
-RG- & GR	0.53	2.40	4.43	4.41
-YG- & YGY	-3.78	-10.55	-2.27	4.38
RYY & RYR	-4.36	1.87	1.79	4.37
BG & GB	3.79	-7.82	-3.73	4.36
YBB & BYY	4.56	-3.28	1.25	4.35
YMM & MMY	-0.74	-4.61	-7.41	4.34
MRR & RMM	-2.62	-1.25	-6.48	4.33
BRR & BR	-0.50	0.81	-5.69	4.30
YRY & YRR	-4.27	1.74	2.15	4.30
MRR & MRM	-2.69	-1.89	-6.25	4.28
MRM & MR	3.89	3.97	3.54	4.28
-MR- & MMR	-3.44	-9.45	-2.39	4.25
RMM & MR	3.83	3.33	3.76	4.24
CMM & MCC	-1.71	10.91	3.26	4.20
-CB- & BCC	-3.19	-2.84	3.67	4.20
YB & YBY	-0.36	-8.11	-0.78	4.15
CMM & CMC	-0.55	11.55	1.52	4.15
-BY- & YBB	-3.48	-1.50	3.36	4.10
MBM & MB	3.91	3.23	-3.93	4.10
MRM & RM	3.35	7.54	3.36	4.07
-MG- & MGG	-3.84	-3.77	-2.93	4.03
RRM & MMR	-1.58	-9.66	-5.23	4.02
YG & YYG	1.34	-4.94	-9.37	4.01
RMM & RM	3.29	6.90	3.58	4.01
RYY & YRR	-3.72	1.75	3.16	4.01
-CY- & YCY	1.71	-4.26	-6.35	3.99
-CB- & CBC	-2.26	-3.35	3.72	3.98
RMR & MMR	-1.98	-6.51	-5.55	3.96
-CR- & CCR	0.07	1.90	3.65	3.94
BMM & MB	4.32	4.07	-1.68	3.93
RBR & RBB	-2.13	-7.28	1.02	3.90
BYY & BYB	-4.45	0.55	1.29	3.89
BY & YBB	-3.04	2.32	3.16	3.88
RYR & RY	3.86	0.87	-1.52	3.86
GC & CGG	-4.03	-2.44	-2.41	3.85
GM & MGG	-4.87	0.54	0.58	3.80
BY & BYY	1.52	-1.04	4.07	3.77
-BR- & RBR	0.15	-0.96	4.99	3.76
-CR- & CR	0.61	1.48	3.54	3.73
MMR & RM	2.54	10.84	1.70	3.71
-BR- & BRR	-0.60	-3.62	4.35	3.69

CB & BC	-3.14	6.24	4.52	3.69
RBB & BRB	0.66	-3.62	3.85	3.68
BMM & MBB	1.58	-7.03	-2.74	3.66
MMR & MR	3.08	7.27	1.91	3.62
MYY & YM	0.80	5.25	5.80	3.61
RY & YRR	-3.23	-0.99	2.92	3.51
-BG- & GB	2.39	-6.66	-3.56	3.47
-MG- & GM	1.03	-4.31	-3.51	3.37
MRR & MMR	-1.87	-5.19	-4.58	3.37
MCM & CMM	0.29	1.89	-3.54	3.37
GY & YGY	-2.53	-7.57	-3.87	3.37
-CB- & CCB	1.56	-12.93	-3.29	3.36
YMY & MY	-1.69	1.44	-5.10	3.35
-RY- & YR	1.25	-0.28	5.82	3.34
-RY- & RYY	-0.63	-5.42	-5.70	3.32
-MB- & MB	1.87	-4.07	4.11	3.28
GCG & CGG	-1.05	-2.18	5.11	3.22
MYM & MMY	0.06	-4.48	-5.44	3.22
CYY & YCY	2.52	2.62	-3.73	3.20
-CY- & YC	0.90	-2.85	-5.54	3.20
-BR- & RB	1.13	2.32	3.87	3.17
-RY- & RY	-1.13	-2.69	-5.49	3.15
-CG- & CG	-2.28	-1.91	4.29	3.08
GMM & MGM	-0.35	2.65	3.04	2.99
BRR & RB	1.73	5.73	-0.85	2.98
YG & GYY	-2.36	-8.43	1.37	2.96
GCC & CCG	-1.19	5.05	4.05	2.93
-YG- & GYY	-1.99	-8.28	-2.10	2.77
-RY- & YRY	-0.09	-5.41	-4.67	2.77
BRR & RBB	-1.39	-4.81	1.35	2.76
CYY & CY	-0.20	3.16	4.43	2.73
YBB & BYB	0.11	-2.69	2.66	2.72
CG & GC	1.41	-2.31	-4.29	2.71
-CY- & CYY	-0.81	-6.89	-2.25	2.71
GY & YG	1.62	3.14	-5.37	2.65
CYY & YC	1.71	4.03	-2.95	2.62
RMR & RM	0.56	4.33	-4.22	2.55
-MY- & MY	-0.85	-3.12	-4.01	2.50
BC & BCC	-1.60	-4.63	1.38	2.47
-MR- & RMR	-1.47	-2.94	3.44	2.45
GCC & CGC	-0.24	0.82	4.36	2.45
-MR- & RRM	-1.86	0.21	3.05	2.44
RRM & MR	1.49	-2.39	-3.48	2.43
BC & CBC	-0.67	-5.14	1.44	2.40
YCC & CYC	-0.49	-5.32	0.54	2.37
GGY & YGG	0.72	4.68	-4.29	2.37
RMR & MR	1.10	0.76	-3.85	2.36
GCG & GGC	1.33	-4.84	-1.58	2.31
CB & CCB	0.02	-8.47	-1.27	2.28

MRR & RM	0.67	5.65	-3.19	2.28
-MR- & MRR	-1.57	-4.26	2.42	2.26
RRM & RM	0.95	1.18	-3.85	2.26
MYY & YMY	1.11	0.29	3.42	2.24
-BY- & BY	-0.45	-3.93	-0.09	2.16
-MY- & YM	0.53	0.40	3.63	2.10
GY & GYY	-0.74	-5.29	-3.73	2.07
GBG & BGG	-0.98	0.27	2.76	2.05
-CY- & CY	-1.01	-3.73	2.46	2.03
-RG- & GRR	-0.53	2.87	0.15	2.03
-CB- & BC	-1.59	1.78	2.42	2.03
MRR & MR	1.20	2.08	-2.85	2.01
-BR- & BR	-1.09	-2.99	-1.64	1.99
CMC & MCC	-1.17	-0.68	2.05	1.96
-RY- & YR	0.18	1.31	3.54	1.92
RBR & RB	0.98	3.16	-1.35	1.90
CCG & CGC	0.95	-4.20	0.55	1.87
GYG & YGG	1.27	2.30	-2.66	1.82
YMY & YM	-0.31	4.97	2.26	1.80
-MY- & MY	-0.27	-4.85	-2.30	1.78
GYG & YGY	-1.79	-2.27	-0.20	1.78
-CB- & CB	1.55	-4.46	-2.17	1.77
MC & MCC	-1.79	-2.39	0.57	1.74
RC & CRC	0.05	1.00	-2.07	1.73
YYR & YR	-1.07	1.59	-2.34	1.63
-CG- & GC	-0.86	-4.23	-0.21	1.63
YBY & BYY	-1.00	-2.43	-0.13	1.62
-CM- & CCM	0.09	-5.77	-2.93	1.61
-MY- & YMY	0.84	-4.56	1.25	1.57
MMR & RMM	-0.75	3.93	-1.69	1.53
-YG- & GY	-1.25	-2.98	1.77	1.49
-YG- & YG	0.37	0.15	-3.68	1.45
MBB & BMB	-0.47	-1.24	-1.91	1.44
MRM & MMR	0.82	-3.30	1.50	1.40
-MB- & BM	-1.52	0.61	-1.06	1.39
MYM & YMM	0.80	0.13	2.04	1.37
BMM & MBM	0.41	0.86	2.10	1.34
BRR & RBR	0.74	2.54	0.42	1.34
YRY & RY	-1.04	2.73	-0.72	1.21
MC & CMC	-0.62	-1.71	-1.53	1.20
CM & CCM	-0.65	-2.63	-1.94	1.18
-BG- & BG	-1.40	1.16	0.15	1.18
MYY & MY	-0.58	1.73	-1.62	1.16
MRR & RRM	-0.29	4.47	0.53	1.14
GYG & GGY	0.55	-2.38	1.65	1.11
-MR- & RM	-0.91	1.39	-0.77	1.03
RM & MR	0.54	-3.57	0.28	1.00
RGG & GRG	0.23	-0.51	-0.92	1.00
YCY & YC	-0.81	1.41	0.87	1.00

RYR & YRR	0.63	-0.12	1.39	0.98
-CM- & CM	0.73	-3.14	-0.95	0.96
BGB & GBB	0.58	-1.08	0.49	0.91
RRM & RMR	0.39	-3.15	0.46	0.88
RYY & RY	-0.50	2.74	0.30	0.79
YRY & RYY	-0.54	-0.01	-1.00	0.74

BCC & CBC	0.92	-0.51	0.06	0.72
-MR- & MR	-0.37	-2.18	-0.48	0.68
MRR & RMR	0.11	1.32	0.96	0.63
CR & CCR	-0.55	0.42	-0.24	0.60
BCB & CBB	0.27	0.58	-0.49	0.59
MRM & RMM	0.07	0.63	-0.19	0.20

Page Two				
	dL'	dC'	dH'	dE2000
MYC & CYM	0.66	3.86	28.06	24.78
MYC & YCM	1.27	2.32	26.02	23.20
MYC & CMY	-0.24	-0.19	25.52	22.07
GRB & BRG	-7.93	-2.11	-24.69	21.89
-CMY- & MYC	0.89	1.89	-23.29	20.89
YGM & MYG	-4.83	-16.98	-18.89	20.22
GYM & MYG	-4.63	-16.79	-18.95	20.19
GYR & RYG	-2.76	0.40	-22.43	19.64
RYC & CYR	-0.05	-5.01	21.90	19.62
YRC & CRY	-2.65	-14.99	20.39	19.56
YGR & RYG	-4.11	-2.28	-22.31	19.55
RGC & GCR	4.10	-1.24	20.71	19.23
YRG & GYR	1.36	-2.93	22.03	19.11
YMC & CYM	0.44	9.49	20.12	18.87
RYC & CRY	-1.55	-12.18	19.55	18.77
YRG & YGR	2.71	-0.19	21.66	18.65
RBG & GRB	6.69	5.96	20.10	18.60
YRC & CYR	-1.15	-7.80	20.55	18.54
RYC & YCR	0.97	-3.62	20.79	18.44
MCY & MYC	0.06	5.58	-19.48	17.77
RGC & CGR	3.82	-3.20	18.70	17.64
RBC & CRB	4.85	-7.56	19.12	17.52
YCM & YMC	-1.04	-7.93	-18.38	17.39
BRC & CRB	5.29	-6.66	18.82	17.29
YRG & GRY	-0.27	-14.76	16.10	17.18
YMC & CMY	-0.47	5.43	19.03	17.01
RGB & BRG	-6.14	2.16	-19.09	16.97
GMR & MRG	-3.47	15.09	-16.49	16.94
GCR & GRC	-1.57	0.71	-18.45	16.92
YCR & YRC	0.13	6.37	-18.93	16.91
-MYG- & MYG	-3.63	-10.37	-16.39	16.79
MRC & CMR	-0.02	-26.09	4.82	16.44
GRY & RYG	-1.13	12.08	-15.85	16.44
YRB & BRY	-6.29	-16.83	-17.40	15.94
-CRY- & RYC	0.47	9.28	-16.40	15.86
GBR & BRG	-4.38	9.69	-15.60	15.86
RMC & CMR	2.40	-23.94	5.40	15.85
GRC & CGR	1.29	-2.67	16.80	15.61
-CMY- & YMC	1.11	-3.75	-16.82	15.48

RMG & GMR	3.40	-13.08	14.83	15.38
-CRY- & YRC	1.57	12.03	-15.07	15.32
GMY & MYG	-2.63	-7.17	-15.56	15.31
GCR & CRG	-5.34	-1.77	17.79	15.26
-RYG- & RYG	-3.14	2.81	-17.13	15.25
RCY & YRC	1.49	17.93	-9.90	14.87
-RYG- & YRG	-1.75	5.33	-16.42	14.61
YBC & CBY	0.56	13.06	12.78	14.55
MGC & GCM	3.11	-4.33	-18.26	14.49
-CRG- & RGC	-2.40	6.38	14.80	14.27
RBC & CBR	1.39	-18.82	5.95	14.16
BRG & BGR	4.25	-9.84	13.50	14.13
MRG & MGR	3.67	-13.58	13.70	14.13
RCY & RYC	0.39	15.15	-10.37	14.10
YBC & CYB	4.49	14.16	10.14	14.01
RBG & RGB	4.89	1.82	15.24	13.91
CRG & CGR	5.06	-0.17	-15.88	13.86
RBV & YRB	4.88	16.07	14.81	13.86
MCR & MRC	-0.40	22.35	-5.62	13.84
MGC & CGM	2.74	-2.08	-16.69	13.74
BRC & CBR	1.83	-17.86	5.82	13.71
YCB & YBC	-3.53	-13.85	-10.07	13.68
-CRG- & GRC	0.13	5.85	-14.08	13.66
MCR & RMC	-2.82	20.24	-7.10	13.63
-CMG- & MGC	-2.65	-2.36	14.80	13.44
RCG & GCR	5.13	4.48	-14.69	13.42
RYB & BRY	-5.45	-13.08	-14.69	13.35
YMG & GYM	2.52	15.40	11.29	13.31
BYC & CYB	5.44	16.13	5.37	13.29
YMG & YGM	2.73	15.58	11.08	13.29
BCY & YBC	-0.85	-10.82	-11.80	13.22
MCY & YMC	0.29	-0.06	-14.47	13.08
MRC & CRM	-1.79	-22.25	1.09	13.04
GRM & MRG	-2.08	13.63	-12.36	13.00
BCR & RBC	-1.66	17.39	-5.80	12.91
BYC & YCB	4.48	15.82	5.33	12.90
CBY & CYB	3.93	1.32	-15.96	12.77
RBG & GBR	3.13	-5.61	12.80	12.69
-CBY- & YBC	-0.47	-10.11	-11.17	12.63
GYB & BYG	-7.01	-14.50	10.04	12.61
MYB & BMY	-4.87	-12.73	-13.65	12.56

RMG & MGR	3.60	-11.57	11.96	12.55
BYC & CBY	1.51	15.03	6.72	12.55
BCR & BRC	-2.11	16.43	-5.74	12.49
YCB & CBY	-2.97	-1.00	15.75	12.47
GCM & GMC	-1.88	1.59	15.40	12.43
YMB & BMY	-4.39	-12.94	-13.58	12.43
RCB & RBC	-2.55	9.18	-12.79	12.36
RMC & CRM	0.64	-20.12	2.85	12.25
YGB & BYG	-6.58	-15.15	9.08	12.24
BRC & RCB	3.00	-8.26	12.66	12.14
RCG & CGR	4.85	2.53	-13.12	12.04
GYB & BGY	-4.71	-8.85	14.06	11.89
BCY & CYB	3.64	3.48	-14.25	11.72
GMC & CGM	1.51	0.57	-13.78	11.68
-CMG- & GMC	-1.41	-4.88	11.76	11.44
GBY & GYB	3.88	6.58	-14.62	11.42
RMG & GRM	2.00	-11.62	10.65	11.42
BCY & YCB	2.68	3.16	-14.06	11.41
MBY & MYB	3.83	10.71	12.91	11.40
RBV & RYB	4.05	12.34	12.16	11.29
BCY & BYC	-1.80	-12.79	-6.20	11.29
MBY & YMB	3.34	10.91	12.84	11.27
YGB & BGY	-4.29	-9.44	12.88	11.17
RBG & BGR	3.01	-5.75	10.88	11.02
GMB & BMG	-6.49	17.41	-2.05	11.00
MGB & BMG	-6.48	16.12	-4.78	10.89
YRG & RGY	0.04	-14.07	7.20	10.86
YCR & CRY	-2.52	-8.24	10.74	10.84
-CMR- & MRC	1.10	19.18	-0.26	10.81
-CBY- & BYC	-1.42	-12.08	-5.88	10.78
MRB & BRM	-6.50	-6.68	-12.05	10.76
-CRG- & CRG	-3.65	3.34	11.56	10.75
-MYG- & YMG	-1.52	-9.10	-10.23	10.63
YGB & GYB	-3.45	-7.15	13.34	10.59
-BRG- & GRB	3.94	10.21	8.45	10.58
YBG & GYB	5.50	12.68	-8.51	10.54
YMG & GMY	0.52	5.94	11.37	10.50
MYG & MGY	2.01	1.00	10.91	10.48
MRB & RBM	-6.00	-4.19	-12.25	10.41
YGM & MGY	-2.83	-15.98	3.52	10.38
RYG & RGY	1.44	-11.41	7.92	10.31
YGR & RGY	-2.67	-12.95	-6.50	10.31
-CBR- & CRB	3.74	5.76	9.70	10.27
-BRG- & BRG	-4.00	8.55	-9.43	10.26
-BMG- & MGB	3.85	-14.58	6.26	10.23
GYM & MGY	-2.63	-15.79	3.23	10.20
YBG & YGB	5.07	13.31	-7.39	10.12
-CMR- & RMC	-1.32	17.07	-2.54	10.08
-BMG- & GMB	3.86	-15.87	3.52	10.03

GRC & CRG	-3.77	-2.49	-11.27	9.92
YGR & GRY	-2.98	-13.62	4.51	9.81
MBG & GMB	5.46	-15.06	2.10	9.73
-MGR- & MRG	-2.65	12.00	-8.34	9.70
MBG & MGB	5.45	-13.74	4.73	9.64
-CBY- & CYB	4.02	4.18	-11.23	9.62
MCG & GCM	3.81	-4.59	-12.74	9.58
GYR & RGY	-1.32	-10.53	-7.11	9.49
CBR & CRB	3.46	10.81	-2.57	9.26
-CBY- & YCB	3.06	3.86	-11.07	9.25
-BRY- & YRB	3.23	7.46	11.06	9.25
CRY & CYR	1.50	6.98	-8.92	9.15
MRC & RCM	-2.08	-16.29	-1.67	9.10
-CRG- & RCG	-3.43	0.64	9.63	9.04
MRB & BMR	-4.71	-10.20	-8.76	8.90
-CBR- & RBC	-1.11	13.70	-1.12	8.88
MYB & BYM	-5.48	-8.68	-8.49	8.86
RCG & GRC	3.56	5.20	8.75	8.78
YBR & BRY	-2.22	-5.64	-10.75	8.76
YRB & BYR	-5.23	-12.69	-6.82	8.67
YMB & BYM	-4.99	-8.88	-8.40	8.64
-BYG- & GYB	2.86	4.74	-11.27	8.60
MCG & CGM	3.44	-2.44	-10.98	8.56
-CBR- & BRC	-1.56	12.75	-1.24	8.44
RGM & MRG	-1.26	11.23	-7.03	8.43
RCY & YCR	1.36	11.19	-1.40	8.34
RCM & CMR	2.05	-9.60	3.33	8.32
RGM & GMR	2.21	-3.97	8.32	8.28
BGC & GCB	4.76	-10.31	-11.01	8.25
RCB & CBR	-1.16	-9.39	3.19	8.23
-CBM- & MCB	3.72	-16.51	2.14	8.20
GRB & BGR	-3.68	-11.44	-1.29	8.20
GCB & GBC	-3.68	8.43	10.88	8.17
-MGR- & RMG	-2.58	9.96	-6.64	8.15
GBR & GRB	3.56	11.29	-1.89	8.15
MGB & BGM	-4.44	8.75	-6.00	8.15
MYB & YBM	-4.53	-6.28	-8.68	8.13
YCM & CMY	-1.51	-2.51	9.57	8.12
-RYG- & GRY	-2.01	-8.82	5.86	8.11
MBR & MRB	3.95	8.12	8.66	8.11
MCY & YCM	1.33	7.89	-7.10	8.06
-CMG- & MCG	-3.34	-1.81	8.79	8.04
MGB & GBM	-4.18	7.93	-6.37	8.04
-BMY- & MYB	3.49	5.55	9.27	8.03
BGC & CGB	5.84	-9.69	-9.90	8.03
GRY & GYR	1.62	11.18	-3.29	8.03
RCM & RMC	-0.35	14.19	-1.08	7.96
MGC & CMG	-0.16	2.80	-8.16	7.92
YBM & YMB	4.04	6.48	8.58	7.91

BCR & CRB	3.19	9.41	1.96	7.88
-BMY- & YMB	3.00	5.75	9.17	7.85
MCY & CYM	0.72	9.46	-5.70	7.83
GBC & CGB	4.75	-7.82	-9.78	7.82
-BMR- & MRB	3.50	3.06	9.61	7.81
GCM & CMG	-3.27	6.81	11.10	7.78
MCB & CBM	-4.17	11.70	-4.07	7.77
GMB & BGM	-4.45	10.12	-3.53	7.74
-CRY- & CRY	-1.08	-2.77	8.38	7.69
-BYG- & YGB	2.43	5.27	-9.83	7.65
YGM & GMY	-2.21	-9.86	6.54	7.65
-CBG- & GBC	-1.37	-4.31	7.35	7.64
RMB & BRM	-4.43	-5.50	-8.62	7.62
BMC & CMB	5.74	-14.16	-5.15	7.61
-BRY- & BRY	-3.05	-9.89	-7.55	7.57
BMC & MCB	5.10	-15.50	-2.67	7.50
MBC & CMB	5.00	-13.17	-6.14	7.50
GBM & GMB	4.19	-9.29	3.92	7.48
RCY & CYR	0.34	9.94	-0.23	7.42
BRY & BYR	1.05	3.51	9.47	7.41
GMY & GYM	2.01	9.67	-6.13	7.35
-BYG- & BYG	-4.15	-10.38	2.08	7.30
-BRG- & RBG	-2.75	4.46	-7.09	7.29
-CBG- & BGC	-2.46	-2.43	7.53	7.27
MBC & CBM	0.18	-2.41	-9.34	7.22
RBM & RMB	3.93	2.94	8.67	7.17
YBR & YRB	4.06	10.71	5.82	7.15
MCB & MBC	-4.35	14.52	3.66	7.13
-CBM- & CMB	4.37	-15.20	-0.26	7.06
-MGR- & GMR	0.82	-3.18	7.21	7.03
RBY & YBR	0.82	4.98	8.41	6.87
CMY & CYM	0.90	4.06	-7.74	6.87
RMG & RGM	1.18	-9.19	5.33	6.87
YMG & MGY	-0.10	-0.19	7.61	6.81
-RYG- & RGY	-1.71	-8.18	-3.70	6.67
-BRY- & RYB	2.40	3.71	8.15	6.66
-MYG- & MGY	-1.62	-9.36	2.01	6.61
-CBR- & RCB	1.44	4.32	6.17	6.60
GYC & CYG	-4.53	-1.16	9.14	6.59
BCM & MCB	4.12	-10.03	3.08	6.59
BCG & CGB	6.46	-11.20	-5.89	6.59
CMG & CGM	2.91	-4.65	-9.26	6.54
CBM & CMB	4.82	-10.44	1.82	6.50
RGB & GBR	-1.76	-7.31	4.05	6.50
RGC & CRG	-1.24	-3.02	-7.20	6.46
-BRG- & RGB	2.14	6.18	4.97	6.45
YMG & MYG	-2.11	-1.19	-6.50	6.45
BCG & GCB	5.38	-11.80	-7.05	6.42
YRM & MRY	-1.45	-7.44	-11.06	6.42

GMC & CMG	-1.40	5.32	-5.24	6.39
CBG & CGB	5.96	-12.12	-5.87	6.38
BCR & RCB	0.89	7.99	-0.14	6.35
RYB & BYR	-4.40	-9.06	-4.30	6.31
BMC & CBM	0.93	-3.46	-8.23	6.30
GCB & CBG	-4.89	12.73	7.03	6.22
RCG & RGC	1.03	5.73	5.33	6.22
RMB & BMR	-2.64	-9.18	-5.56	6.21
-CMR- & CMR	1.08	-6.76	2.54	6.16
YMR & MRY	-1.17	-4.86	-10.83	6.14
MCR & RCM	-2.47	6.00	-4.19	6.13
YGC & CYG	-4.22	-4.37	8.16	6.12
BCM & MBC	-0.24	4.14	8.02	6.10
-CBM- & MBC	-0.63	-2.33	7.31	6.01
GYC & CGY	-2.54	-1.37	9.49	5.96
-BRG- & GBR	0.38	-1.16	6.08	5.83
GBY & BYG	-3.13	-8.43	-0.55	5.83
-CMG- & CMG	-2.81	0.42	6.98	5.74
GRY & RGY	0.30	0.62	-6.05	5.70
-BRY- & RBY	-1.65	-9.12	-4.97	5.70
RBY & BYR	-0.35	2.87	7.19	5.67
RGM & MGR	2.41	-2.46	5.61	5.63
GBC & CBG	-1.21	4.54	-4.68	5.58
RGB & BGR	-1.88	-7.45	1.24	5.57
-CYG- & CYG	-4.50	-10.88	2.78	5.56
-MRY- & MRY	-1.91	-7.08	-9.12	5.55
BCM & CMB	4.76	-8.78	0.85	5.54
YGC & CGY	-2.24	-4.59	8.53	5.51
-BMY- & BMY	-1.39	-7.88	-5.29	5.50
MCG & MGC	0.70	-0.48	6.07	5.48
-BYG- & YBG	-2.64	-8.50	-0.07	5.47
RMY & YRM	0.97	6.46	9.44	5.44
-CBR- & CBR	0.28	-5.08	3.15	5.42
YBM & BMY	-0.34	-7.00	-5.58	5.29
BCM & BMC	-0.98	5.18	6.92	5.28
MBR & RMB	1.88	7.01	5.34	5.27
BCG & GBC	1.71	-3.60	4.58	5.25
RMY & YMR	0.69	3.88	9.24	5.19
-CYG- & GYC	0.02	-9.69	-7.52	5.18
RGC & GRC	2.53	-0.53	5.66	5.13
-CBG- & CGB	3.38	-11.86	-3.44	5.10
MRY & MYR	0.52	3.84	9.08	5.07
GCY & GYC	1.68	-0.64	-8.48	5.07
-CBM- & BMC	-1.38	-1.27	6.10	5.04
-CRG- & GCR	1.70	5.13	-3.28	4.99
-CBG- & GCB	2.30	-12.47	-4.63	4.98
BGC & CBG	-0.13	2.65	-4.80	4.90
RCB & CRB	2.30	1.46	4.75	4.80
YBG & GBY	1.62	6.56	2.84	4.78

RYB & YBR	-3.23	-7.06	-3.26	4.76
-CRY- & RCY	0.08	-5.73	1.12	4.72
-CYG- & CGY	-2.52	-11.09	3.20	4.69
-BMR- & RMB	1.43	1.80	5.99	4.62
MYC & YMC	0.22	-5.63	2.85	4.62
RYM & MRY	-0.88	-5.54	-7.96	4.59
-MRY- & RMY	-1.44	-6.10	-7.49	4.54
GBM & BMG	-2.31	7.59	3.30	4.53
BCG & BGC	0.62	-1.71	4.69	4.52
RCY & CRY	-1.16	2.98	3.93	4.52
RGB & GRB	1.79	4.04	3.97	4.49
RCM & CRM	0.29	-5.84	1.39	4.49
RGM & GRM	0.82	-2.48	4.58	4.48
YGC & GCY	-1.38	-2.57	7.44	4.46
-CMY- & YCM	2.15	4.20	-3.86	4.43
GMY & MGY	-0.62	-6.16	-0.87	4.42
BMY & BYM	-0.61	4.25	5.14	4.35
BYG & BGY	2.30	5.96	0.83	4.31
-MGR- & MGR	1.02	-1.67	4.45	4.26
-RYG- & GYR	-0.39	2.25	4.73	4.24
-CMY- & CMY	0.64	1.69	4.74	4.23
-BYG- & BGY	-1.86	-4.42	3.88	4.18
RYC & YRC	1.10	2.99	4.49	4.16
-CBR- & BCR	0.55	-3.67	2.81	4.16
RMY & MYR	0.05	2.86	7.49	4.15
YCG & GYC	2.39	-4.04	-5.87	4.12
-BMY- & MBY	-0.34	-5.63	-4.24	4.08
MCG & GMC	1.93	-3.07	3.26	4.07
MBY & YBM	-0.70	4.75	4.56	4.07
-CMY- & MCY	0.82	-3.69	3.45	4.06
-BRG- & BGR	0.26	-1.30	4.13	4.04
-CMY- & CYM	1.55	5.76	-1.81	4.03
-RYG- & YGR	0.97	4.69	3.41	4.01
-CYG- & YGC	-0.28	-6.49	-6.30	3.98
CMR & CRM	-1.76	3.76	-1.84	3.98
-MYG- & YGM	1.21	6.59	-1.77	3.95
BMG & BGM	2.04	-6.84	-2.65	3.94
-MYG- & GMY	-1.00	-3.22	4.17	3.93
GMR & GRM	-1.39	1.49	-3.87	3.91
-BRY- & BYR	-2.00	-5.75	3.05	3.82
-CMR- & MCR	1.50	-3.16	2.92	3.82
-CRY- & YCR	1.44	5.44	0.05	3.81
-MYG- & GYM	1.00	6.39	-1.33	3.72
MCY & CMY	-0.18	5.38	0.17	3.71
-BRY- & YBR	-0.83	-3.63	4.29	3.71
-BMR- & BMR	-1.21	-7.78	-0.29	3.63
RMY & RYM	0.41	4.56	6.34	3.63
MRC & RMC	-2.43	-2.10	-4.28	3.62
-CMG- & GCM	0.46	-6.37	-4.63	3.60

YBG & BGY	0.78	4.10	2.97	3.60
-BMR- & BRM	-3.00	-3.85	-2.93	3.59
RBM & BMR	1.29	-6.78	2.11	3.56
-CRG- & CGR	1.42	3.17	-2.60	3.56
MBG & GBM	1.27	-5.37	-3.04	3.55
-CYG- & GCY	-1.66	-9.08	1.87	3.49
MBY & BYM	-1.65	2.01	4.17	3.49
-CBG- & BCG	-3.08	-0.71	2.88	3.43
YCG & CYG	-2.13	-5.21	3.81	3.39
-MGR- & GRM	-0.58	-1.70	3.44	3.35
-CRY- & CYR	0.42	4.18	2.02	3.34
-CBY- & CBY	0.09	2.94	3.38	3.34
MCR & CMR	-0.42	-3.59	0.89	3.30
MRB & RMB	-2.07	-1.26	-3.63	3.27
MBR & RBM	-2.05	4.44	-2.63	3.18
YCG & YGC	2.09	-0.83	-4.68	3.17
-BYG- & GBY	-1.02	-1.98	3.69	3.12
-BMG- & GBM	-0.32	-6.32	-1.22	3.12
YCG & CGY	-0.15	-5.42	4.20	3.09
GMR & MGR	0.20	1.51	-3.03	3.03
RBG & BRG	-1.25	4.11	-1.63	3.01
MBR & BRM	-2.55	1.75	-2.80	2.96
-CBG- & CBG	-2.59	0.22	2.85	2.93
MBG & BGM	1.01	-4.60	-2.40	2.91
BMR & BRM	-1.79	4.09	-2.29	2.87
-CYG- & YCG	-2.37	-5.67	-1.35	2.87
-BMR- & RBM	-2.50	-1.16	-2.74	2.82
-BMG- & BGM	-0.59	-5.58	-0.55	2.76
-BMG- & BMG	-2.63	1.13	2.26	2.70
YRG & RYG	-1.40	-2.75	-2.26	2.63
RYB & YRB	0.83	3.68	2.70	2.59
GCY & CYG	-2.85	-1.80	0.86	2.58
MCG & CMG	0.53	2.23	-1.99	2.50
MCR & CRM	-2.18	0.17	-1.94	2.47
-BMR- & MBR	-0.45	-5.48	0.14	2.47
MGC & GMC	1.23	-2.73	-2.62	2.45
-CMR- & CRM	-0.68	-3.00	0.48	2.42
YCR & CYR	-1.02	-1.30	2.50	2.36
-CMR- & RCM	-0.97	2.84	-1.06	2.31
-BMY- & BYM	-1.99	-3.51	0.23	2.30
-BMG- & MBG	-1.60	-1.10	2.01	2.29
YCM & CYM	-0.61	1.53	2.64	2.27
-CBY- & BCY	0.39	0.71	2.60	2.26
YGR & GYR	-1.35	-2.50	1.67	2.23
YBG & BYG	-1.51	-1.85	1.62	2.21
-CBM- & BCM	-0.40	-6.39	-1.33	2.19
YCG & GCY	0.71	-3.41	2.98	2.16
RCG & CRG	-0.21	2.70	-0.52	2.12
RBV & BRY	-1.40	-0.65	-2.28	2.04

-CMG- & CGM	0.10	-4.23	-2.60	2.02
-CBM- & CBM	-0.45	-4.68	-2.53	1.98
MCB & CMB	0.65	1.10	-2.06	1.97
BYC & YBC	0.95	1.96	0.02	1.96
BCR & CBR	-0.27	-1.40	1.38	1.91
RYM & YRM	0.57	1.91	3.12	1.84
GBR & BGR	-0.12	-0.15	-1.86	1.77
RMG & MRG	-0.08	2.04	-1.97	1.74
CYG & CGY	1.98	-0.21	0.38	1.71
MGB & GMB	0.01	-1.44	-1.60	1.70
RYM & YMR	0.28	-0.67	3.03	1.69
MBY & BMY	-1.05	-2.29	-1.13	1.63
GBY & BGY	-0.84	-2.46	0.43	1.61
GCM & CGM	-0.37	2.12	2.03	1.60
YRM & MYR	-0.93	-3.60	-1.80	1.59
-MRY- & MYR	-1.39	-3.24	0.17	1.58
YBR & BYR	-1.17	-2.00	-1.05	1.56
-MGR- & RGM	-1.39	0.78	-1.13	1.54
GRM & MGR	1.60	0.02	0.94	1.51
GCR & CGR	-0.28	-1.95	0.51	1.47
YBM & BYM	-0.95	-2.67	-0.18	1.47
BCY & CBY	-0.30	2.23	0.59	1.45
-MRY- & YMR	-0.75	-2.22	1.94	1.40
BCM & CBM	-0.05	1.70	-1.08	1.39
YGC & GYC	0.30	-3.20	-1.36	1.37
MBG & BMG	-1.03	2.27	0.19	1.30
RBM & BRM	-0.50	-2.75	-0.31	1.30
YGB & GYB	0.43	-0.39	-1.75	1.29
GCY & CGY	-0.87	-2.02	1.24	1.28
MBR & BMR	-0.76	-2.28	-0.39	1.25
-MRY- & RYM	-1.03	-1.55	-1.13	1.25
BMC & MBC	0.74	-1.07	1.28	1.23
GCB & CGB	1.07	0.57	1.11	1.19
-MRY- & YRM	-0.47	0.36	2.02	1.19
YMR & MYR	-0.64	-1.02	-1.73	1.18
BGC & GBC	1.09	-1.91	-0.01	1.17
RMY & MRY	-0.48	-0.98	-1.62	1.02
-BMY- & YBM	-1.04	-0.83	0.43	0.98
RYM & MYR	-0.36	-1.69	1.27	0.88
YCB & CYB	0.96	0.31	-0.07	0.80
GBM & BGM	-0.26	0.77	0.63	0.67
YMR & YRM	0.28	2.58	0.04	0.67
BRC & RBC	0.44	0.94	0.29	0.65
BCG & CBG	0.49	0.93	-0.06	0.56
MYB & YMB	-0.48	0.18	-0.13	0.43
YGM & GYM	-0.20	-0.22	0.51	0.41

D.2. Graphed Colour Reproduction Experimental Results

These graphs correspond to the colour reproduction experiments undertaken as part of my secondment to the National Gallery. The nineteen reference samples refer to the nineteen locations measured from the target painting, Michelangelo Merisi da Caravaggio's *The Supper at Emmaus* (Chapter 5, Figures 5.1 and 5.2). The following includes all research results described in Chapter 5.

