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The Development of Methodologies for Color Printing in Digital Inkjet Textile Printing and the Application of Color Knowledge in the *Ways of Making* Project

Becky Gooby

Becky Gooby is a 3D3 Research Doctoral Student at the Centre for Fine Print Research (CFPR), University of the West of England (UWE). Her research interests include digital textile printing, practice-as-research, color management, digital color and interwar design history. This work was supported by 3D3 Centre for Doctoral Training, funded by the Arts and Humanities Research Council (AHRC). becky@beckygooby.co.uk

ABSTRACT Digital textile printing (DTP) offers creative potential and entrepreneurial business models in textile design. Designers are no longer restricted to a number of colors or pattern repeat. It has become possible to print fabric without large set-up costs. This relatively sustainable technology reduces water-usage and dye-wastage. DTP meets Just in Time, Concept to Consumer demand, reducing stock wastage. However, there is a marked difference between screen-color to print-color and software allows a user to select colors unprintable using CMYK (cyan, magenta, yellow, black) colorants. Color results are further affected by factors such as structure and composition of the fabric, dye type, printer

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communications, fabric pre-treatments and secondary processes. A textile designer will be required to understand and experiment with a number of variables in order to feel color-confident. This paper presents investigations which focused on developing methods to aid a designer's color expectation knowledge, using a Practice-as-Research methodology. Outcomes include a color reference book, digital lap dip tests presented as color maps, and a set of indicator ICC profiles, generated from data accumulated through measuring printed color differences on a variety of substrates. These visual prompts are intended to support designers to build their own internal color look-up table enabling them to predict and resolve color issues during the design process. Finally, the paper concludes by presenting a Case Study detailing an application of these color methods by the researcher for the *Ways of Making* project, a collaboration between Sir Peter Blake, Worton Hall Studios and Centre for Fine Print Research (CFPR) at University of West of England (UWE). Here, the indicator profiles were applied to Blake's images, altering the color data to create experimental color modifications and printed onto silk. An initial selection of works from the project were exhibited at London Original Print Fair, Royal Academy, April 2019.

KEYWORDS: Digital textile printing, color, sustainability, digital color, digital economy, art and design

Introduction

The development of digital printing is a major change within the textile design process as a designer is no longer restricted to number of colors or repeat patterns and may include photographic images and intricate detail in their design work (Tyler 2005). It has become possible to print a meter, or hundreds of meters, at the click of a button, without large set up costs, leading to new entrepreneurial business models in the textile industry (Ujiie 2006). Digital textile printing (DTP) provides unprecedented opportunity for designers to offer bespoke and customization of designs (Polston et al. 2015). Just in Time and Concept to Consumer production models (King 2006, ASBCI 2014) benefit from short print runs and expedited strike-offs, product sampling and testing made possible by DTP (Dawson 2006).

Reduced ink wastage and water use makes DTP a more environmentally sustainable printing method (Dawson 2010). Digital Print Bureaus (DPBs) are likely to be located in an urban environment, local to their customers, with reduced transport costs, and occupying less space than a traditional textile mill or factory. Short print runs and the ability to react quickly to market trends allow businesses to carry less stock, reducing storage costs, and the likelihood of stock wastage as fabric is printed to demand (Ujiie 2006). These changes offer exciting possibilities for designers and small and medium-sized enterprises (SMEs) working in the textile industry.

There are however, concerns about color consistency and outcome. For example, there is a marked difference between screen-color and print-color. Software allows users to select colors unprintable using CMYK (cyan, magenta, yellow and black) colorants (Campbell and Xin 2006). The range of printing machines, and the methods that they use to apply and represent color, also impede the designer's understanding (Romano 2017). Fabric pre-treatment, secondary processes, and the printer's achievable gamut all affect final result (Hawkyard 2006). A user may choose from a variety of image-editing software and print via inkjet or dye sublimation processes, onto numerous fabrics. A textile designer will be required to experiment with a number of variables in order to feel color confident which may be time consuming, costly and imprecise (Campbell and Xin 2006).

The wider research project connected to this paper considers how designers can ensure color assurance when digitally printing on a range of fabrics through an exploration of existing color tools and methods. The aim is to establish a best practice guide for designers wishing to obtain a more acceptable print-color match. Thus, a number of variables have been tested to determine the impact on printed color outcome, using a Practice-as-Research methodology, where knowledge is acquired through doing, and developed upon critical reflection. Additionally, working with cloth is naturally a tangible experience and so research undertaken in this field requires visual and tactile signposting. The inquiry was therefore representational of studio practice and informed by Nelson's (2013) understanding of Practice-as-Research and follows the know-how, know-that, know-what model of praxis (Nelson and Arlander 2013) (Figure 1).

This paper presents investigations established through variable testing, which focused upon the development and generation of

Figure 1
Gooby, B. Personal mindmap using Nelson's Praxis model (researcher's own collection).

visual indicator methods to aid a designer's color expectation knowledge. Outcomes include a color reference book, digital lap dip tests presented as color maps, and a set of indicator ICC profiles, generated from data accumulated through measuring printed color differences on a variety of substrates. These visual prompts are intended to support designers to build their own internal color look-up table, enhancing their digital print-color knowledge, enabling them to predict and resolve color issues during the design process. ICC profiles are used by digital files to convert colour data between devices such as computer screen to printer. The profile translates colours, not found in both devices' colour spaces, to an alternative, dependent on the print environment.

Finally, the paper concludes by presenting a case study detailing an application of these color methods by the researcher for the *Ways of Making* project, a collaboration between Sir Peter Blake, Worton Hall Studios and CFPR, UWE. Here, the indicator ICC profiles were applied to Blake's visuals to alter color composition. The images were printed onto silk satin and form part of the *Ways of Making* project archive. Initially exhibited at The London Original Print Fair, Royal Academy, April 2019. *Ways of Making* is an ongoing project showcasing the breadth of materials and technology available with which artists may create.

Background

Digital textile inkjet printing is a non-surface-impact print process where colorants, primarily dyes, but increasingly pigment inks, are jetted in a dithered matrix of dots, onto specially treated fabric, to create the appearance of solid color (Carden 2015). The colorant sits on the surface although secondary processes allow dye molecules to further permeate the fibers (Freire 2006). Additionally, DTP may include dye sublimation, solvent, latex, ultra-violet and direct-to-garment printing, for example T-shirt printers.

Digital screen-color, a mix of red, green and blue light, has a broader color range to printed color, a mix of cyan, magenta, yellow and black (CMYK) pigment primaries (Feisner and Reed 2014). Whilst there are overlaps between the two color spaces there are many colors possible in one but not the other, thus out-of-gamut (Dawson 2010). A gamut represents the boundaries of the range of colors a device can reproduce determined by the colorants used and tonal information, i.e. the darkest producible black and the brightest white (Loser and Tobler 2010). Design software allows a user to select colors from the screen gamut, unprintable using CMYK colorants, leading to frustration and confusion when printed designs don't match expectations (Henry 2014).

Color matching problems are not limited to DTP; color assurance is also an issue in paper printing (Parraman et al. 2013). Yet as DTP is a more recent technology, color management software and technological solutions have been developed for reprographic and photographic printing industries and adapted for textile printing (Caccia and Nespeca 2006). Such methods aim to regulate color processes and enhance color data conversion. However, due to a greater number of variables not accommodated for, managing color results in DTP is more challenging and lacks standardization (Ding 2016).

DTP is primarily an outsourced process for designers and SMEs who lack finances and access to the space needed to operate their own print room. A standard industry wide-format digital inkjet textile printer will cost upwards of £150,000 and requires a controllable print environment. There are further costs associated with maintenance, operating software and substrate storage. Secondary processes such as steaming and washing impact final color results necessitating a powerful steamer and suitable washing and drying facilities (Hawkyard 2006). The colorants used for printing can cost as much as gold (Raymond 2006). Therefore, DTP is largely carried out by DPBs. This removal from the printing process impedes users' knowledge of the systems and challenges involved in achieving successful color results, hindering their ability to resolve color mismatches (Mckeegan 2017).

Digital color management structures do not yet accommodate for the chemistry of pre-and post-treatment processes, although there have been developments (Ding 2016). The characteristics of cloth substrates, and the pre-requisites of their end use, further compromise methods optimized for paper printing (Provost 2011). For example, the drop shape of the colorant emitted by an inkjet print head alters when it hits the fabric substrate, spreading differently to a smooth paper surface. Changes to the dot shape will affect the achievable color gamut as color is built up through a dithered matrix of dots. Additionally, colorant chemistry has been modified from traditional textile practices where binders and thickeners which enhance chemical activity are applied in a pre-treatment stage rather than included in dye paste (Kim 2006). This ensures better viscosity and drop flow, decreasing the likelihood of print head malfunctions but adding further variables to control.

Digital color education is inconsistent across undergraduate design curricula and understanding is lacking in the wider design community which hinders comprehension of digital print processes (Kelly 2014). Additionally, there is a gap between what a designer is led to believe is possible, and what is achievable (Henry 2014). This design mirage is created through a number of means. Firstly, software allows users to select unprintable colors, viewed on a luminous screen, able to display a broad range of saturated, bright colors through additive mixing (Henry 2014). Printed color does not convey the same intensity and brightness of color because it is subtractive color perceived by the absorption of light rather than reflected. This perception can mask the limitations of conversion from screen to print, which may lead to disappointment with the printed outcome (Burton 2005). Secondly communications between DPBs and designer are problematic partly due to financial barriers, commercial sensitivity and vocabulary misunderstandings. Designers are unable to ask the right questions because they are unsure of which questions to ask (McKeegan 2017).

Traditionally gaining industry experience has improved designers' comprehension of production processes, however opportunities have decreased with changes to the way design work is commissioned. The entrepreneurial potentials of DTP have led to more designers setting up their own businesses, but without the support of such experience (McKeegan 2017). DTP is accessible to designers from other disciplines without textile know-how leaving them unprepared to solve color issues related to textile chemistry and substrate characteristics (McKeegan 2017). Color is critical in the textile industry both in terms of meeting trends, client requirements and obtaining consistent color (Udale 2014). Achieving the correct colors and meeting seasonal trends can ensure a product's success (Cassidy and Tracy 2005).

Experimental

Color Reference Book

To evidence that there is a difference between screen-color and print-color, and further variations between substrates, a color chart was created, using the 1137 colors in the Pantone© solid uncoated color library in Adobe Photoshop Creative Cloud (APCC). The chart was printed onto four different substrates (wool, linen, cotton and silk) using a digital textile inkjet Mimaki TX2-1600 printer, with reactive dyes (cyan, magenta, yellow, black, light cyan, light magenta, red and blue). The fabric swatches were compiled in a color reference book alongside the corresponding color space numerical values, and a paper print, as the closest visual match to the screen-color (Figure 2). This provided a broad range of colors and data for comparison. The book demonstrated differences between screen-color and printed color, as well as between substrates, particularly in neutral ranges such as greys, blacks and browns, and colors from the blue and magenta tonal ranges.

Initial analysis revealed that 227 of the 1137 colors were considered out of the printable gamut of a generic CMYK printer by APCC's out-of-gamut warning tool. Of these 227 the majority were from the magenta tonal range (53 purple and 38 pink), whilst 46 were classified by the researcher as green, 27 red, 21 blue, 20 yellow, 20 orange and 2 brown. Some colors, flagged as unprintable, had a better color match than expected. For example, shades of warm reds and oranges were frequently flagged yet printed color was a close visual match. However other hues, such as neutral greys, were not flagged, yet differed greatly from the color seen on screen. This discovery highlights how color tools cause further confusion.

Figure 2
Gooby, B. Example page from color reference book (researcher's own collection).

The research envisages that the color reference book, as part of an online color toolkit, could be used to look up hues to get a sense of how they might print upon different substrates. Currently Pantone© offer color system swatches printed onto cotton, nylon and polyester but not silk, wool or linen (Pantone Color 2020). The swatches are dyed rather than printed. Several DPBs such as Spoonflower have a color chart that you can purchase with corresponding digital color data. Spoonflower allows users to upload designs to sell. A search of these shows several color charts recommended as designer reference tools with positive reviews, supporting the idea that this form of color tool is helpful and aids color expectation and assurance (Spoonflower 2017). The color reference book demonstrates that achromatic colors and hues with a high magenta or blue tone are problematic and will require careful color testing (Figure 3). Therefore, designers may wish to consider how they use these colors within a design.

Digital Lab Dip Tests – Color Maps

A series of indicator color maps were produced using mean averages of hue, saturation and brightness (HSB) value shifts for a set of colors. Data analysis (Table 1) indicated that in general printed color decreased in both saturation and brightness by 10–20% and shifted around the hue circle from 2 to 25 degrees from the screen-color. Digitized swatches were plotted onto the color maps to visualize printed color changes from the screen-color. The digitized swatches symbolize a digital lab dip test and illustrate how a color might be expected to print, depending on substrate. A lab dip is the term for a fabric sample used by the manufacturer to establish a color match with the buyer's supplied swatch or color standards (Best 2012).

Figure 3
Gooby, B. Further example pages demonstrating color discrepancies between blues (top left, bottom left), achromatics (top right), and better than expected matches for colors flagged as out-of-gamut (bottom right) (researcher's own collection).

Table 1 Median hue, saturation and brightness value shift by substrate

Substrate	Average hue shift	Average saturation shift	Average brightness shift
Wool	Reduced by 4 degrees	Reduced by 18.5 %	Reduced by 29 %
Linen	Increased by 3.5 degrees	Reduced by 26.5 %	Reduced by 24 %
Cotton	Increased by 3 degrees	Reduced by 30 %	Reduced by 20 %
Silk	Reduced by 4 degrees	Reduced by 25.5 %	Reduced by 24 %

The maps offer visual prompts to allow designers to build their own internal color look up table, enhancing their digital print-color knowledge and enabling them to predict and resolve color issues during the design process (Figure 4). The data was obtained through measuring a set of swatches from the color reference book. This set consisted of prints from the first 24 Pantone© colors representing a range of highly saturated, spectral hues (red to purple). These were measured using a Kodak-Minolta FD-7 spectrodensitometer which returns sophisticated color measurements using filters to measure the wavelengths reflected from the color sample. The spectrodensitometer was set up to measure the reflectance value under D65 illuminant conditions, the standard for measuring textiles, and return LAB and wavelength (nm) values from 380 to 730 nm (Society of

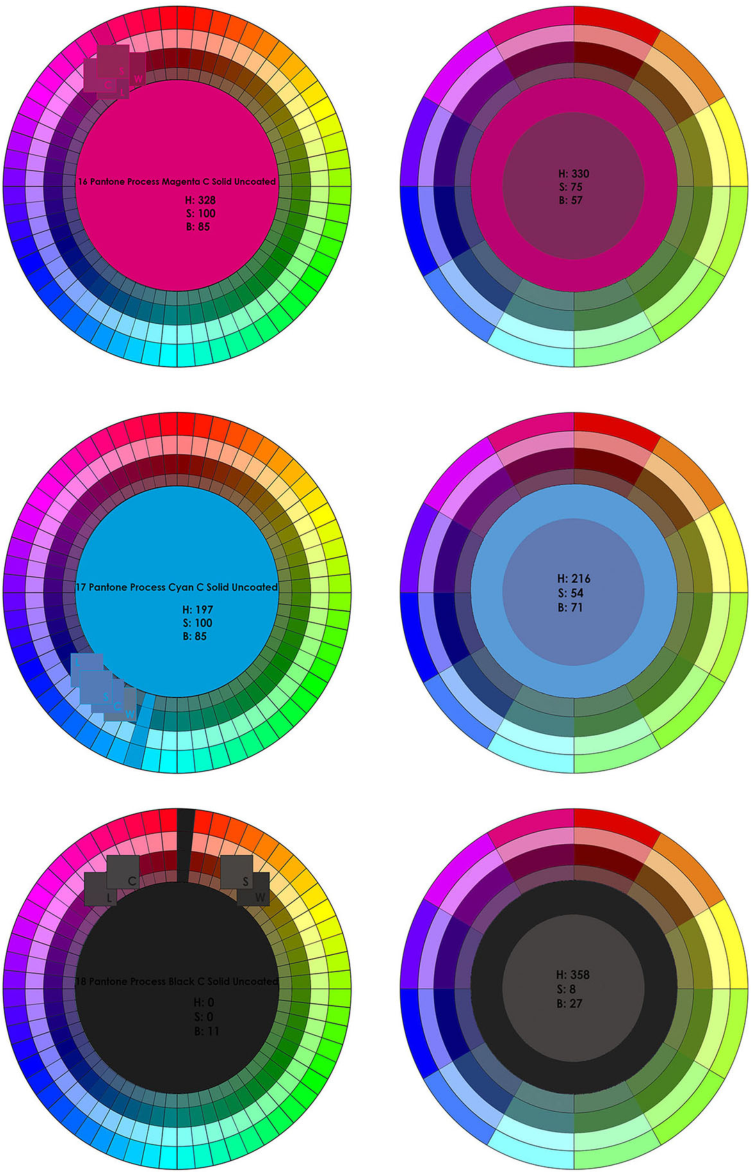

Figure 4

Gooby, B. Examples of color maps (left column) and complementary color maps with central indicator color (right column). The square swatches, labelled C, W, S and L, correspond to the fabric types cotton, wool, silk and linen (researcher's own collection).

Dyers and Colourists 2008). The LAB coordinates were entered into the color picker tool in APCC to display a digitized version of the printed swatch, representing a digital lab dip test. Finally, the corresponding HSB value was recorded so that the numerical data could be compared. The use of the HSB color model allowed simpler

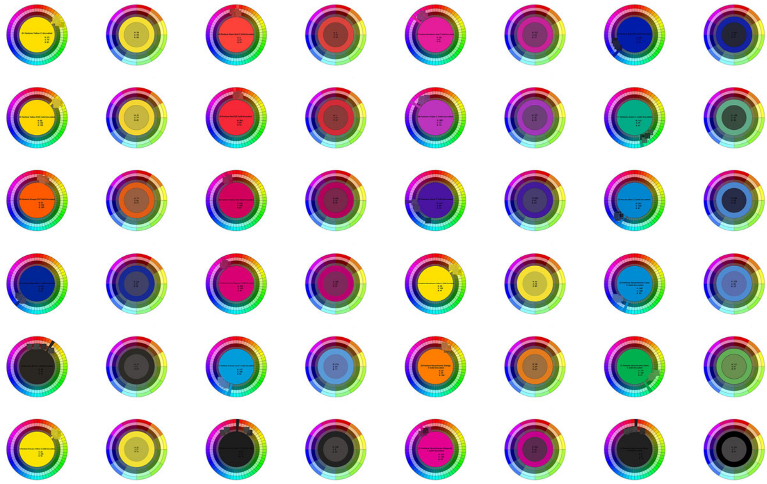

Figure 5
Gooby, B. Series of color maps (researcher's own collection).

average comparisons to be made which were more of a challenge to calculate using the LAB model.

Each map is a 360-degree hue color circle that has inner rings decreasing in saturation and brightness. The digitized swatches show a clear reduction in saturation and brightness, expected when printing on to fabric. Additionally, the swatches illustrate some discernible differences in hue. For example, results for Pantone© Violet were on average 8 degrees bluer than the screen-color and halved in saturation as well as decreasing in brightness. Color measurement of the prints of Pantone© Black and Pantone© Hexachrome Black demonstrated an increase in magenta undertones. Likewise, prints of Pantone© Hexachrome Cyan shifted twenty degrees clockwise towards magenta in the hue circle. Yellow, orange and red hues seemed less affected with minimal hue differences but large disparities between screen and print saturation and brightness. In contrast Pantone© Green, and Pantone© Hexachrome Green, decreased nineteen degrees, anticlockwise, becoming yellower when printed onto fabric substrates.

A complementary map representing an overall color expectation shift was also produced. An average HSB value was taken using the measurements of all substrates, for each Pantone©, and the resulting color and values placed at the circle's center, encompassed by the screen-color. These secondary maps offer an immediate idea of expected color changes to designers by juxtaposing the screen-color with an average, anticipated print-color.

The maps (Figure 5) reveal that detailed color testing and adjustments will be required to obtain satisfactory color matches, particularly for prints on wool, silk and linen. Blacks, magenta tones and cooler blues and greens demonstrated the greatest hue shifts and changes to saturation and brightness, supporting analysis from the color reference book. The diagrams demonstrate the gamut mapping process, visualizing the shifts that have taken a color from the input color range on screen to that of the printed output color space. Gamut mapping is the recalculation of hue values from one color space to another (Hunt 2005). The methods applied are known as rendering intents. Converting pixels of light on screen to printed dots of color involves considerable modifications. A rendering intent will prioritize certain color qualities over others, depending on the desired image outcome (Fraser et al. 2004). For example, a perceptual rendering intent is used to obtain an equivalent color balance in the output image to the input image. A uniform gamut compression is applied to the entire input color range, maintaining color relationships, and preserving lightness and saturation (Fraser et al. 2004). This is useful for printing photographs where light and tone will be important. In contrast, a relative colorimetric rendering intent will prioritize out-of-gamut colors, shifting these to the closest in-gamut hue from the output color range. Colors that are in-gamut remain the same. However, there is the potential for a loss of overall tonal quality as out-of-gamut colors are mapped to similar hues as in-gamut colors (Fraser et al. 2004). This method is useful for proofing because gamut mismatches become clearer allowing amendments to be made to the original design (Fraser et al. 2004).

Rendering intents have been developed for enhancing prints on paper and subsequently do not account for textile substrates (Dawson 2006). Additionally, there is a lack of industry standardization around the selection of rendering intents (Ding 2016). It is likely that a designer will not even be aware of the rendering intent used by the DPB nor their purpose and impact on color outcome. The fabric prints tested as part of this research used a perceptual rendering intent which is the standard gamut mapping method used in UWE's DPBs. The color maps and digital lab dip tests are a means of visualizing this complex process in order to allow designers to resolve color issues within their design process. Understanding how a color might appear when printed onto different substrates and anticipating which colors may be more challenging to reproduce using visual prompts supports a designer's understanding of DTP and improves their digital color knowledge.

Indicator ICC Profiles

The research observed changes to the overall appearance of an image displayed on screen by assigning different virtual device profiles to a specifically created color test collage in APCC. Consequently, the research considered whether a display profile could be created which indicated to the viewer the color alterations to expect when printing onto different textile substrates. The profiles were developed using the existing data (Table 1). The aim was to provide an indication of expected color changes to a designer viewing their image on a computer display, allowing them to make adjustments to obtain a better color relationships and balance prior to printing.

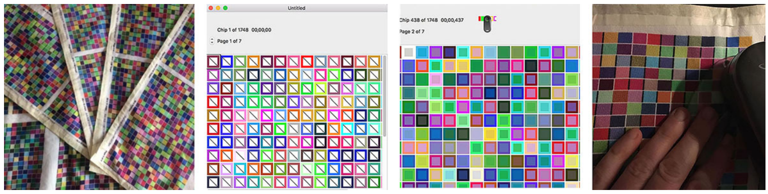

Figure 6
Gooby, B. Screenshot images and photographs of color target measuring process of altered targets (researcher's own collection).

Profiling is a means of comparing measured reflectance data, from RGB (red, green and blue) or CMYK color ranges, produced by a particular device or devices, with known reflectance data from International Color Commission (CIE) models. ICC profiles were developed by the International Color Commission (CIE) in 1993 as an open profile format which could be used universally across different software and devices (Fraser et al. 2004). Data is stored in a look up table, used for mapping an input to an output value to provide information about numerous color possibilities. Profile maker software uses a color target as a means of gathering information about the device's color reproduction. A color target is a set of color swatches which range in number depending on the software used and user selection. The target is measured, and the returned data is used to provide an overview of color options for the look up table, limiting the amount of data to be stored (Fraser et al. 2004).

Color Management processes such as profiling have been developed to maximize a device's achievable gamut. These processes use data from the print environment to optimize the print outcome. A profile is like a color recipe, used to transfer data on color construction to output devices. This aids conversions between RGB pixels of light and solid CMYK dots of colorant (Green 1995). It would be expected that a DPB service would carry out color management procedures. They may recommend that supplied artwork be assigned a particular ICC profile, generally a virtual device profile, for example Adobe RGB 1998 or sRGB IEC61966-2.1, which have been developed for general color management use (Fraser et al. 2004). However, these profiles provide a false idea of color reproduction possibilities as their gamut boundaries are far wider than the colors achievable using CMYK colorants (Fraser et al. 2004).

An analysis of profile creation software was conducted to determine whether it was possible to edit profiles as well as generate them. However initial investigations established that extensive knowledge of programming would be required. Consequently, a more creative option was taken. The color targets were directly altered in order to modify the information returned to the profile maker software (Figure 6). To create the indicator profiles a color target, consisting of 1748 swatches used by Printer Cal, profile maker software for AVACADCAM, was repeatedly modified in APCC. AVACADCAM is a

Figure 7
Gooby, B. Color collages with assigned profiles. Top Row L-R Wool, Linen, Silk. Bottom Row L-R Cotton, sRGB IEC61966-2.1, Adobe RGB 1998 (researcher's own collection).

specialist software for textile and decorative surface designers and producers (AVACADCAM 2020). The modifications were made using existing data (Table 1) and focused on HSB shifts for different substrates as well as red/blue wavelength adjustments and greyscale calculations. The targets were printed onto cotton satin and measured. Finally, the data were returned to create ICC Profiles using Printer Cal software. Next, the profiles were assigned to the specifically created color test collage image in APCC to observe the color changes on screen.

Indicator Profiles Developed to Demonstrate Color Differences by Substrate

Six color collages images were examined; four images with assigned indicator profiles modified using data on hue, saturation and brightness shifts for four substrates (wool, linen, cotton, silk), and an additional two, using assigned standard, Virtual Device ICC profiles (sRGB IEC61966-2.1 and Adobe RGB 1998) as comparables (Figure 7). Visual analysis observed subtle color differences between the appearance of the six images (Table 2).

All indicator profiles demonstrated a loss of brightness and saturation in comparison with the standard, generic profiles which was in keeping with the reduced brightness and saturation appearance of printed textiles, and subtractive color. These results had some correlation with the findings of visual analysis of differences from screen to print-color using the color reference book. Linen, a cellulose fiber constructed from flax plants, does not absorb dye particularly well (Ingamells 1993). The juniper linen tested had the loosest weave of all

Table 2 Visual analysis of indicator profiles when applied to the color collage

Profile	Observation
Wool	The image had a slightly orange appearance which was most noticeable in the neutral color ranges. The colors appeared muted in comparison with the images assigned with sRGB IEC61966-2.1 and Adobe RGB 1998 profiles. Colors from the blue / magenta tonal ranges were most vivid and green tones appeared bluer. The neutral ranges had a soft contrast and appeared to have a sepia like appearance.
Linen	The image had a slightly yellower appearance which was most noticeable in the neutral color ranges and in the red tones. Blue and green tonal ranges appeared yellower. Neutral tones had a strong contrast but instead there was a loss of tone quality.
Silk	The image had a slightly magenta appearance which was most noticeable in the neutral color ranges. The red tonal ranges appeared strong and spectral colors were saturated. Neutral ranges appeared darker than the linen or wool images, with a strong contrast.
Cotton	The image had a slightly orange-red appearance. The neutral ranges did not appear to influenced by this tint. The colors were strong and saturated similar to the silk profile except that there was improved tonal quality and decreased contrast which achieved a better color balance.
sRGB IEC61966-2.1	The image had strong saturated colors in comparison to the indicator profiles with no apparent overall color tint. The neutral ranges had a slight green quality to them, but contrast, tonal quality and color balance were all good.
Adobe RGB 1998	The image had incredibly strong saturated colors, particularly in the blue tonal ranges, in comparison to the indicator profiles with no apparent overall color tint. There was strong contrast but a lack of tonal quality. The neutral ranges had no apparent color tint.

four substrates and whilst color matches on linen appeared good, the saturation was greatly reduced. Wool is a keratin protein, animal fiber which naturally repels moisture but does absorb dyes (Ingamells 1993). However, whitening pre-treatments are complex and wool substrates prepared for DTP tend not to be bleached in order to reduce costs (Provost 2013). The wool substrate used in this research was in its natural state which has a yellow undertone affecting the printed color. Similarly, silk is an animal fiber and absorbs dye well (Ingamells 1993). The smooth texture and reflective qualities of the satin silk tested provided strong color results but darker than the screen-color.

Table 3 Output channel red percentage adjustments

Profile name	Output channel red – red percentage	Output channel red – green percentage	Output channel red – blue value percentage
RGB wavelength profile	67 %	0%	33%

Cotton is cellulose, derived from cotton plants, but absorbs and retains dye well (Ingamells 1993). Like the silk, both the linen and cotton were bleached white in the preparation for print.

The resulting profiles offer a visual indication on screen to designers of the overall color shifts that may occur when printing onto different substrates. This improves the designer's color knowledge and prompts color resolution practice at the design stage, prior to hard proofing, saving time and reducing costs. The results are subtle and not as apparent as some of the variations in the color reference book. Color differences can be less obvious when viewed within an overall design rather than separate swatches. Yet a designer used to gauging color changes can utilize the indicator profiles to detect which color ranges may need adjusting when choosing an end substrate.

Speculative Indicator Profiles

Three further profiles were developed using comparison data and observations from the color reference book. These loosely trialed speculative ideas produced to highly experimental profiles. The profiles were later applied as part of the *Ways of Making* project detailed later in this paper as a case study (Table 3).

Wavelength Red and Blue Adjustments An ICC profile was created using data from wavelength analysis of screen to print changes to alter a 1748 RGB color target. Wavelength measurements of swatches from the color reference book demonstrated that on average the fabric prints reflected a greater amount of higher red wavelengths to the swatches printed on paper. Additionally, the fabric prints absorbed a greater amount of the lower wavelengths (violet-indigo and blue) to the paper prints. This led to the hypothesis that reducing the red content whilst increasing the blue content of the R component of an RGB color space, using the red output color channel in APCC, might counteract the greater color difference occurring in the fabric prints. The target was altered accordingly and used to create an ICC profile. The profile was intended to be a corrective profile for use in printing rather than on screen (Figure 8, Tables 3 and 4).

Figure 8
Gooby, B. Color collages with assigned profiles. L-R RGB wavelength profile, Adobe RGB 1998 as comparison (researcher's own collection).

Table 4 Visual analysis of red-blue profile when applied to the color collage

Profile	Observation
RGB wavelength profile	The image has a strong blue tint and contrast which was most noticeable in the neutral color ranges. The colors appeared saturated and darker in comparison with the images assigned with sRGB IEC61966-2.1 and Adobe RGB 1998 profiles. Colors from the blue / magenta tonal ranges were most vivid and green and red tones appeared bluer. The neutral ranges had a strong contrast with the darks, darker and whites, brighter.

Greyscale Adjustments The color reference book established that neutral colors, particularly those from the greyscale were particularly problematic to replicate in print. An equal amount of cyan, magenta and yellow dots in a dithered dot matrix should create the perception of grey. However, variations in the spectral quality of colorant, particularly cyan, allow a magenta dominance, rendering greys with a pinkish appearance. To simulate this on screen the median value of HSB difference between a set of greyscale hues printed onto cotton satin was used to alter a 1748 RGB color target and used to create an ICC profile. The hue average difference of 60 degrees shifted the target colors significantly, radically altering the color information for the profile creator (Figure 9, Table 5). The resulting profile when assigned to the color collage image was dramatic with a strong magenta tint although the image quality was greatly reduced (Figure 10). To reduce the intensity of the magenta shift and create a more realistic representation on screen of how greys might print the profile

Table 5 Median hue, saturation and brightness value shift for greyscale profile

Profile Name	Average Hue Shift	Average Saturation Shift	Average Brightness Shift
Greyscale	Reduced by 60 degrees	Increased by 11 %	Reduced by 4 %

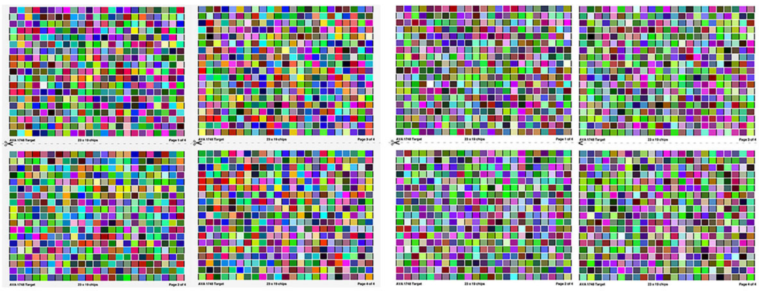

Figure 9
Gooby, B. L-R: AVARGB1748 color target with greyscale adjustments, AVARGB1748 color target original as comparison (researcher's own collection).

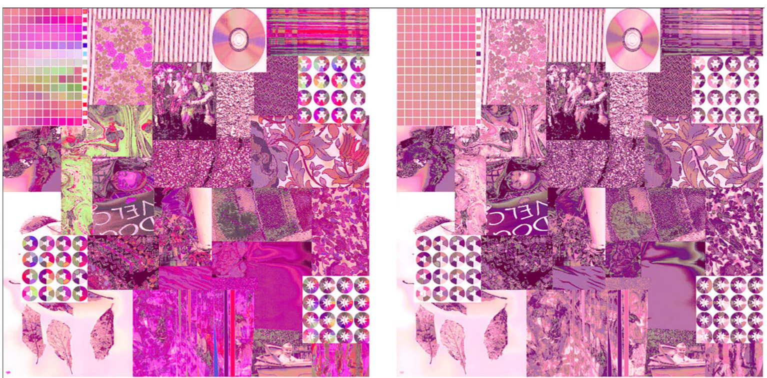

Figure 10
Gooby, B. Color collages with assigned profiles. Greyscale profile (left) color collage converted to greyscale mode then greyscale profile assigned (right) (researcher's own collection).

was applied to a greyscale version of the color collage. This softened the effect and offered a subtler color shift although unfortunately the image quality still decreased. The reduced image quality is an issue but the vivid change to color through the application of the greyscale profiles produces some thought-provoking color results which could have creative possibilities.

Experimental Conclusion

As outlined, the research has established several primary causes which contribute to screen to print-color differences in DTP; gamut mismatches, numerous variables and adapted technology and processes. In addition, the removal of the designer from the print process and inconsistent design education around DTP, impedes ability to problem solve and resolve color matching issues. The three color tools outlined in the Experimental section, have been developed to support the research project's aim to create an online tool kit, accessible to artists, textile practitioners and similar, without access to commercial resources and chemical color knowledge/science, providing guidance on color assurance in DTP.

The creation of a color reference book evidenced that there is a color match issue between screen and printed color and further differences between substrates. Particularly achromatic colors and hues with a high magenta or blue tone are problematic and will require careful consideration when choosing a color palette and in the proofing stages. Providing designers with access to the book, via the toolkit, enables them to look up colors, and substrates, to ascertain which might need careful testing and consideration when printing digitally.

A color diagram was created to visualize digital lab dip tests, mapping HSB changes for prints on different substrates and posing indicator colors to support color expectation knowledge. The maps revealed that detailed color testing and adjustments will be required to obtain satisfactory color matches, particularly for prints on wool, silk and linen. Blacks, magenta tones, cooler blues and greens demonstrated the greatest hue shifts and changes to saturation and brightness, supporting analysis from the color reference book. The diagrams support designers' color expectation knowledge so that they might confidently gauge printed color results and make alterations to designs accordingly.

Finally, the color measuring exercise provided the basis for the development of several indicator ICC profiles which offer a visual indication on screen to designers of the overall color shifts that may occur when printing onto different substrates. Several highly experimental indicator profiles were produced based on two speculative ideas. The first that reducing the red content whilst increasing the blue content might counteract color differences when printed. The second that simulating a sixty-degree increase in hue value might inform designers about potential magenta undertones to printed greys.

The substrate profiles offer a visual indication on screen to designers of the overall color shifts that may occur when printing onto different substrates. The results whilst subtle, allow a designer to detect which color ranges may need adjusting when choosing an end substrate. The experimental greyscale profiles produced exciting color outcomes with creative potential by exaggerating the tendency of greys to be perceived as pinkish when printed. The red-blue

Figure 11
Gooby, B. Photographs of Ways of Making project installation at Original Print Fair London Royal Academy April 2019 (researcher's own collection).

corrective profile produced an appealing color balance which may be used to as an aesthetic design tool.

These methods will form part of an online toolkit to be published in the spring of 2021. The toolkit will be a pedagogical tool to support designers' digital color knowledge in DTP. Increasing understanding of potential color changes and enabling adjustments to be made during the design process will allow designers more control over color outcome. Several of the indicator profiles were employed in an application of color knowledge for the *Ways of Making* project. CFPR was commissioned by the project to produce a number of prints to demonstrate the range of skills and resources at UWE. The prints were developed from a selection of Blake's images which depict a primrose in a bowl, inspired by a line in Dylan Thomas' Under Milk Wood, 'from one of the fingerbowls a primrose grows'. An initial selection of works from the project were exhibited at the Original London Print Fair, Royal Academy in April 2019 (Figure 11) with further exhibitions and publications planned around the project. The contribution of the research project has been summarized as a case study and is outlined below.

Case Study - An Application of Color Knowledge for the Ways of Making Project

The *Ways of Making* Project is a collaborative project between Sir Peter Blake, Worton Hall Studios and CFPR, UWE. The aim was to create an archive of every known medium, exploring edition making through creating multiple versions of an image through a variety of processes. The project brief asked researchers to reinterpret Blake's visuals through their print discipline, drawing upon their particular knowledge and skill set. These prints covered a wide range of disciplines which are explored within CFPR. Two sample digital textile prints were made, one on silk satin and the other on juniper linen. Prints on silk produce vivid colors, and the silk satin selected was highly reflective with a tight weave. In comparison color prints are

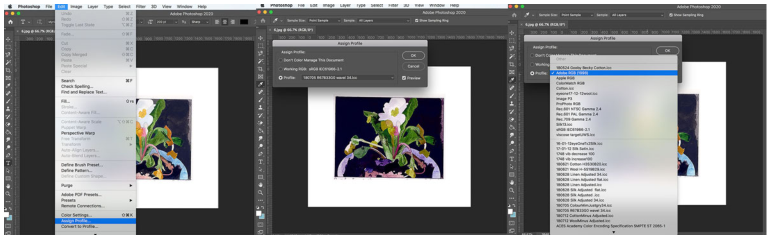

Figure 12
Gooby, B. Screenshot images of applying a profile in APCC (researcher's own collection).

muted on linen which does not absorb dye well. Linen cloth has natural slubs and a looser weave creating a distressed quality to printed images. The images were printed using standard color management settings, with an sRGB IEC61966-2.1 profile applied, using a digital textile inkjet Mimaki TX2-1600 printer, with reactive dyes. After presenting the samples to Blake, final prints were commissioned, including a number of digital textile prints on silk satin. Consequently, a number of digital textile prints were made which further modified Blake's visuals through the application of ICC profiles developed by the researcher and outlined in the Experimental section of this paper. In addition, several multi pass prints and two pattern repeats were produced, printed on silk satin.

Modification: Color Information Altered through the Application of Experimental Color Profiles

A series of profiles were applied to eight different images of a primrose, producing forty prints (Figure 12). Figures 13 presents each set of eight Blake images applying the five different profiles. Figures 14 and 15 compare the color changes by applying one of the five profiles, for each Blake image. The profiles altered the color data to create experimental color modifications (Table 6).

Additionally, two types of multi pass print were made. DTP creates prints in a single pass. The print head travels across the fabric depositing cyan, magenta, yellow and black colorant in a matrix of tiny dots to produce what is perceived as a full color print. The prints, a layered method which printed key colors as separate layers, and an overprint, where the primary palette was re-printed on top of a single pass print, were observed to have a visual 3D effect (Figure 16). Finally, two pattern repeats were generated using one of Blake's primrose paintings as a motif (Figure 17).

The silk profile print was exhibited at the introductory *Ways of Making* exhibition held by Worton Hall at the Original London Print Fair, Royal Academy London in April 2019. The remaining prints form part of the archive and wider body of work which will be exhibited

Figure 13
Gooby, B. Photographs of each set of prints using the different profiles (researcher's own collection).

Figure 14
Gooby, B. Photographs of comparison sets of prints made using the experimental indicator profiles. Images 1–4 (researcher's own collection).

internationally alongside publications about the project. The production of these prints presented a means of applying color knowledge, developed by the researcher, to demonstrate the creative and exploitative potential of digital textile printing. Color management processes use mathematical models and scientific theory to convert pixels to dots to produce perceived color ranges. Algorithms are

Figure 15
Gooby, B. Photographs of comparison sets of prints made using the experimental indicator profiles. Images 5–8 (researcher’s own collection).

Table 6 Profile details and color observations

Adobe RGB 1998: virtual device profile	A generic, standard profile developed by Adobe to maximize the potential for CMYK (printer) colorants to capture as many of an RGB (screen) saturated hues. Prints are bright and colors vivid.
Experimental profile 1: red-blue profile	Digital fabric prints were shown to reflect a greater amount of higher, red wavelengths, and absorb more of the lower, blue wavelengths, than digital prints on paper, altering color perception. A profile was developed using data which examined these differences in reflected and absorbed spectral wavelengths to adjust the red and blue balance of a profile target. The resulting profile produces deeper blacks, deepens blue hues and shift reds towards magenta tones and yellows towards green.
Experimental profile 2: silk profile	Silk satin is highly reflective and finely woven fabric which produces vibrant, printed color. Silk fibers absorb dye well promoting color saturation and can yield brighter than intended, brash colors. A profile was created using the measured Hue, Saturation and Brightness differences between screen and printed color swatches on silk and applied to a profile target to reduce the potential for colors to appear garish. The resulting

(*Continued*)

Table 6 (*Continued*).

Adobe RGB 1998: virtual device profile	A generic, standard profile developed by Adobe to maximize the potential for CMYK (printer) colorants to capture as many of an RGB (screen) saturated hues. Prints are bright and colors vivid.
	profile produces strong colors which have a warm blue undertone, whilst blacks and neutrals have a softer appearance.
Experimental profile 3: grey profile	Grey profile – CMYK prints create greyscale by printing equal amounts of cyan, magenta and yellow dots, which theoretically should be perceived as tones of grey. However, spectral quality issues with cyan colorants lead to a magenta dominance in color perception, resulting in pinkish greys. A profile was developed using measurements of the differences between screen and print hues in the greyscale range. These were applied to a profile target, radically altering the measured target color set, and consequently the profile. The resulting profile produces saturated, pink images with fuzzy tonal and image quality. Large greyscale areas have a shimmery appearance.
Experimental profile 4: grey profile two	The grey profile was applied to the image set after greyscale conversion, discarding all original color information. This produces a subtler effect with an overall cooler, color temperature.

automatically performed out of sight and seemingly with little input from the user. Yet in this instance the technology was harnessed to produce aesthetically interesting and experimental color outcomes retaining designer creativity. The *Ways of Making* project was initially inspired by visit to an art college where Blake became concerned with the usurpation of many forms of craft and hand skills by computer usage. This work demonstrates that a designer may exert control in the realm of digital color printing by manipulating computer algorithms, preserving the designer's eye as ultimate color control.

Figure 16
Gooby, B. Multi pass print examples. Color separation layer print (left), over print (right) (researcher's own collection).

Figure 17
Gooby, B. Detail of the two pattern repeat prints for the Ways of Making project (researcher's own collection).

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