Investigation into Digital Print Hard Copy Quality, Longevity and Durability

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Abstract. The main purpose of the research project was to investigate whether deskjet ink jet printing could produce A-4 size images on a par with conventional silver halide continuous tone photographic media prints. To this end, equivalent images were produced using both dye-based and pigment-based deskjet ink jet prints. To assist the research project, a multi-cultured array of observers were enlisted to give individual responses to a range of specific questions appertaining to the image characteristics of the A-4 size images produced. In addition, in order to assess the image stability and print durability of both the conventional silver halide prints and the ink jet prints, a range of laboratory tests were undertaken in the areas of light fastness, water fastness and both dry and wet rub fastness.

1. Introduction
Digital cameras have now taken over from conventional film cameras as the dominant form of image capture, whether that be via a phone camera, compact camera or single lens reflex camera. This has changed the landscape for the production of hard copy prints of these digitally captured images. One commonly used method of achieving hard copy prints is by means of a Minilab printer system such as the Fujifilm 700 series, which ranges from the compact LP 7000 model through to the high performance LP 7900 model. These printers use a combination of a high quality scanner, digital imaging processing software and RGB lasers, to create images on laser optimised silver halide papers such as the Fujicolor Crystal Archive brand.[1] The prints are commonly produced dry to dry in approximately four minutes, following development in a modified RA4 chemistry using CP-48S chemicals. However, many amateur, semi-professional, and professional photographers favour producing their own colour prints using either drop-on-demand technology deskjet ink jet printers [2, 3, 4, 5] or thermal dye transfer printers [6, 7], with ink jet printing being the more common technology in the United Kingdom.

2. Image Generation and Printing Procedure
Three individual images were recorded for the project. These comprised of a landscape photograph of Knaresborough viaduct (see figure 1); a group portrait image of six international students showing a range of different skin tones (see figure 2); and a multi-coloured image of predominantly fruit and vegetables (see figure 3). All three images were captured as RAW files using a Nikon D700 digital single lens reflex camera, fitted with a Sigma 18-50mm zoom lens. The first two images were captured in daylight and the third captured using tungsten photographic lamps (colour temperature 3200K).

Following post production in Photoshop CS4 and conversion to TIFF file format images, the images were printed as follows:
(a) A Fujifilm Frontier 700 series minilab printer was used to generate the silver halide prints on Fujifilm Crystal Archive glossy paper.
(b) An Epson Stylus Photo 1400 printer, fitted with an OEM ink set, was used to generate the dye-based ink jet prints on Epson Premium Glossy Photo paper.

(c) An Epson Stylus Photo R800 printer, fitted with an OEM ink set, was used to generate the pigment-based ink jet prints on Epson Premium Glossy Photo paper.

For the ink jet images, an X-Rite/Pantone ColorMunki photo spectrophotometer was utilised to calibrate both the PC monitor and for creating the profiles for the printer paper/ink combinations. [8, 9]
3. Observer Exercise
A total of thirty people of different nationalities were recruited for the observer part of the research project. The split in nationalities was ten European, ten Chinese and ten ‘other nationalities’ (participants from Iran, Pakistan, Korea and Saudi Arabia). The gender distribution was equal i.e. fifteen males and fifteen females.

Observation of the prints was undertaken using a standard neutral grey painted viewing cabinet, fitted with D65 daylight equivalent lighting (see figure 4).

Figure 3. Multi-coloured fruit/vegetable image

Figure 4. Print viewing conditions
In order to compare the images generated by the different printing methods, a number of questions were created for each individual print series, and also for the combined images.

The questions generated for the observer exercise were as follows:

(a) Landscape image
Question 1. Which of the images is the most true to life?
Question 2. Which of the images do you prefer?
Question 3. Which of the images do you think has the best resolution?

(b) Group portrait image
Question 1. Which of the images do you think represents the correct skin tone?
Question 2. Which of the images is the most true to life, with respect to the overall colour?
Question 3. Which of the images do you prefer?
Question 4. Which of images do you think has the best resolution?

(c) Multi-coloured fruit/vegetable image
Question 1. Which of the images is the most true to life, with respect to the colour?
Question 2. Which of the images do you prefer?
Question 3. Which of the images do you think has the best resolution?

(d) Combined images
Question 1. Which of the six images do you think has the best resolution?
Question 2. Which of the six images do you think has the best contrast?
Question 3. Three of the six images are silver halide photographic images – please choose which three.

4. Laboratory Testing
In order to test the light fastness and durability of the individual prints a range of laboratory tests were undertaken, namely light fastness, water fastness, and both dry and wet rub fastness.

4.1 Light Fastness Testing
The light fastness testing was undertaken, as an accelerated ageing method, for assessing identical areas of the individual images, following exposure to artificial light.

The method undertaken involved the use of the Atlas Xenotest Alpha LM, fitted with a Xenon arc lamp. This test method is a British Standard / ISO method [10] developed primarily for the textile industry, yet was utilised here due to the fact that although there is a specified ISO standard for photographic prints [11], there is still no specific ISO standard for predicting the life of digital prints exposed to light on display, stored in albums or other dark places, or exposed to ambient ozone in homes or offices.[12] Thus, as with a number of research projects undertaken in the Department of Colour Science / Department of Colour and Polymer Chemistry at Leeds University [13, 14, 15, 16], this method of light fastness testing was employed.

Identical area sections were cut from the six individual prints (approximate size 4.5 x 1.5cm) and these were attached to standard white card (size 4.5 x 13cm). About 50% of each area section was then masked over by attaching a piece of white card along the length of the assembly. The card assembly was then placed into a metal sample holder which was placed into the Atlas Xenotest light fastness chamber.

In addition, a series of Blue Wool Standards was also prepared in identical fashion, to be exposed alongside the test samples. As for the test samples, the Blue Wool Standards were also cut to the same size (4.5 x 1.5cm) and attached to a piece of white card (size 4.5 x 13cm). The dyes utilised for the Blue Wool Standards 1 to 7 are tabulated in table 1 below.
Table 1. Dyes for Blue Wool Standards 1 to 7

| Blue Wool Standard | Dye Colorants – Colour Index Designation |
|--------------------|------------------------------------------|
| 1                  | C.I Acid Blue 104                        |
| 2                  | C.I. Acid Blue 109                       |
| 3                  | C.I. Acid Blue 83                        |
| 4                  | C.I. Acid blue 121                       |
| 5                  | C.I. Acid Blue 47                        |
| 6                  | C.I. Acid Blue 23                        |
| 7                  | C.I. Solubilised Vat Blue 5              |

The Xenon arc lamp, fitted in the Atlas Xenotest Alpha LM light fastness equipment, gives a very similar spectral distribution to natural daylight. The lamp itself is surrounded by seven infrared borosilicate filters. The following equipment conditions were used for the light fastness testing, with the test and reference samples being monitored every four hours until a Blue Wool Standard grade six had been reached.

- Equipment running mode – non-turning
- Chamber temperature - 20ºC
- Relative humidity – 60%
- Input energy – 55

4.2 Water Fastness Testing

The water fastness testing procedure was used to evaluate the relative water resistance of the respective silver halide-based, dye-based and pigment-based images. The method used for this had been devised during a previous research project [17] and involved removal of specific areas from each of the printed images, followed by an equal volume of distilled water being placed onto the surface of the image via a pipette. Duration times of 30 seconds, 1 minute, 5 minutes and 15 minutes were used for the testing. A stop-watch was used to ensure time accuracy, and filter paper was used to soak-up the deposited water, following the specified time duration. The filter papers were then dried and retained for observation to see if any colorant had transferred from the surface-wetted print onto the filter paper. All samples were subsequently photographed. Any indication of colour transfer onto the filter paper would prove to be an indication of colorant migration and therefore reduced water resistance.

4.3 Dry Rub Fastness Testing

The dry rub fastness test procedure mimicked that procedure developed for a previous research project [17] and was used to evaluate the relative mar resistance of the individual prints under dry conditions.

The first stage was to cut-out individual pieces from the same area of each of the prints for direct comparison. The samples were fixed in a horizontal position and a single cotton bud used for the rub fastness procedure. This involved rubbing the surface one hundred times in a circular manner, ensuring that the strength applied was uniform for all the samples. All test samples were retained for visual comparison and a series of photomicrographs of the rub-tested print surface areas were recorded.

4.4 Wet Rub Fastness Testing

The wet rub fastness procedure was also developed for a previous research project [17] and was used to evaluate the relative mar resistance of the prints under wet conditions.

As for the dry rub fastness procedure, individual pieces were cut from the same area of the prints for direct comparison, and the procedure was identical with the exception that the cotton buds were thoroughly wetted in distilled water prior to undertaking the one hundred circular motions. Again, all samples were retained for visual comparison and a series of photomicrographs recorded of the rub-tested print surface areas were recorded.
5. Experimental Results

5.1 Observer Exercise

Table 2 below shows the distribution of the observer response to the questions relating to the landscape prints.

| Observer nationality | Question number | Ink Jet Dye-based image | Ink Jet Pigment-based image | Silver halide-based image |
|----------------------|------------------|-------------------------|-----------------------------|---------------------------|
| European             | 1                | 4                       | 3                           | 3                         |
|                      | 2                | 8                       | 0                           | 2                         |
|                      | 3                | 7                       | 0                           | 3                         |
| Chinese              | 1                | 6                       | 4                           | 0                         |
|                      | 2                | 9                       | 0                           | 1                         |
|                      | 3                | 7                       | 2                           | 1                         |
| ‘Other nationalities’| 1                | 6                       | 1                           | 3                         |
|                      | 2                | 8                       | 2                           | 0                         |
|                      | 3                | 9                       | 0                           | 1                         |

Table 3 overleaf shows the distribution of the observer response to the questions relating to the group portrait prints.

| Observer nationality | Question number | Ink Jet Dye-based image | Ink Jet Pigment-based image | Silver halide-based image |
|----------------------|------------------|-------------------------|-----------------------------|---------------------------|
| European             | 1                | 4                       | 1                           | 5                         |
|                      | 2                | 5                       | 3                           | 2                         |
|                      | 3                | 7                       | 0                           | 3                         |
|                      | 4                | 8                       | 2                           | 0                         |
| Chinese              | 1                | 3                       | 2                           | 5                         |
|                      | 2                | 5                       | 3                           | 2                         |
|                      | 3                | 6                       | 2                           | 2                         |
|                      | 4                | 6                       | 4                           | 0                         |
| ‘Other nationalities’| 1                | 2                       | 1                           | 7                         |
|                      | 2                | 3                       | 3                           | 4                         |
|                      | 3                | 7                       | 1                           | 2                         |
|                      | 4                | 6                       | 3                           | 1                         |

Table 4 below shows the distribution of the observer response to the questions relating to the multi-coloured fruit/vegetable prints.

| Observer nationality | Question number | Ink Jet Dye-based image | Ink Jet Pigment-based image | Silver halide-based image |
|----------------------|------------------|-------------------------|-----------------------------|---------------------------|
| European             | 1                | 6                       | 3                           | 1                         |
|                      | 2                | 8                       | 2                           | 0                         |
|                      | 3                | 9                       | 0                           | 1                         |
| Chinese              | 1                | 5                       | 4                           | 1                         |
|                      | 2                | 10                      | 0                           | 0                         |
|                      | 3                | 9                       | 1                           | 0                         |
| ‘Other nationalities’| 1                | 6                       | 3                           | 1                         |
|                      | 2                | 8                       | 2                           | 0                         |
|                      | 3                | 7                       | 3                           | 0                         |

Table 5 overleaf shows the observation response to the questions regarding the combined images.
Table 5. Image observation response to the combined images

| Observer nationality | Question number | L-IJ -DB | L-IJ -PB | L-SHB | P-IJ -DB | P-IJ -PB | P-SHB | MC-IJ -DB | MC-IJ -PB | MC-SHB |
|----------------------|-----------------|---------|---------|-------|----------|----------|-------|-----------|-----------|--------|
| European             | 1               | 7       | 0       | 0     | 1        | 0        | 0     | 2         | 0         | 0      |
|                      | 2               | 1       | 0       | 0     | 4        | 0        | 0     | 4         | 0         | 1      |
|                      | 3               | 3       | 1       | 6     | 2        | 2        | 6     | 3         | 3         | 4      |
|                      | 2               | 1       | 0       | 0     | 5        | 0        | 0     | 4         | 0         | 0      |
|                      | 3               | 3       | 4       | 3     | 6        | 1        | 3     | 4         | 3         | 3      |
| Chinese              | 1               | 1       | 0       | 0     | 3        | 1        | 1     | 4         | 0         | 0      |
|                      | 2               | 2       | 0       | 0     | 4        | 0        | 1     | 3         | 0         | 0      |
|                      | 3               | 7       | 0       | 3     | 6        | 1        | 3     | 7         | 1         | 2      |
| ‘Other nationality’  | 1               | 1       | 0       | 0     | 3        | 1        | 1     | 4         | 0         | 0      |
|                      | 2               | 2       | 0       | 0     | 4        | 0        | 1     | 3         | 0         | 0      |
|                      | 3               | 7       | 0       | 3     | 6        | 1        | 3     | 7         | 1         | 2      |

Key for table 5:
- L-IJ – DB = Landscape/Ink Jet/Dye based.
- L-IJ – PB = Landscape/Ink Jet/Pigment based.
- L-SHB = Landscape/Silver halide based.
- P-IJ – DB = Group Portrait/Ink Jet/Dye based.
- P-IJ – PB = Group Portrait/Ink Jet/Pigment based.
- P-SHB = Group Portrait/Silver halide based.
- MC-IJ – DB = Multi-Coloured/Ink Jet/Dye based.
- MC-IJ – PB = Multi-Coloured/Ink Jet/Pigment based.
- MC-SHB = Multi-Coloured/Silver halide based.

Table 6 below illustrates the breakdown of table 5 into the basic selections of either ink jet dye-based, ink jet pigment based, or silver halide based.

Table 6. Basic print selections

| Observer nationality | Question number | Ink Jet Dye-based image | Ink Jet Pigment-based image | Silver halide-based image |
|----------------------|-----------------|-------------------------|----------------------------|--------------------------|
| European             | 1               | 10                      | 0                          | 0                        |
|                      | 2               | 9                       | 0                          | 1                        |
|                      | 3               | 8                       | 6                          | 16                       |
| Chinese              | 1               | 9                       | 1                          | 0                        |
|                      | 2               | 10                      | 0                          | 0                        |
|                      | 3               | 13                      | 8                          | 9                        |
| ‘Other nationality’  | 1               | 8                       | 1                          | 1                        |
|                      | 2               | 9                       | 0                          | 1                        |
|                      | 3               | 20                      | 2                          | 8                        |

5.2 Laboratory Testing Results

5.2.1 Light Fastness Testing. Table 7 overleaf illustrates the light fastness testing results obtained for the print samples.

Table 7. Light fastness test results

| Sample reference | Blue Wool Standard Grade |
|------------------|--------------------------|
| Landscape – Ink Jet Dye-based | 6 |
| Landscape – Ink Jet Pigment-based | 6 |
| Landscape – Silver halide-based | 6 |
| Group portrait – Ink Jet Dye-based | 6 |
| Group portrait – Ink Jet Pigment-based | 6 |
| Group portrait – Silver halide based | 6 |
| Multi-coloured – Ink Jet Dye-based | 6 |
| Multi-coloured – Ink Jet Pigment-based | 6 |
| Multi-coloured – Silver halide-based | 6 |
5.2.2 Water Fastness Testing. There was no evidence of the transfer of the colorant onto the filter paper, over the full time duration, for either the ink jet pigment-based prints or the silver halide-based prints. However, although there was no evidence for the transfer of colorant from the ink jet dye-based prints over the time duration of 30 seconds and 1 minute, there was evidence of a minor quantity of colorant having transferred to the filter paper after 5 minutes and 15 minutes.

5.2.3 Dry Rub Fastness Testing. Following the dry rub fastness process for the ink jet dye-based print, the tip of the cotton bud showed no evidence for any of the colorant having transferred across from the print. However, for both the ink jet pigment-based print and the silver halide-based print, some black colorant was transferred onto the respective cotton bud tips used for the test. Inspection of the respective prints, following the rub fastness process, did not show any undue change to their respective surfaces.

5.2.4 Wet Rub Fastness Testing. Following the wet rub fastness process on the ink jet pigment-based print, there was no evidence of pigment having transferred across to the cotton bud tip. Thus the wet mar resistance properties of the pigment-based print are better than the dry mar resistance.

For the ink jet dye-based print, the colorant proved relatively easy to rub off and therefore, the wet cotton bud tip darkened quickly.

The silver halide print proved to have the weakest wet mar resistance as most of the colorant transferred across onto the cotton bud tip, following the 100 cycle rubbing procedure. This meant that the rubbed area of the print was practically clear of the presence of colorant, revealing the surface of the substrate.

6. Discussion and Conclusions

6.1 Observer Exercise

For the observation exercise, comparing the A-4 size images produced on the Epson ink jet dye-based printer, the Epson ink jet pigment-based printer and the Fujifilm Minilab digital system, the following conclusions can be drawn:

(a) With respect to the prints of the landscape image, there is a very strong agreement between the three observer groups that the dye-based ink jet print is their preferred choice (80-90%) and also deemed to be of the highest resolution (70%). However, although this particular print was also the preferred choice in the true-to-life category, the result was not as clear-cut. Whereas 60% of both the Chinese and the ‘Other nationalities’ chose this print, only 40% of the European observers did so. From the results it is clear that the true-to-life question appears to have been the most difficult to answer. Whereas none of the Chinese observers chose the silver halide print in this category, 30% of the observers for both the European and the ‘Other nationalities’ did so. However, overall across the board, the pigment-based ink jet print was marginally in front of the silver halide print for second choice.

For the group portrait image, once again there is very good agreement between the three observer groups with respect to their preferred print (60-70%) and the print deemed to be of the highest resolution (60-80%). The other two questions however received a more varied response. Although the highest percentage of the observers chose the silver halide print as their choice for best skin tone representation, the result was not unanimous, with overall 47% of the thirty observers choosing the silver halide print, 33% the dye-based ink jet print and 30% the pigment-based ink jet print. The true-to-life, with respect to overall colour, choice of print also proved to be a difficult decision to make for the observers. For this category, the dye-based ink jet print was the favoured choice for both the European and Chinese observers (both 50%). However, the silver halide print was the favoured choice for the ‘Other nationality’ observers (40%). Overall, 43% chose the dye-based ink jet print, 30% chose the pigment-based print and 27% chose the silver halide print.

For the multi-coloured fruit/vegetable image, the response from each of the observer groups was very similar for each of the questions presented. The dye-based ink jet print was the preferred choice in each of the categories i.e. highest resolution print (70-90%), preferred image (80-100%) and true-
When the six prints were placed together for viewing, the previous trend continued, with 80-100% of all observers choosing a dye-based ink jet print as having the highest resolution. In addition, between 90-100% of the observers chose a dye-based ink jet print in the highest contrast category. However, with respect to being able to pick out the three silver halide prints from the ink jet prints, only the European observers had a modicum of success with a correct response rate of 57%. Both the Chinese and the ‘Other nationalities’ observer groups had a meagre success rate of only 27%.

The overall verdict from the observers when combining the data from all the images is illustrated below in table 8.

| Question category         | Dye-based ink jet print (%) | Pigment-based ink jet print (%) | Silver halide-based print (%) |
|---------------------------|-----------------------------|--------------------------------|------------------------------|
| True-to-life image        | 51                          | 30                             | 19                           |
| Preferred image           | 79                          | 10                             | 11                           |
| Highest resolution image  | 79                          | 14                             | 7                            |
| Best skin tone representation | 30                        | 13                             | 57                           |
| Highest contrast image    | 93                          | 0                              | 7                            |

6.2 Laboratory Testing

The laboratory testing undertaken on the ink jet dye-based, the ink jet pigment-based and the silver halide based prints, revealed the following findings:

(a) The light fastness testing results indicate that all the different print types achieved at least a Blue Wool standard value of 6 (see table 7). The results achieved are not surprising for an ink jet pigment-based print and a silver halide based print, but are a remarkable testament to the light stability of the Clariant dyes used in the Claria Epson OEM dye-based inks. Two web sites however indicate that prints made with Claria inks will last for 98 years in a photo frame and 200 years in a photo album. [18, 19] Part of the reason for the high light fastness values associated with the black, magenta and cyan dyes appears to be the increased molecular weight of the respective structures. [20, 21, 22]

(b) For the water fastness testing exercise, there was no transfer of colorant onto the filter paper from either the ink jet pigment-based print or the silver halide-based print. However, there was transfer of colorant onto the filter paper, following exposure for 5 and 15 minutes, for the ink jet dye-based print. The levels transferred though, were of a very minor quantity and did not appear to affect the surface of the print.

(c) With respect to the dry rub fastness testing, the ink jet dye-based print showed no evidence for the transfer of colorant to the cotton bud tip, whereas both the ink jet pigment-based print and the silver halide-based print did show clear evidence of colorant removal.

(d) For the wet rub fastness testing, the ink jet pigment-based print proved to be the most successful with no colorant having been transferred. Whereas, both the ink jet dye-based print and the silver halide-based print showed transfer of colorant onto the cotton bud tip. The ink jet dye-based print showed little or no surface damage, when viewed under an optical microscope (see figure 5), whereas the silver halide-based showed clear evidence for surface print damage when viewed under identical conditions (see figure 6).

(e) Following the combined observer and laboratory testing exercises, the digital printing method that takes most of the honours is the ink jet dye-based system. The only negative aspect with respect to the laboratory testing exercise was a minor weakness in the water fastness test, and some transfer of colorant in the wet rub fastness exercise. However, in the observer exercise this printing method was the overwhelming favourite in all categories, with the exception of skin tone representation. In this category the silver halide-based print was the favoured choice. Thus, despite the improvement in skin tone representation for ink jet dye-based prints following the introduction of light magenta and light cyan inks, it would seem that this has not put the system on a par with silver halide technology. This certainly illustrates why the current image permanence test methods in photography, such as ISO 18909:2006, really require full tonal scale human skin tone colours in the fading evaluation,
especially when approximately 80% of all amateur photographs include people in the scene and for all professional wedding and portrait photographers, this increases to 100%. [23]

**Figure 5.** Photomicrograph of ink jet dye-based print surface following wet rub fastness testing

**Figure 6.** Photomicrograph of silver halide-based print surface following wet rub fastness testing

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