Mixed Integer Ink Selection for Spectral Reproduction (Supplementary Material)

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This supplementary document provides the spectra of a Canon CMYK set used for comparison, and names and spectra of both our watercolor paints and library inks. It also shows results of further tests on spectral reflectance and transmittance reconstruction using our regression approach, the name and spectra of virtual illuminations used in calculation of metamerism potential, and high-resolution captures of our paintings and their physical reproduction.

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1 CANON CMYK INK SET

In a few experiments in the manuscript, we use a set of CMYK inks from Canon as a standard CMYK. Figure 1 shows the spectral plots of these four inks.

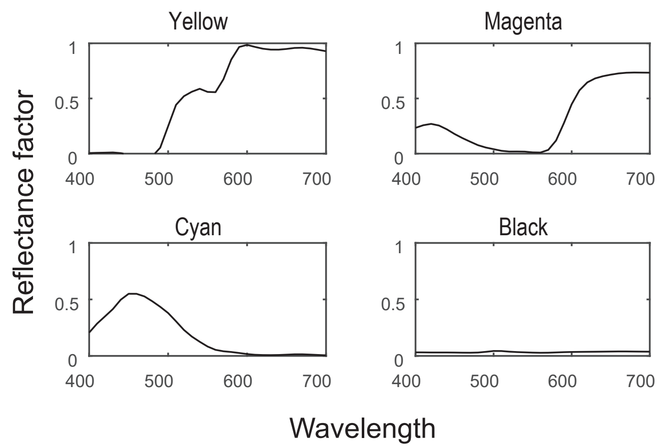

Fig. 1. The spectral plots of four CMYK Canon inks.

2 WATERCOLOR PAINTS

We collaborate with an artist who produces different paintings and a manually prepared swatch made of uniform paint patches. For our watercolor paintings, we purchase 14 *Schmincke* paint tubes listed in Table 1. The spectral plots of these paints are also shown in Figure 2.

Table 1. Names of 14 watercolor paints used to produce different paintings and a manually prepared swatch.

ID	Paint
1	Lemon Yellow
2	Cadmium Yellow Light
3	Yellow Ochre
4	Transparent Orange
5	Cadmium Red Light
6	Permanent Carmin
7	English Venetian Red
8	Phthalo Green
9	Permanent Green Olive
10	Prussian Blue
11	Ultramarine finest blue
12	Cobalt Violet Hue
13	Sepia Brown
14	Ivory Black

3 METAMERISM POTENTIAL IN RGB-BASED SPECTRAL RECONSTRUCTION

Instead of a spectral camera we are using an RGB-based spectral reconstruction. If applied carelessly, RGB-based spectral reconstruction is prone to metamerism. In order to assess the potential of metamerism, we compare our spectral reconstruction with a near-ideal setup where we capture the watercolor swatch using our camera under three lamps with different colors. For the new setup, we perform the same regression operation except on 9D RGB signals (a set of three different captures under three different lights) instead of previous RGB triplets. We calculate the metamerism potential of the 9D setup, which is expected to be very low, and compare it against our original capturing setup. For this purpose, we use the coefficient of variation (standard deviation normalized by mean) of colorimetric error of reconstructed patches under 9 different illuminations, such as A, D65, TL84, etc. (see the spectra of these light sources in Figure 3) [Smagina et al. 2019]. We verify that the obtained value (0.396) is very close to the value calculated

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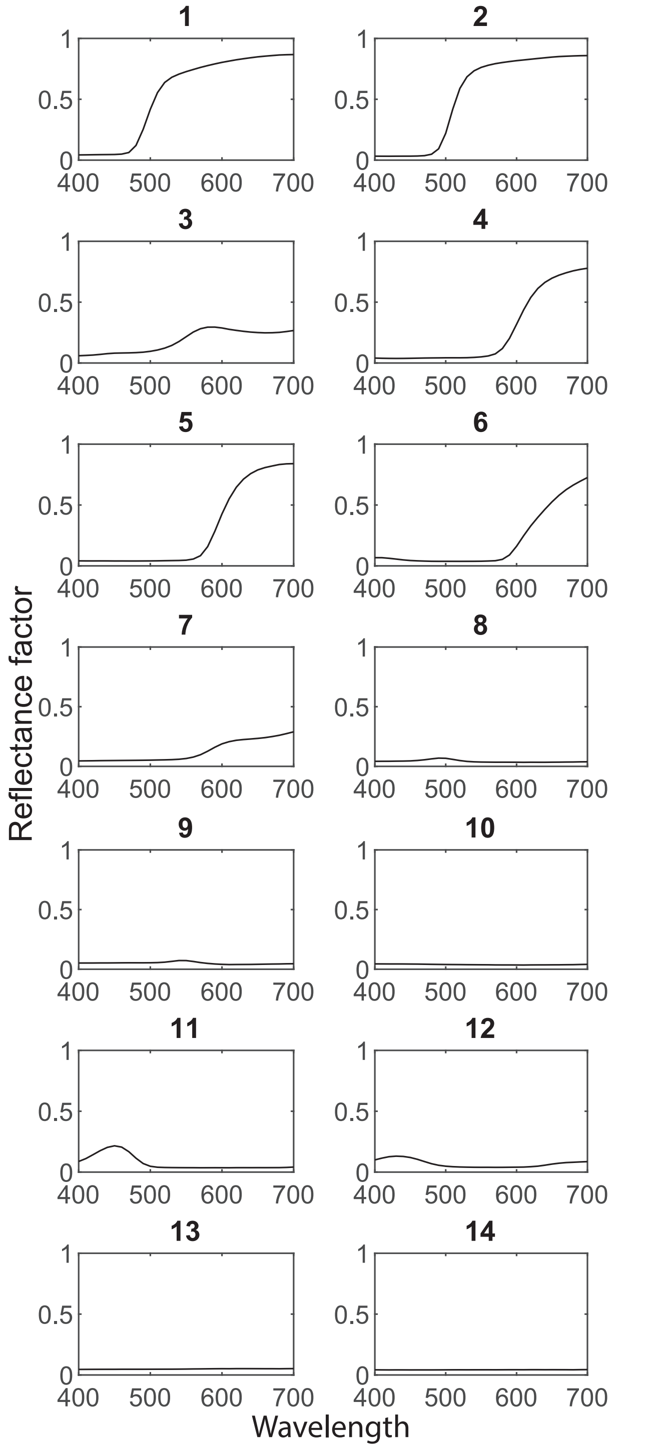


Fig. 2. The spectra of 14 watercolor paints used to produce different paintings and a manually prepared swatch.

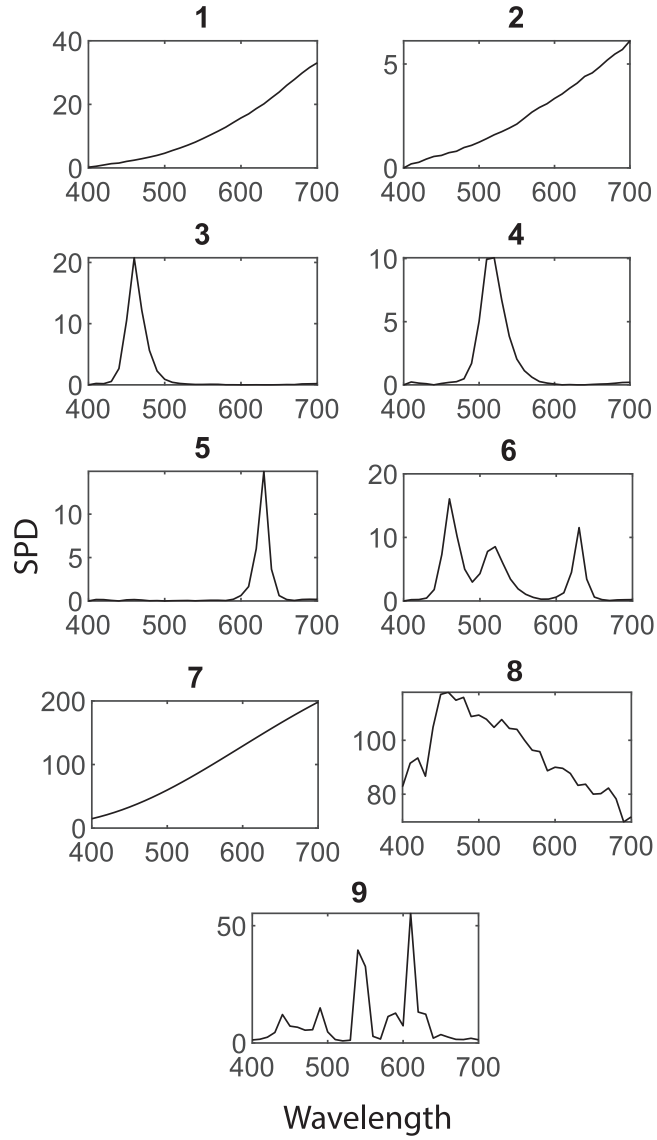


Fig. 3. Spectral power distribution (SPD) of 9 light sources used for calculation of the coefficient of variation of colorimetric error of the reconstructed spectra from RGB data.

for our original, single-lamp setup (0.340) implying that, indeed, the metamerism potential of our spectral reconstruction is negligible. Table 2 shows that the reconstruction of a spectral signal from a 9D RGB signal has a better accuracy in comparison to an RGB signal. Despite the improvement that we obtained through this approach, we decided to use the simpler and faster reconstruction by RGB signals.

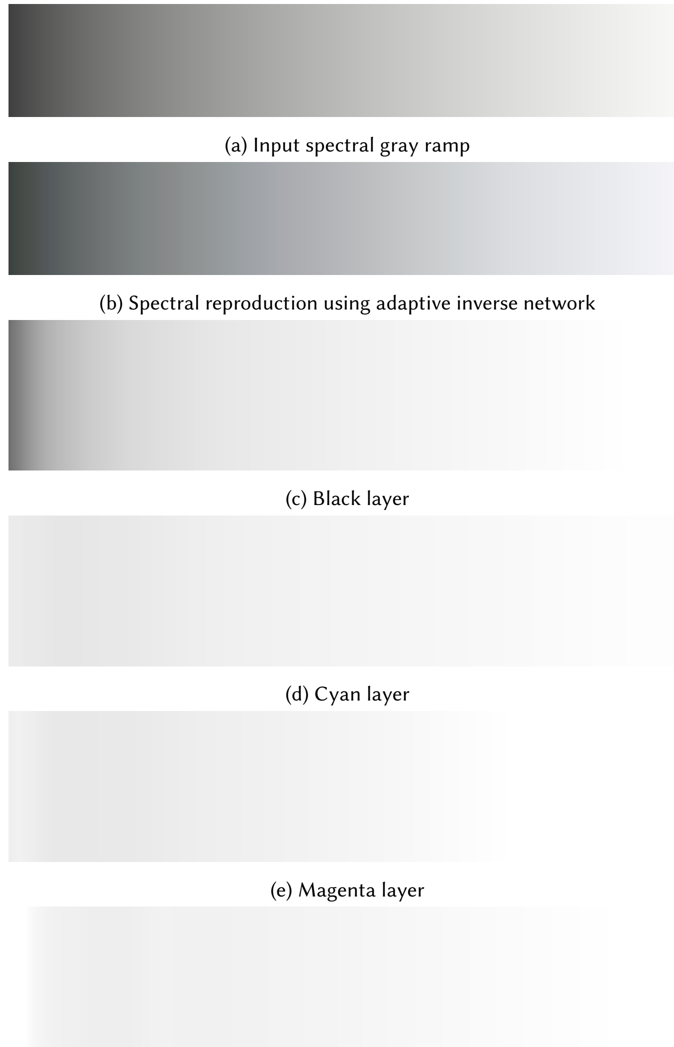
4 NEURAL SPECTRAL SEPARATION IN GRADIENT IMAGES

Due to spectral redundancy in the printing systems (where various ink combinations may result in a very similar reflectance [Rosen et al. 2004]), point-wise separation approaches (separating a single pixel at a time) may yield completely different ink combinations.

Table 2. Comparison between the ΔE_{00} of reconstruction based on RGB and 9D RGB signals (a set of three different captures under three different lights). The mean RMSE value of 24 test watercolor patches for RGB and 9D RGB signals are 3.97% and 3.03%, respectively.

ID	Illumination	ΔE_{00} RGB	ΔE_{00} RGB 9D
1	Desk lamp	2.36	1.36
2	Halogen lamp	2.33	1.33
3	LED blue	5.47	2.50
4	LED green	5.53	2.66
5	LED red	2.76	1.35
6	LED 100% illumination	3.53	1.15
7	A	2.31	1.31
8	D65	2.67	1.34
9	TL84	2.69	1.87

When pixels with similar colors are reproduced with highly different ink combinations, banding artifacts (and other undesirable transitions) are expected. However, on top of our regularization term, neural networks tend to learn low-frequency functions (an effect known as 'spectral bias' [Rahaman et al. 2019]). Therefore, unlike gamut subdivision schemes used for N-ink printing, our neural spectral separation does not show abrupt changes. By reproducing a gray ramp with adaptive learning approach and looking at its separation images (continues map of area coverage of different inks) in Figure 4 we show that our neural spectral separation is robust against such artifacts.



(a) Input spectral gray ramp

(b) Spectral reproduction using adaptive inverse network

(c) Black layer

(d) Cyan layer

(e) Magenta layer

(f) Yellow layer

Fig. 4. Gray ramp, its reproduction, and its separation images (continues map of area coverage of different inks). The lack of high frequencies in the separation images is an evidence of smooth behaviour of our neural network. Thus, we do not expect abrupt changes (banding artifacts) in the reproduced gray ramp.

5 INK LIBRARY

Table 3 lists the names and information of 43 inks in our library and the substrate fine art paper. Figure 5 shows the inks in the library as well as the reference Canon CMYK inks in the a^*b^* chromaticity plot. Their corresponding spectral reflectances are shown in Figure 6.

6 SPECTRAL REFLECTANCE AND TRANSMITTANCE RECONSTRUCTION

In the main manuscript we reported the reconstruction accuracy of the regression method when estimating paint swatch reflectance spectra from its RGB data obtained by a DSLR (Canon 5D Mark II). Here, we report the result of the same method for two other types of reconstruction we performed for printed patches on paper and transparency. We use 270 large (2.5×2.5 cm) printed patches on paper for spectral reconstruction of thousands of small patches used in calibrating the spectral separation network. Testing this model on 30 unseen patches, we obtain average RMSE = 1.47% and average ΔE_{00} = 0.83 and 0.85 under D65 and A illuminants, respectively. In Figure 7, we plot 24 test spectra against their ground-truth measurements carried out by the spectrophotometer. Also, 270 large (2.5×2.5 cm) printed patches on transparency sheets are used for spectral transmittance reconstruction of small patches used in the R2T network. Testing the transmittance reconstruction model on 30 unseen patches, we obtain average RMSE = 4.57% and average ΔE_{00} = 4.76 and 4.45 under D65 and A illuminants, respectively. Again, we plot 24 transmittance spectra against their ground-truth measurements carried out by the spectrophotometer in Figure 8.

7 HIGH RESOLUTION IMAGE OF PAINTINGS AND REPRODUCTIONS

Figure 9 to 12 show high-resolution captures of the physical reproductions of a few paintings.

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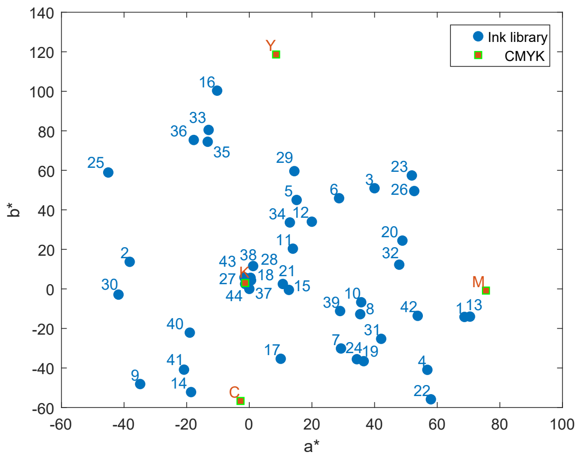

Fig. 5. a^*b^* chromaticity plot under D65 illumination for all the inks in the library as we as Canon CMYK reference inks. The inks' information corresponding to each index can be found in Table 3.

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Mitchell R Rosen, Edward F Hattenberger, and Noboru Ohta. 2004. Spectral redundancy in a six-ink ink jet printer. *Journal of Imaging Science and Technology* 48, 3 (2004), 194–202.

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Table 3. Names and further information of the inks inside our library.

ID	Color	Manufacturer	Type	Details
1	magenta	Epson	water-resistant	T3240-T3249, Surecolor SC-P400
2	green	Epson	pigment	compatible arici inkjet art paper
3	orange	Epson	pigment	compatible arici inkjet art paper pigment ink-0045
4	blue	Epson	dye - water-resistant	compatible ultra premium anti uv dye ink - light-resistant, water-resistant
5	red	Epson	dye	t0540-t0549; photo r800-r1800-0049
6	red	Epson	dye - water-resistant	compatible ultra premium anti uv dye ink - light-resistant, water-resistant
7	blue	Epson	pigment	t0540-t0549; photo r800-r1800-0021
8	blue		sublimation	
9	cyan	Canon		37-40-38-41-0031
10	red	Epson		t3240-t3249, surecolor sc-p400
11	orange		pigment - water-resistant	high pigment
12	orange	Epson		t3240-t3249, surecolor sc-p400
13	magenta		pigment - water-resistant	high pigment
14	cyan	Epson	water-resistant	t3240-t3249, surecolor sc-p400
15	gray		pigment - water-resistant	high pigment
16	yellow		pigment - water-resistant	high pigment
17	blue	Canon	pigment	compatible arici inkjet art paper
18	gray		sublimation	
19	blue	Epson	dye	t0540-t0549; photo r800-r1800-0057
20	red		sublimation	
21	gray		sublimation	
22	blue	Epson	pigment	t0540-t0549; photo r800-r1800-0029
23	red	Epson	pigment	compatible arici inkjet art paper
24	blue		pigment - water-resistant	high pigment
25	green		pigment - water-resistant	high pigment
26	red		pigment - water-resistant	high pigment
27	white		sublimation	
28	light light grey		pigment - water-resistant	high pigment
29	orange	Epson	dye - water-resistant	compatible ultra premium anti uv dye ink - light-resistant, water-resistant
30	green	Epson	dye - water-resistant	compatible ultra premium anti uv dye ink - light-resistant, water-resistant
31	blue	Epson	pigment	compatible arici inkjet ultra premium
32	red	Epson	pigment	t0540-t0549; photo r800-r1800-0021
33	yellow	Epson		t3240-t3249, surecolor sc-p400
34	red	Epson	pigment	compatible arici inkjet ultra premium
35	yellow	Canon		37-40-38-41-0031
36	yellow	Epson	pigment	original r 2880
37	light light black	Epson	pigment	original r 2880
38	light black	Epson	pigment	original r 2880
39	light magenta	Epson	pigment	original r 2880
40	light cyan	Epson	pigment	original r 2880
41	cyan	Epson	pigment	original r 2880
42	magenta	Epson	pigment	original r 2880
43	black	Epson	pigment	original r 2880
44	paper	Hahnemühle		Archival Inkjet Textured Fine Art 280

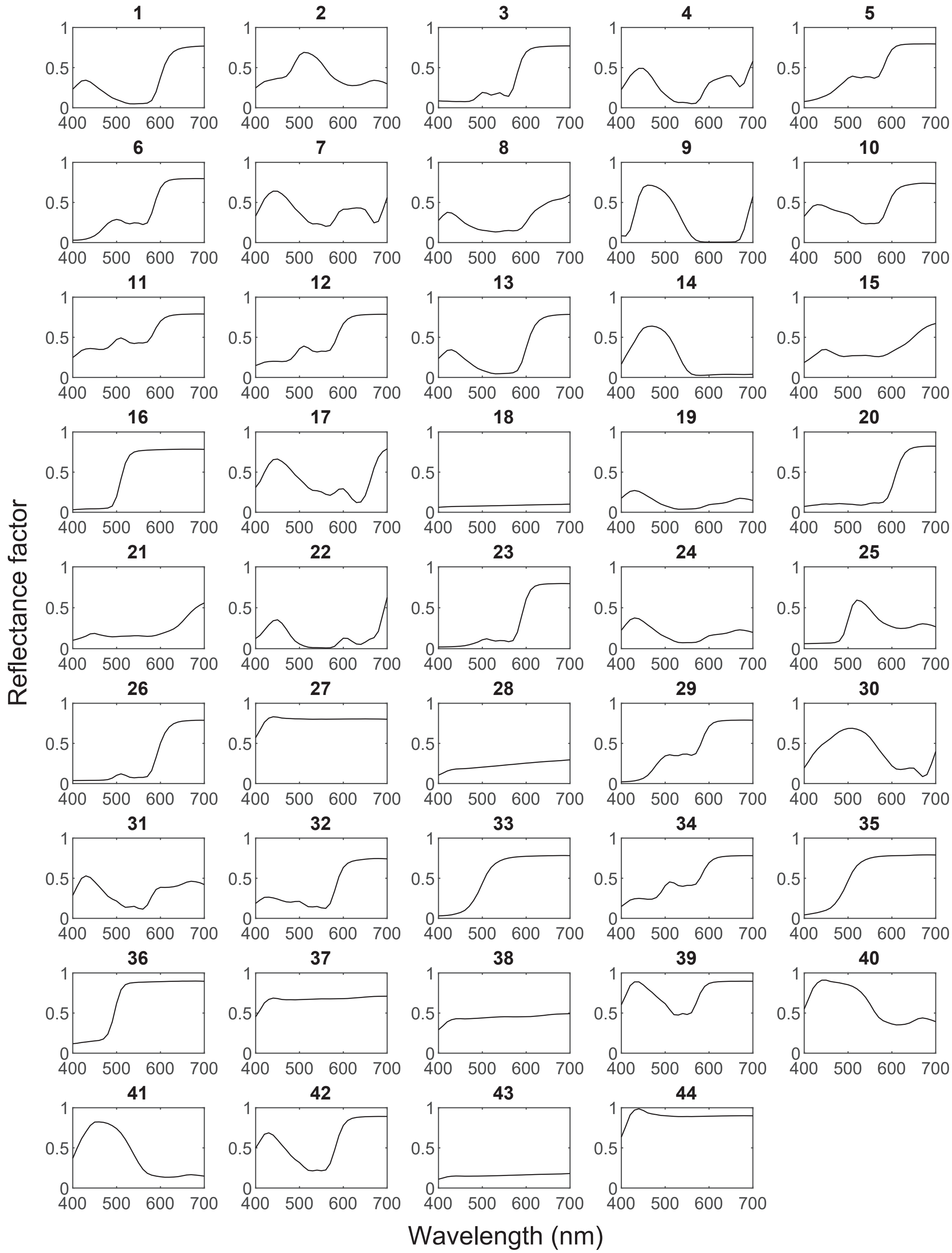


Fig. 6. Reflectance spectra of 43 inks in our library and the reflectance of our fine art paper.

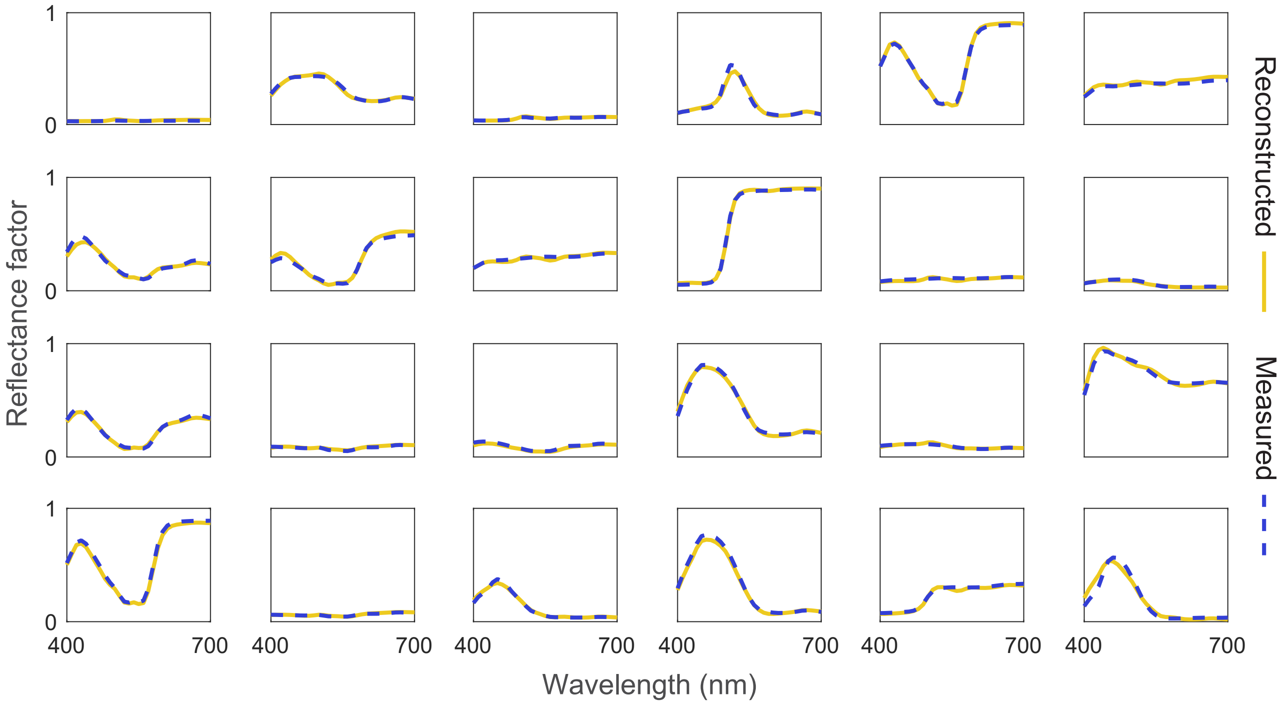


Fig. 7. Reconstruction of 24 test reflectance spectra (printed on paper) against their ground-truth measurements.

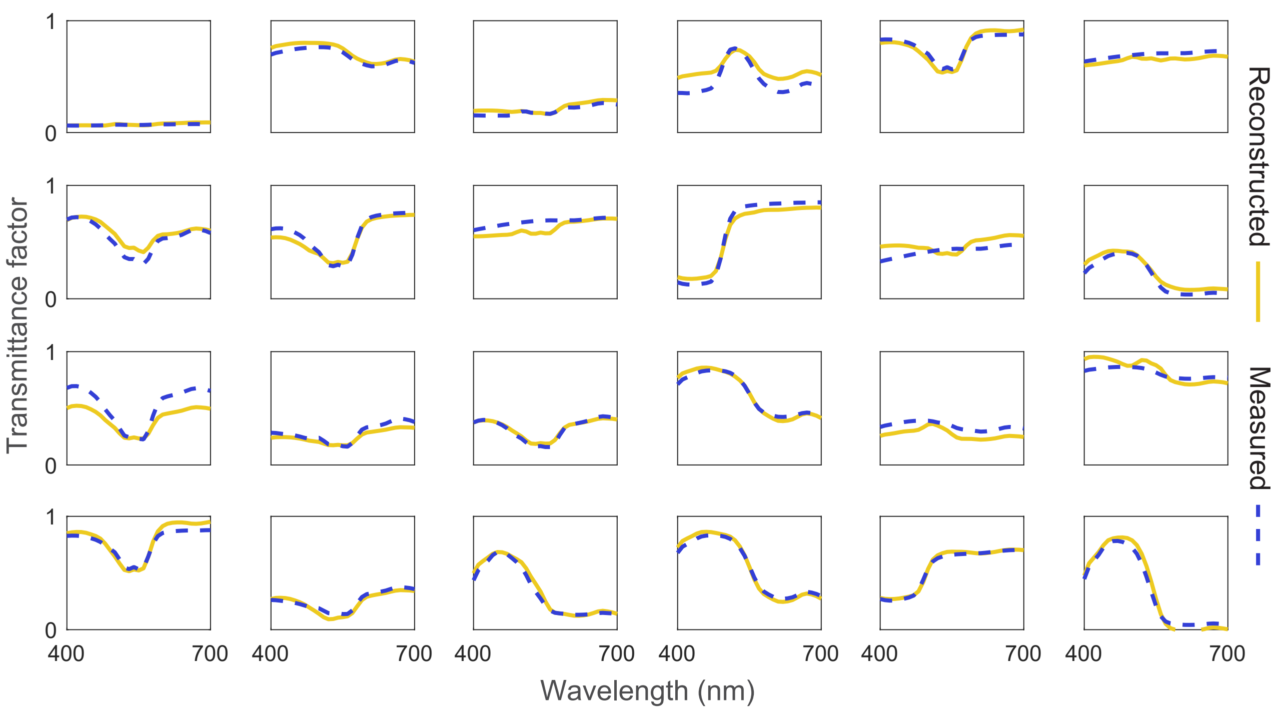
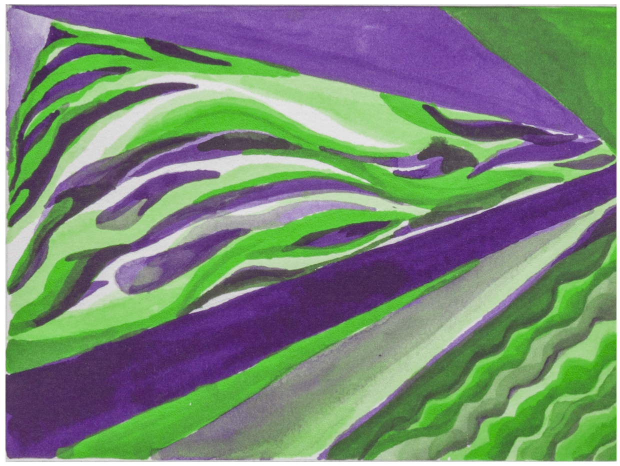
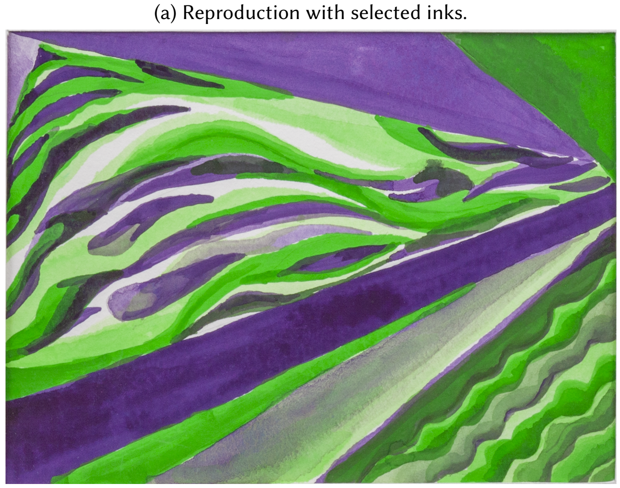


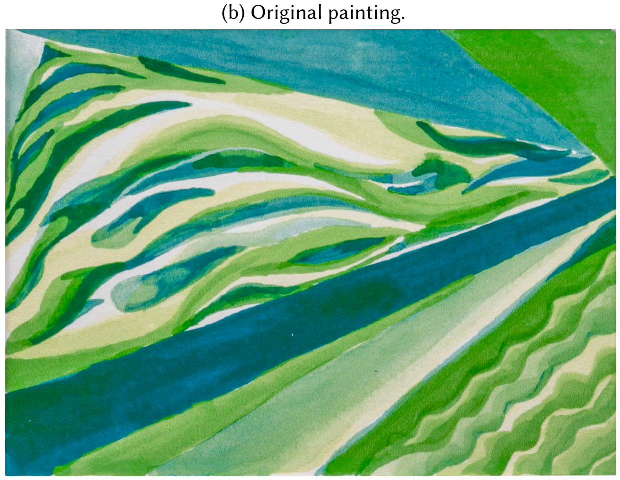
Fig. 8. Reconstruction of 24 test transmittance spectra (printed on transparency) against their ground-truth measurements.



(a) Reproduction with selected inks.



(b) Original painting.



(c) Cyan-yellow reproduction.

Fig. 9. Our mixed integer ink selection for spectral duotone (two-ink) printing. Our selected inks reproduce a limited-palette painting with remarkable accuracy (a). The best pair from a CMYK ink set (cyan and yellow) generates a poor reproduction (c). Duotone reproduction provides powerful visual evidences of the quality of our ink selection method as the smallest mistake would stand out prominently. While the problem size in this particular example is small, we show that our method gives the optimal result when selecting tens of inks from libraries of thousands in a reasonable time.

(a) Painting 5500K (b) Painting 4250K (c) Painting 3000K

(d) Reproduction 5500K (e) Reproduction 4250K (f) Reproduction 3000

Fig. 10. Photographs of a painting and its printed reproduction under three different physical illuminations. The selected inks by our MILP algorithm are Epson Cyan (ID 41 in the ink library in supplementary materials), Epson Magenta (ID 42), Waterproof Yellow (ID 16), and Gray Sublimation (ID 21)).

(a) 2 inks

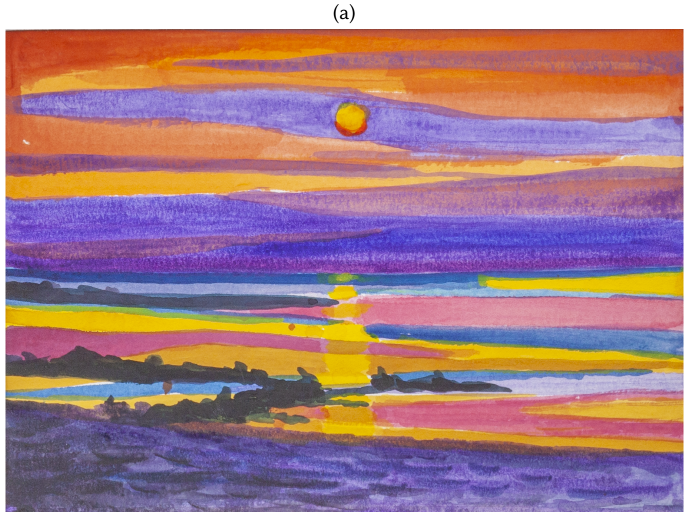
(b) 3 inks

(c) 4 inks

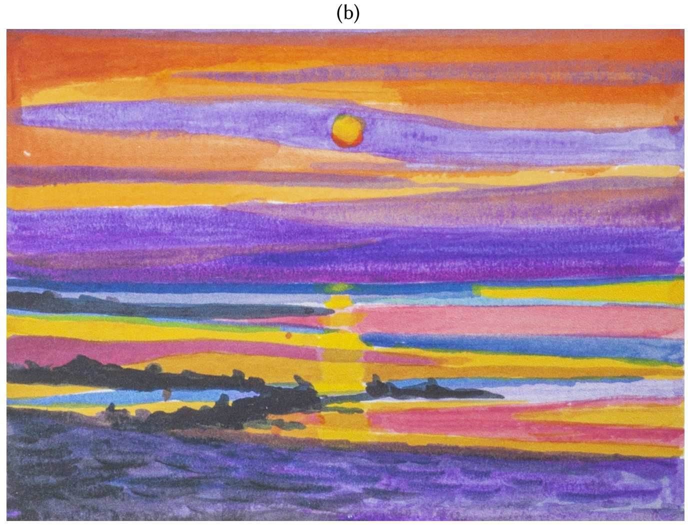
(d) Painting

Fig. 11. Effect of the number of selected inks on the reproduction quality for *Cat*. Photographs of reproduction with (a) 2 inks: Epson Yellow (ID 36), Waterproof Blue (ID 24), (b) 3 inks: Epson Cyan (ID 41), Magenta (ID 42), and waterproof Yellow (ID 16), (c) 4 inks: Epson Cyan (ID 41), Magenta (ID 42), Waterproof Yellow (ID 16), and Gray Sublimation (ID 21). (d) Photograph of the original painting.

(a)



(b)



(c)

Fig. 12. (a) Reproduction using 4 selected inks (Waterproof Yellow (ID 16), Epson Cyan (ID 41) and Magenta (ID 42), Sublimation Red (ID 20)). (b) Original painting. (c) Reproduction using standard Canon CMYK.