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ESTIMATION OF SPECTRAL REFLECTANCE FROM COLORIMETRY

NTNU, GJØVIK

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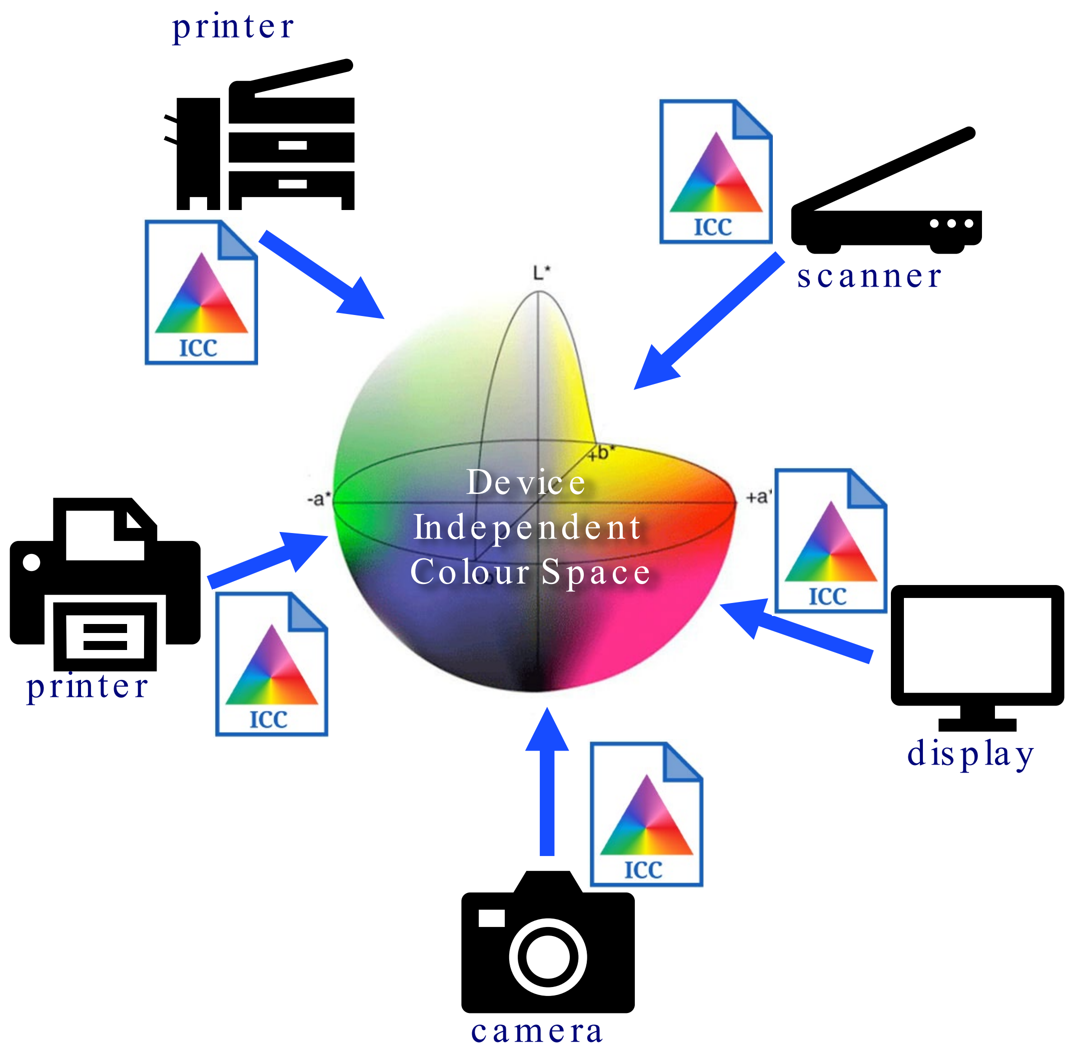
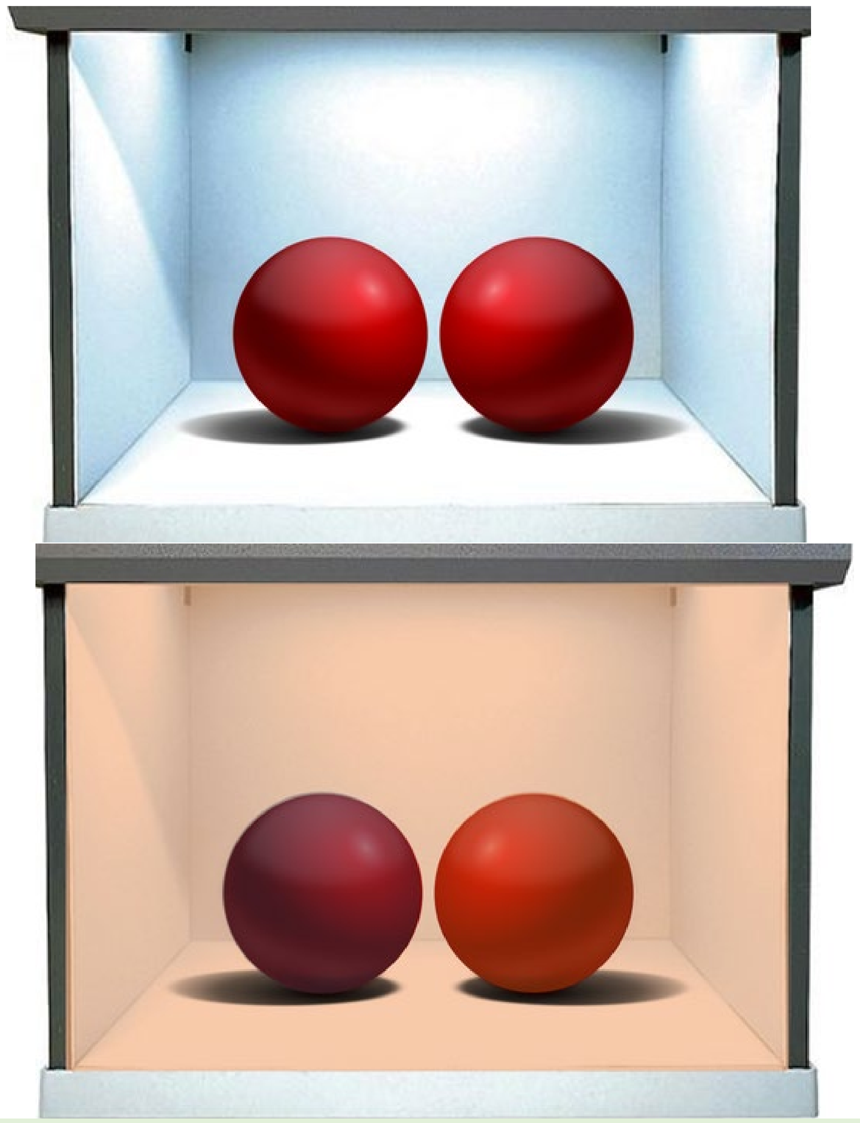
PRESENTATION OUTLINE

BACKGROUND



COLOUR MANAGEMENT



METAMERISM

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BACKGROUND

- iccMAX — The ability to use spectral data
- iccMAX — The ability to use different illuminants and observers without the need for chromatic adaptation
- iccMAX — The ability to embed procedural algorithms in profiles through calculator elements
- iccMAX — More support for total colour appearance, including texture and gloss

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OBJECTIVE

Investigate the efficacy of various spectral estimation methods in handling metamerism for different print datasets and develop a framework for spectral estimation in a colour management workflow.

BACKGROUND

SAT

Sensor adjustment transform - used to estimate some form of sensor excitations under one set of observing conditions based upon the sensor excitations under a different set of observing conditions.

CAT

Chromatic adaptation transform – used to predict corresponding colours (same sensor excitations) and preserve colour constancy under different observing conditions.

MAT

Material adjustment transform – used predict material constancy or how sensor excitations for an object color change with changes in observing conditions

Derhak, M. W., & Berns, R. S. (2015). Introducing Wpt (Waypoint): A color equivalency representation for defining a material adjustment transform. *Color Research & Application*, *40*(6), 535-549.

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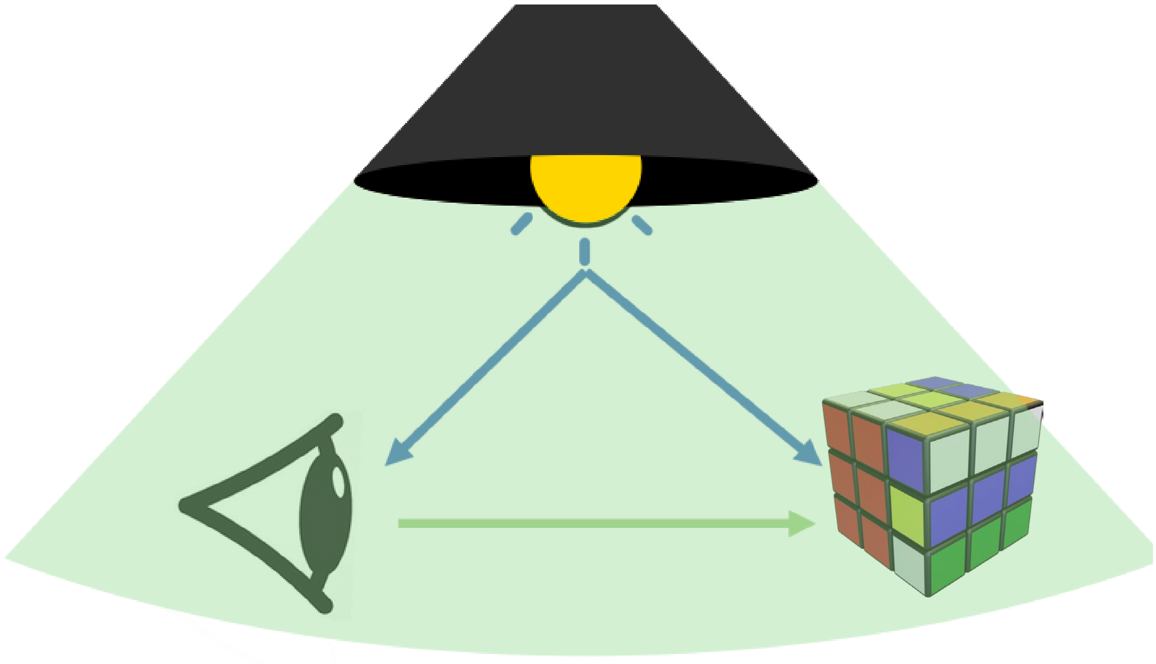
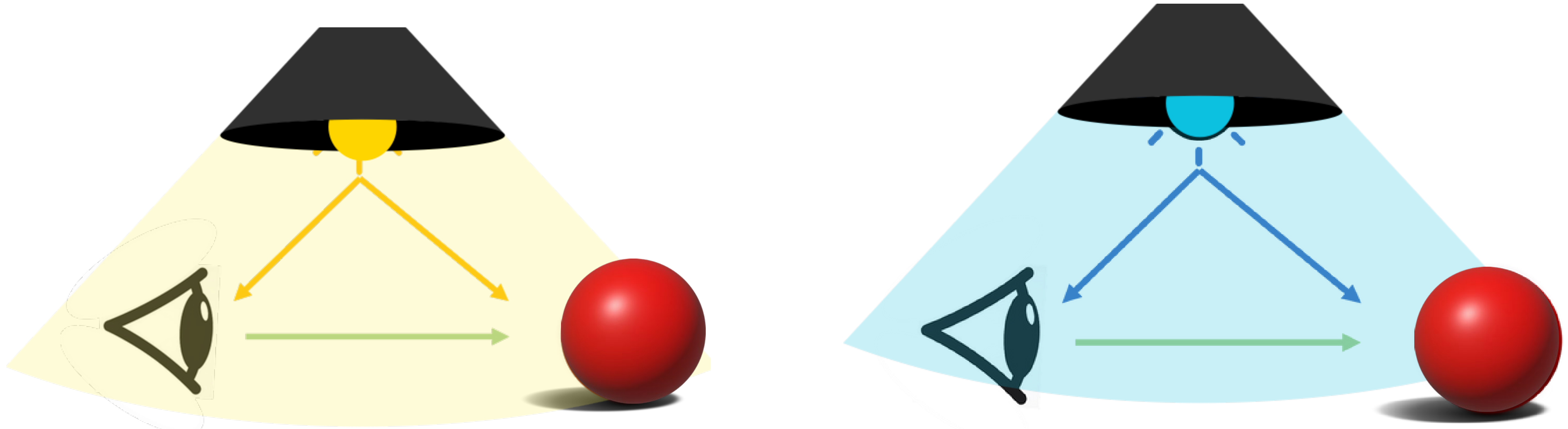
SENSOR ADJUSTMENT TRANSFORM (SAT)

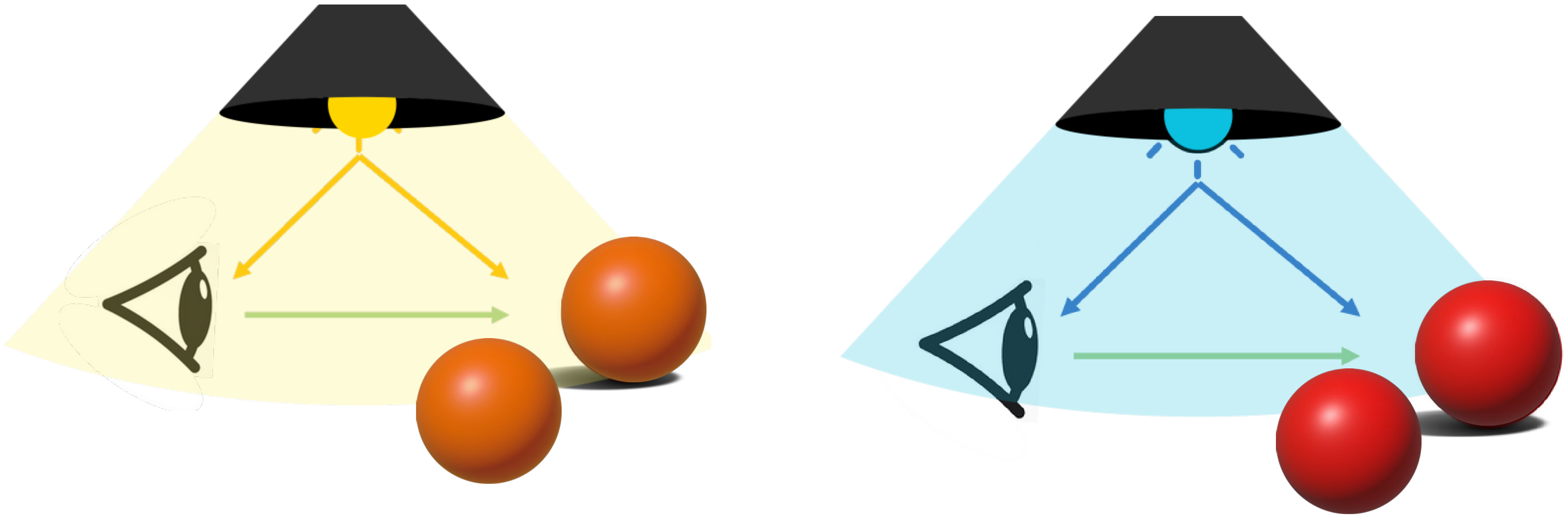


DESTINATION ILLUMINANT

SOURCE ILLUMINANT



CORRESPONDING COLOUR



MATERIAL CONSTANCY

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KEY RESEARCH QUESTIONS

Can training data required for spectral estimation represent a group of printing conditions such that standarised training data selection can be proposed for spectral estimation in colour management?

Can a spectral estimation method be used as an alternative to a material adjustment transform and what is their performance in predicting corresponding colours compared to a CAT?

Develop a suitable spectral estimation workflow that can be easily integrated into colour management?

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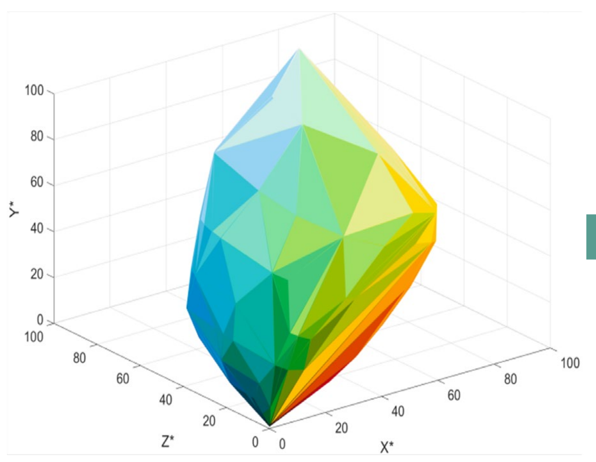
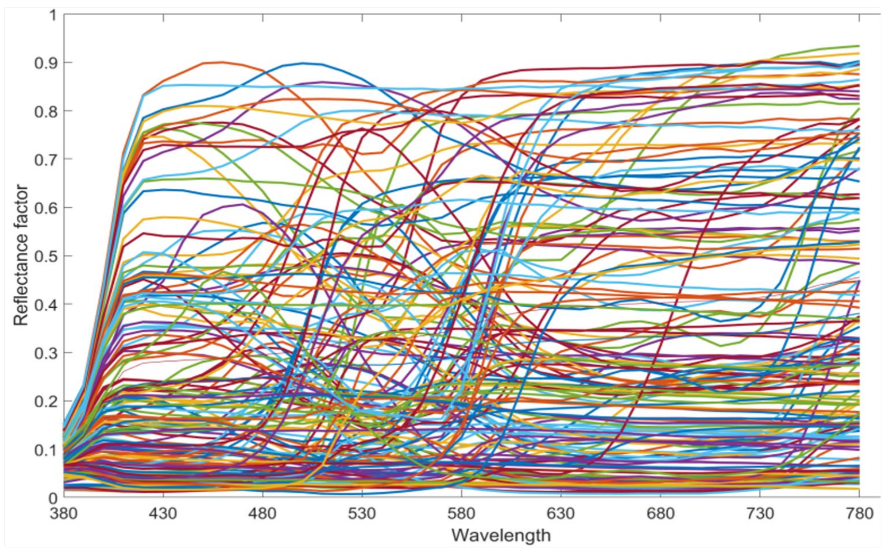
SPECTRAL ESTIMATION FROM COLORIMETRY



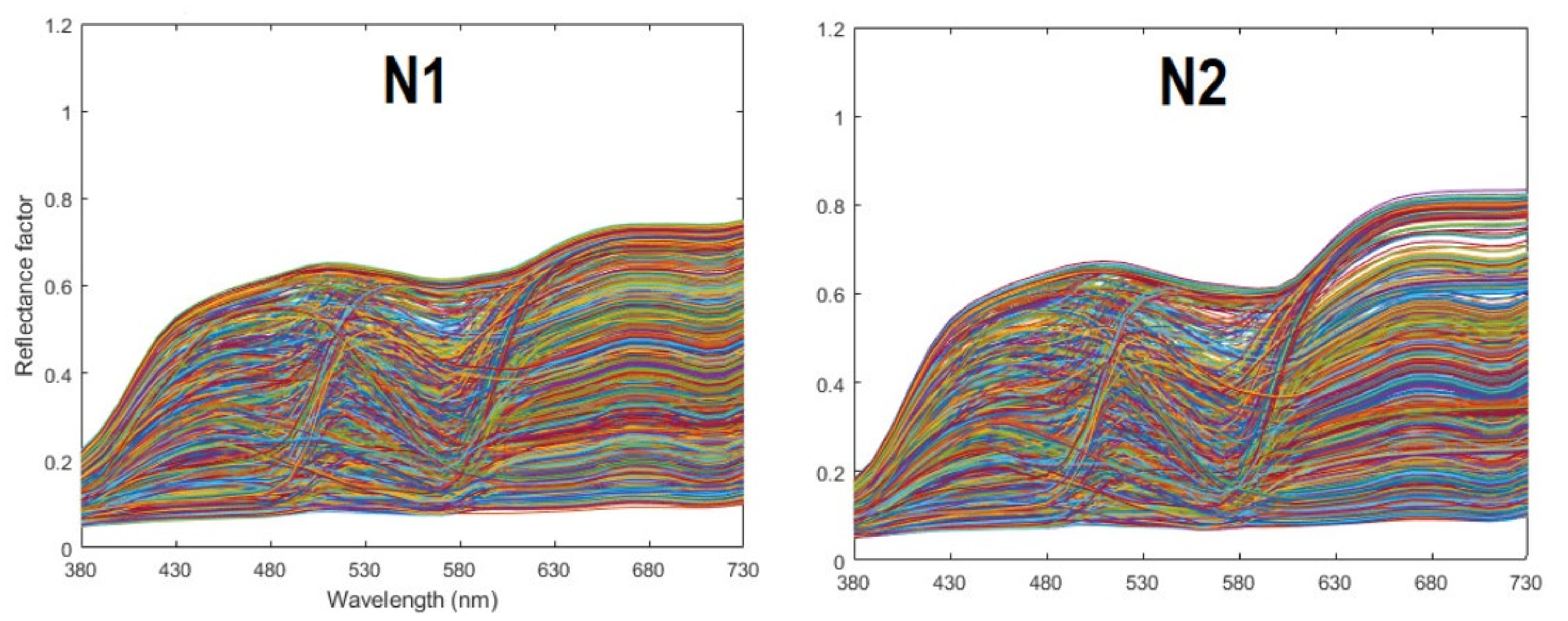
XYZ

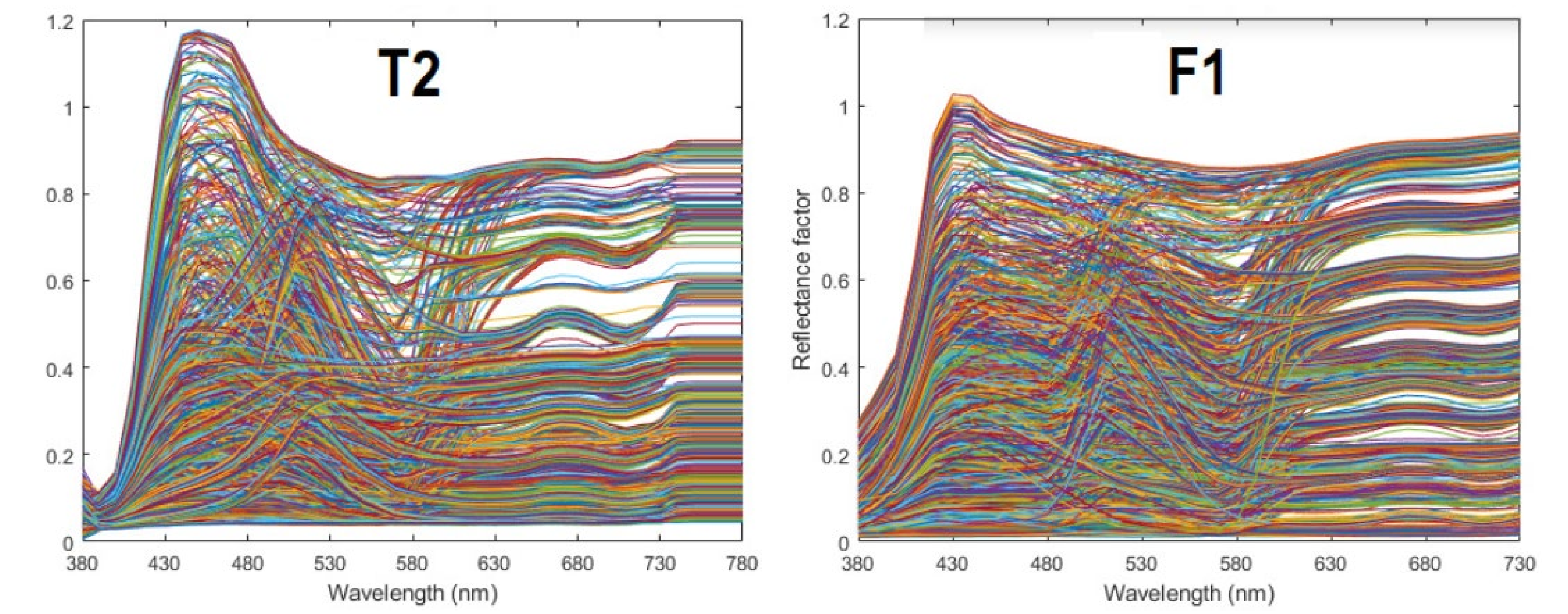


ESTIMATED REFLECTANCE

Identifier	Test data	Training data	Printing Conditions	Substrates (Test/Training)
N2-M1	N2	M1	Dissimilar	Newsprint/Colour chip
N2-W1	N2	W1	Dissimilar	Newsprint/Light coated paper
N2-N1	N2	T1	Similar	Newsprint/Newsprint
N1-N2	N1	N2	Similar	Newsprint/Newsprint
T2-M1	T2	M1	Dissimilar	Textile/Colour chip
T2-F1	T2	F1	Dissimilar	Textile/Premium coated paper
T2-W1	T2	W1	Dissimilar	Textile/Light coated paper
T2-T1	T2	N1	Similar	Textile/Textile
T1-T2	T1	T2	Similar	Textile/Textile

TEST AND TRAINING DATA SET





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DATASETS & METHODS

Identifier	Test data	Training data	Printing conditions	Substrates (Test/Training)
N2–M1	N2	M1	Dissimilar	Newsprint/Colour chip
N2–W1	N2	W1	Dissimilar	Newsprint/Light coated paper
N2–N1	N2	T1	Similar	Newsprint/Newsprint
N1–N2	N1	N2	Similar	Newsprint/Newsprint
T2–M1	T2	M1	Dissimilar	Textile/Colour chip
T2–F1	T2	F1	Dissimilar	Textile/Premium coated paper
T2–W1	T2	W1	Dissimilar	Textile/Light coated paper
T2–T1	T2	N1	Similar	Textile/Textile
T1–T2	T1	T2	Similar	Textile/Textile

Identifier	Spectral Estimation Methods
Wiener	Wiener Estimation
PCA	Principal Component Analysis
wPCA	Wieghted Principal Component Analysis
PInverse	Pseudo Inverse
wPInverse	Weighted Pseudo Inverse
Polynomial 2	Second Order Polynomial 2
Polynomial 3	Third Order Polynomial
Waypoint-R	Waypoint Reconstruction

Standard Illuminants
D50, D65, A, F11 and LED VI

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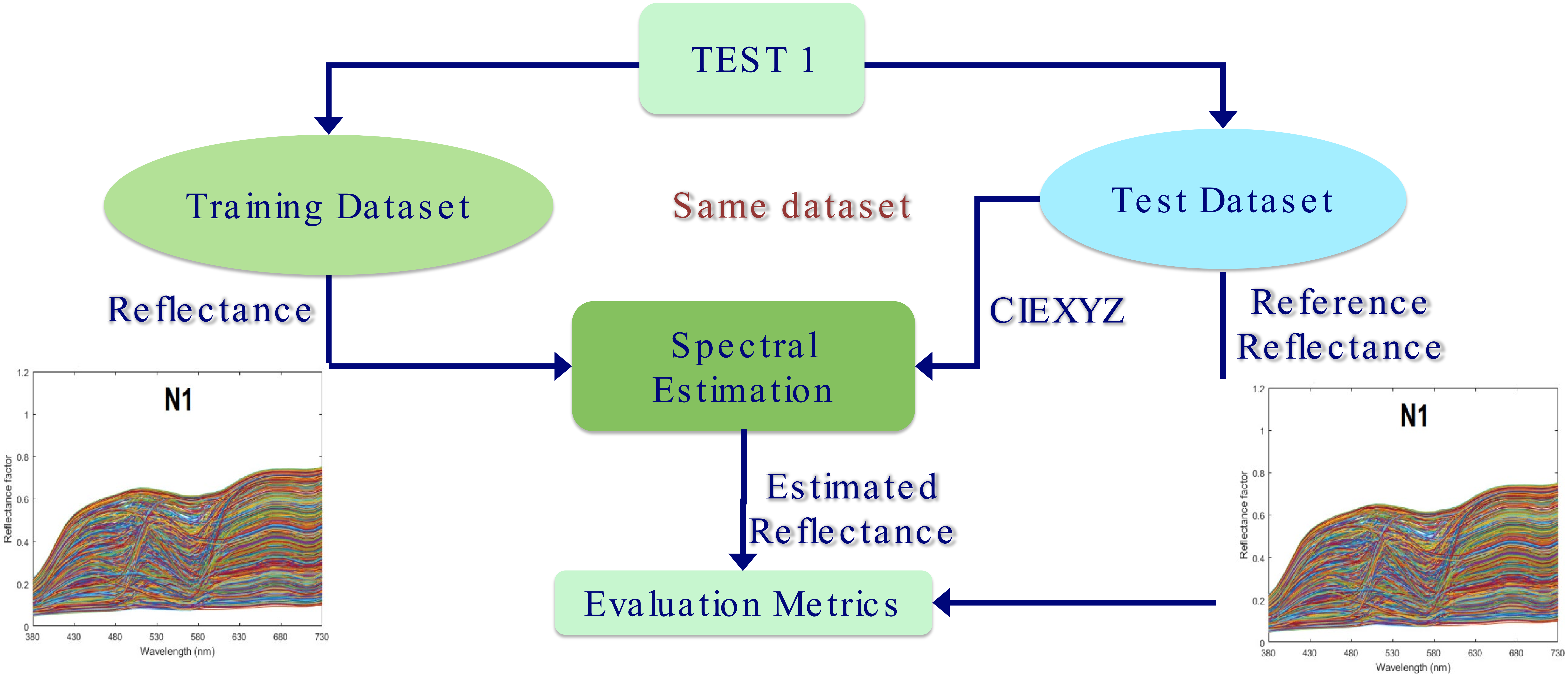
TEST 1



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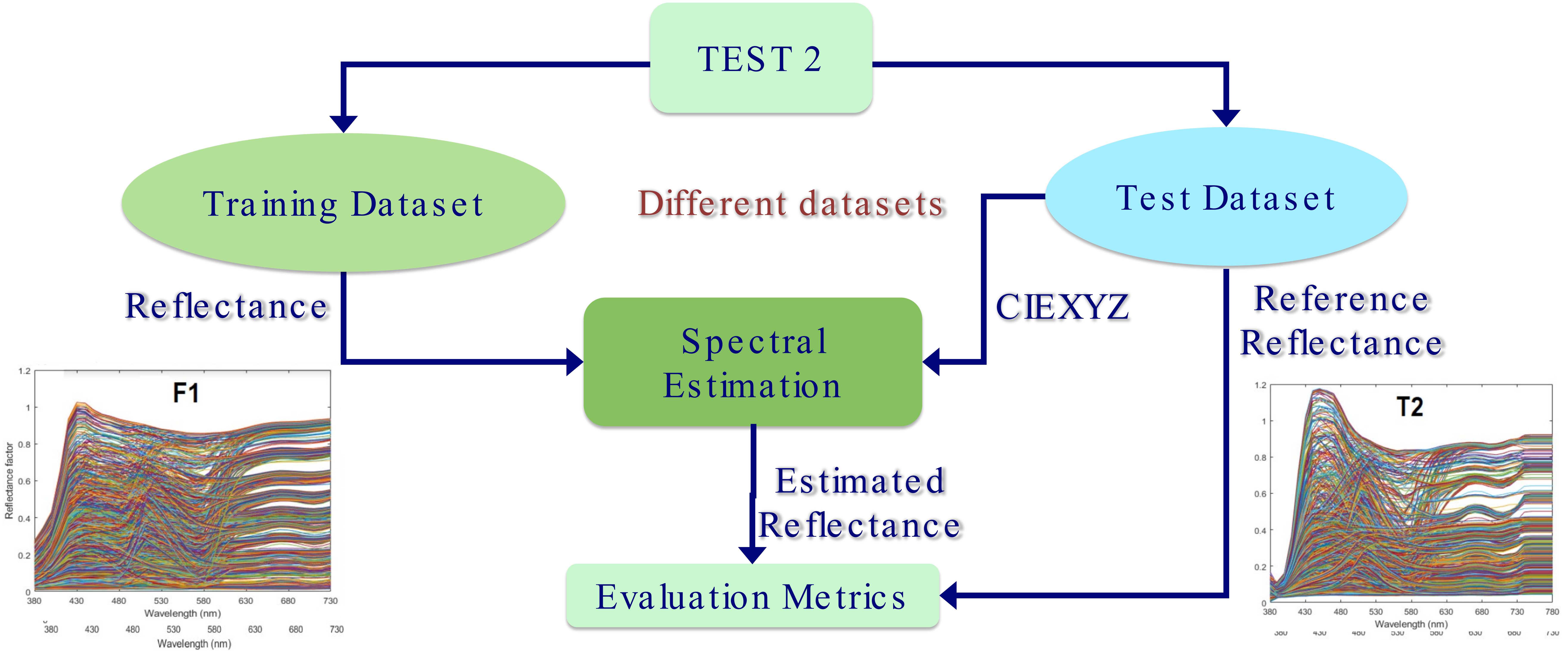
TEST 2



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TRISTIMULUS INTEGRATION

Spectral power distributions of illuminants with narrow peaks, particularly certain fluorescent illuminants, cannot be interpolated to 10 nm from 1 nm without creating large errors in the resulting tristimulus values

Optimum weighting tables of 10 nm interval were generated using the CIE illuminant and observer functions to ensure that the tristimulus values were correctly calculated

Optimum weights have bandpass corrections applied to the weighting factors which are the products of the illuminant multiplied to the observer functions which can be directly applied to the reflectances to get tristimulus values

TRISTIMULUS INTEGRATION

THE LI–WANG–LUO METHOD

Testing the accuracy of methods for the computation of CIE tristimulus values using weighting tables. Li, C., Ronnier Luo, M., Melgosa, M., & Pointer, M. R. (2016).

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RESULTS TEST 1

Mean (max) ΔE_{ab}, metameric difference under illuminant D65 from Test 1.

Dataset	Wiener	PCA	wPCA	PInverse	wPInverse	Polynomial 2	Polynomial 3	Waypoint-R
M1–M1	0.59 (4.46)	0.65 (4.02)	0.3 (3.04)	0.6 (4.33)	0.32 (2.83)	0.44 (3.04)	**0.32 (2.38)**	**0.33 (2.52)**
F1–F1	0.99 (3.99)	0.84 (5.53)	0.28 (1.5)	0.71 (3.87)	**0.29 (1.27)**	0.34 (2.02)	**0.23 (0.96)**	0.48 (1.76)
W1–W1	0.82 (3.44)	0.69 (4.38)	0.27 (1.51)	0.62 (3.26)	**0.25 (1.28)**	0.31 (1.78)	**0.24 (1.07)**	0.96 (3.92)
N1–N1	0.41 (1.42)	0.28 (1.04)	0.13 (0.6)	0.27 (1.17)	**0.12 (0.43)**	0.12 (0.48)	**0.1 (0.46)**	0.66 (1.18)
N2–N2	0.38 (1.49)	0.3 (1.16)	0.13 (0.6)	0.29 (1.3)	**0.13 (0.5)**	0.13 (0.51)	**0.1 (0.51)**	0.83 (1.86)
T1–T1	0.66 (3.07)	0.66 (2.59)	**0.25 (1.27)**	0.6 (2.91)	0.25 (1.35)	0.35 (1.4)	**0.23 (1.04)**	0.61 (2.08)
T2–T2	0.79 (3.42)	0.85 (2.78)	0.34 (1.35)	0.71 (3.15)	**0.32 (1.1)**	0.42 (1.69)	**0.31 (0.95)**	0.63 (1.95)

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RESULTS TEST 1

Mean (max) ΔE_{ab}, metameric difference under illuminant A from Test 1.

Dataset	Wiener	PCA	wPCA	PInverse	wPInverse	Polynomial 2	Polynomial 3	Waypoint-R
M1–M1	1.50 (12.31)	1.67 (12.09)	0.83 (13.8)	1.52 (12.08)	0.81 (8.26)	1.13 (9.47)	**0.81 (7.07)**	**0.83 (6.78)**
F1–F1	0.99 (15.04)	2.40 (14.39)	0.82 (5.61)	2.10 (14.43)	**0.83 (4.41)**	0.95 (5.68)	**0.66 (2.68)**	1.40 (6.71)
W1–W1	0.82 (11.95)	1.97 (12.08)	0.76 (5.46)	1.79 (11.33)	**0.68 (3.38)**	0.85 (4.98)	**0.67 (3)**	2.74 (11.05)
N1–N1	0.41 (4.86)	0.83 (3.5)	0.38 (1.86)	0.81 (4.01)	**0.36 (1.34)**	0.36 (1.43)	**0.31 (1.41)**	1.63 (3.52)
N2–N2	0.38 (5.33)	0.88 (4.01)	0.39 (1.84)	0.84 (4.6)	**0.37 (1.52)**	0.37 (1.56)	**0.30 (1.55)**	2.20 (5.29)
T1–T1	0.66 (9.95)	1.71 (8.02)	0.62 (3.64)	1.56 (9.29)	**0.57 (4.07)**	0.84 (3.46)	**0.54 (2.2)**	1.24 (6.49)
T2–T2	0.79 (11.03)	2.21 (8.75)	0.82 (4.15)	1.84 (10.02)	**0.74 (3.4)**	1.00 (3.97)	**0.71 (2.03)**	1.35 (5.5)

RESULTS TEST 2

Mean (max) ΔE_{ab}, metameric difference under illuminant D65 from Test 2.

Dataset	Wiener	PCA	wPCA	PInverse	wPInverse	Polynomial 2	Polynomial 3	Waypoint-R
N2–M1	1.04 (2.62)	0.84 (2.31)	**0.91 (1.78)**	0.93 (2.49)	0.93 (1.9)	1.02 (1.95)	1.03 (1.73)	**0.90 (2)**
N2–W1	0.57 (1.77)	0.33 (1.29)	0.27 (1.16)	0.30 (1.29)	**0.20 (0.7)**	0.23 (0.86)	**0.22 (0.84)**	0.83 (2.99)
N2–N1	0.5 (1.65)	0.31 (1.23)	0.17 (0.7)	0.31 (1.42)	**0.16 (0.55)**	0.17 (0.43)	**0.14 (0.4)**	0.83 (1.86)
N1–N2	0.32 (1.27)	0.3 (0.96)	0.15 (0.65)	0.28 (1.06)	**0.15 (0.47)**	0.16 (0.58)	**0.14 (0.57)**	0.76 (1.77)
T2–M1	1.12 (3.78)	1 (3.68)	0.92 (3.04)	1.03 (3.7)	**0.88 (2.63)**	0.98 (2.94)	0.93 (2.52)	**0.86 (3.12)**
T2–F1	1.15 (4.23)	1.09 (3.2)	0.73 (2.32)	0.89 (3.91)	**0.64 (2.25)**	0.67 (2.12)	**0.61 (1.99)**	0.77 (2.69)
T2–W1	0.86 (3.79)	0.95 (3.14)	0.73 (2.52)	0.80 (3.46)	**0.63 (2.03)**	**0.61 (2.06)**	0.65 (2.23)	0.99 (3.93)
T2–T1	0.87 (3.56)	0.79 (2.96)	0.47 (1.68)	0.75 (3.2)	**0.44 (1.51)**	0.48 (1.85)	**0.44 (1.37)**	0.86 (3.12)
T1–T2	0.63 (3.23)	0.81 (2.66)	0.5 (1.22)	0.65 (2.95)	0.47 (1.51)	**0.44 (1.57)**	**0.43 (1.51)**	0.76 (2.77)

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RESULTS TEST 2

Mean (max) ΔE_{ab}, metameric difference under illuminant A from Test 2.

Dataset	Wiener	PCA	wPCA	PInverse	wPInverse	Polynomial 2	Polynomial 3	Waypoint-R
N2–M1	2.83 (6.43)	**2.26 (5.97)**	2.39 (5.01)	2.50 (6.11)	2.48 (5.15)	2.72 (5.07)	2.74 (4.94)	**2.35 (5.13)**
N2–W1	1.66 (5.62)	0.93 (3.84)	0.73 (3.27)	0.86 (4.62)	**0.54 (1.85)**	0.57 (2.25)	**0.57 (2.14)**	2.31 (8.9)
N2–N1	1.61 (5.77)	0.92 (4.21)	0.51 (2.21)	0.92 (4.93)	**0.47 (1.92)**	0.49 (1.25)	**0.42 (1.22)**	2.20 (5.29)
N1–N2	1 (4.47)	0.87 (3.22)	0.44 (2.04)	0.81 (3.71)	**0.42 (1.4)**	0.45 (1.75)	**0.40 (1.73)**	1.99 (4.95)
T2–M1	2.61 (11.35)	2.4 (11.16)	2.05 (9.04)	2.43 (11.07)	**1.93 (7.19)**	2.25 (8.87)	2.14 (6.84)	**1.78 (7.75)**
T2–F1	2.62 (12.57)	2.79 (8.8)	1.78 (5.63)	2.06 (11.37)	**1.34 (5.31)**	1.49 (4.77)	**1.34 (4.24)**	1.48 (6.97)
T2–W1	2.1 (11.31)	2.47 (8.86)	1.89 (7.24)	1.98 (10.21)	**1.54 (5.72)**	**1.41 (4.85)**	1.64 (6.87)	2.47 (10.5)
T2–T1	2.54 (10.35)	2.11 (8.28)	1.21(4.51)	2.04 (9.74)	**1.11 (3.54)**	1.23 (3.73)	**1.12 (3.3)**	1.78 (7.75)
T1–T2	1.65 (10.27)	2.19 (8.05)	1.37 (3.45)	1.75 (9.28)	1.26 (3.38)	**1.18 (3.89)**	**1.14 (3.22)**	1.57 (6.94)

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RESULTS OF SPECTRAL ESTIMATION AS A MAT

Mean ΔE_{00} between reference tristimulus values and chromatically adapted/estimated.

		D50			D65			A			F11			LED-V1			
		D65	A	F11	D50	A	F11	D50	D65	F11	D50	D65	A	D50	D65	A	Avg
N2-N2	CAT02	0.96	2.59	1.77	0.95	3.47	2.03	2.78	3.76	2.70	1.81	2.07	2.58	2.47	3.28	1.15	2.29
	CAT16	1.02	2.83	1.87	1.01	3.76	2.25	2.97	4.01	2.70	1.92	2.32	2.62	2.69	3.56	1.17	2.45
	L-Bradford	0.93	2.38	1.81	0.91	3.21	2.10	2.62	3.60	2.53	1.85	2.16	2.38	2.20	3.00	1.14	2.19
	Oleari-MAT	0.53	1.75	2.54	0.53	1.98	2.79	1.76	1.99	1.45	2.57	2.78	1.56	—	—	—	1.85
	Waypoint-MAT	0.92	2.37	1.32	0.90	3.19	1.73	2.62	3.63	2.47	1.30	1.68	2.13	—	—	—	2.02
	Burns-CAT	0.96	2.61	1.85	0.94	3.46	2.22	2.83	3.85	2.58	1.87	2.25	2.45	2.52	3.34	1.11	2.32
	Burns-R	0.80	2.10	1.20	0.79	2.79	1.65	2.29	3.17	1.95	1.66	2.07	1.90	1.76	2.37	1.10	1.84
	wPInverse	**0.11**	**0.34**	**0.37**	**0.11**	**0.45**	**0.46**	**0.37**	**0.48**	**0.26**	**0.39**	**0.47**	**0.25**	**0.36**	**0.46**	**0.08**	**0.33**
	Polynomial 3	**0.1**	**0.29**	**0.33**	**0.1**	**0.38**	**0.42**	**0.32**	**0.42**	**0.2**	**0.35**	**0.43**	**0.2**	**0.31**	**0.4**	**0.04**	**0.29**
N2-M1	wPInverse	0.78	2.11	1.18	0.77	2.81	1.33	2.31	3.16	2.46	1.18	1.33	2.14	1.82	2.47	1.01	1.79
	Polynomial 3	0.87	2.34	1.32	0.85	3.14	1.48	2.55	3.48	2.96	1.28	1.43	2.52	2.00	2.71	1.13	2.00
N2-W1	wPInverse	0.18	0.48	0.74	0.17	0.65	0.79	0.52	0.70	0.78	0.77	0.80	0.77	0.52	0.64	0.25	0.58
	Polynomial 3	0.20	0.54	0.81	0.20	0.72	0.88	0.58	0.78	0.79	0.83	0.86	0.79	0.56	0.70	0.25	0.63
N2-N1	wPInverse	0.14	0.41	0.49	0.14	0.54	0.56	0.44	0.58	0.49	0.52	0.57	0.50	0.40	0.52	0.12	0.43
	Polynomial 3	0.13	0.39	0.44	0.13	0.52	0.49	0.43	0.56	0.51	0.46	0.5	0.51	0.37	0.49	0.11	0.40

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RESULTS OF SPECTRAL ESTIMATION AS A MAT

Mean ΔE_{00} between reference tristimulus values and chromatically adapted/estimated.

		D50			D65			A			F11			LED-V1			
		D65	A	F11	D50	A	F11	D50	D65	F11	D50	D65	A	D50	D65	A	Avg
T2–T2	CAT02	0.84	2.32	2.91	0.83	3.11	3.31	2.32	3.11	2.83	3.01	3.46	2.76	2.58	3.16	1.67	2.55
	CAT16	0.98	2.84	2.99	0.98	3.78	3.53	2.82	3.76	2.86	3.12	3.77	2.82	2.98	3.67	1.68	2.84
	L-Bradford	0.80	2.03	2.96	0.79	2.75	3.37	2.15	2.94	2.51	3.07	3.55	2.42	2.17	2.68	1.66	2.39
	Oleari-MAT	0.61	1.82	3.38	0.60	2.18	3.61	1.82	2.21	2.69	3.40	3.61	2.85	—	—	—	2.40
	Waypoint-MAT	0.74	1.66	2.15	0.72	2.31	2.67	1.82	2.61	1.87	2.12	2.62	1.77	—	—	—	1.92
	Burns-CAT	0.86	2.30	3.12	0.85	3.09	3.70	2.42	3.32	2.50	3.21	3.92	2.36	2.64	3.21	1.63	2.61
	Burns-R	0.72	1.46	2.14	0.68	2.04	2.57	1.67	2.47	1.52	2.41	2.96	1.58	1.67	1.93	1.66	1.83
	wPInverse	**0.24**	**0.58**	**0.89**	**0.24**	**0.80**	**1.10**	**0.64**	**0.90**	**0.50**	**0.95**	**1.15**	**0.53**	**0.64**	**0.85**	**0.28**	**0.69**
	Polynomial 3	**0.25**	**0.59**	**1.02**	**0.24**	**0.81**	**1.20**	**0.68**	**0.95**	**0.66**	**1.16**	**1.38**	**0.70**	**0.63**	**0.88**	**0.16**	**0.75**
T2–M1	wPInverse	0.58	1.30	1.73	0.56	1.81	2.12	1.42	2.03	1.44	1.77	2.15	1.44	1.59	1.92	1.37	1.55
	Polynomial 3	0.62	1.47	1.87	0.61	2.03	2.24	1.60	2.25	1.69	1.92	2.30	1.66	1.66	2.02	1.40	1.69
T2–F1	wPInverse	0.41	0.94	1.32	0.41	1.31	1.58	1.03	1.44	1.07	1.39	1.65	1.05	1.13	1.38	0.76	1.12
	Polynomial 3	0.45	1.12	1.56	0.45	1.52	1.87	1.21	1.64	1.06	1.63	1.93	1.05	1.37	1.63	0.76	1.28
T2–T1	wPInverse	0.30	0.74	1.43	0.29	0.99	1.62	0.85	1.18	1.16	1.51	1.7	1.2	1.28	1.54	0.77	1.10
	Polynomial 3	0.30	0.77	1.39	0.29	1.02	1.58	0.91	1.25	1.09	1.56	1.79	1.13	1.11	1.42	0.53	1.08

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PREDICTION OF CORRESPONDING COLOUR DATA

Overall ΔE_{94} between destination tristimulus values of corresponding colours and adapted/estimated tristimulus values under varying destination lights.

Method	CSAJ	Helson	Lam & Rigg	Lutchi	Average
Cat02	3.67	3.60	2.98	3.41	3.42
Cat16	3.94	4.13	3.47	3.30	3.71
L-Bradford	3.71	3.47	2.84	3.43	3.36
Burns-CAT	3.81	4.19	3.15	3.68	3.71
Oleari-MAT	4.63	4.72	3.89	4.27	4.38
Wpt-MAT	4.28	4.02	3.83	4.53	4.17
wPInverse(M1)	4.14	3.76	3.48	4.51	3.97
Polynomial 3 (M1)	4.22	3.77	3.51	4.46	3.99
wPInverse (N2)	4.71	3.65	3.42	4.29	4.02
Polynomial 3 (N2)	4.39	3.76	3.47	4.34	3.99
wPInverse (T2)	4.69	3.65	3.46	4.36	4.04
Polynomial 3 (T2)	4.35	3.57	3.31	4.37	3.90

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SPECTRAL ESTIMATION USING iccMAX

```
<MainFunction>
    {
        in(0,3) <!-- places tristimulus values from the input channel onto the stack -->
        tput(0,1) <!-- places first input value (X) on temporary memory storage -->
        tput(1,1) <!-- places second input value (Y) on temporary memory storage -->
        tput(2,1) <!-- places third input value (Z) on temporary memory storage-->
        <!-- Values on temporary memory storage will be used by Poly3Expansion macro -->
        call{Poly3Expansion} <!-- Places the X,Y,Z polynomial terms on the stacks-->
        mtx{M} <!-- performs matrix multiplication of the polynomial terms
                    on the stack and matrix M and places the output on the stack-->
        out(0,41) <!-- places 41 values from the stack onto the output channel -->
    }
</MainFunction>
```

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SPECTRAL ESTIMATION USING iccMAX

```
iccApplyNamedCMM lutchid50.txt 3 0 xyzD50toref.icc
```

```
"nc001F"      ; Data Format
icEncodeFloat    ; Encoding

;Source Data Format: 'XYZ '
;Source Data Encoding: icEncodeFloat
;Source data is after semicolon

;Profiles applied
; xyzD50toref.icc

   0.6441     0.9077     0.9852     0.9981     1.0052     1.0087     1.0136     1.0216
   1.0256     1.0218     1.0218     1.0222     1.0095     0.9897     0.9787     0.9808
   0.9823     0.9826     0.9932     1.0090     1.0180     1.0211     1.0218     1.0256
   1.0310     1.0388     1.0473     1.0510     1.0528     1.0543     1.0564
   ;     0.9709     1.0000     0.8310

   0.1849     0.2205     0.2278     0.2287     0.2295     0.2284     0.2265     0.2236
   0.2168     0.2059     0.1952     0.1847     0.1720     0.1599     0.1532     0.1531
   0.1540     0.1603     0.1740     0.1962     0.2182     0.2359     0.2482     0.2575
   0.2650     0.2723     0.2791     0.2832     0.2858     0.2878     0.2899
   ;     0.2035     0.1842     0.1831
```

```
iccApplyProfiles RGB_D65_2deg.tif  D65_2deg_Reflectance.tif 2 0 1 0 1
argb2xyzD65toref.icc 3
```

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KEY CONCLUSIONS

Based on material components, a single reflectance dataset can represent a group of printing conditions

Spectral estimation methods can be used as an alternative to MAT.

Third-order polynomial spectral estimation method can be effectively encoded inside an ICC profile using iccMAX

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FUTURE SCOPE

- Spectral training data evaluation should be done for industrial use cases for ICC to recommend standard training datasets required for implementing spectral estimation through ICC profiles.
- Spectral estimation can be adopted to connect colour profiles through a spectral PCS.
- Spectral estimation can be recommended as a sensor adjustment transform whenever a profile needs to connect to another profile having different colorimetry.
- Spectral reproduction workflows through ICC colour management will require a good testing paradigm to assess both spectral and colorimetric quality.

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THANK YOU