A new connection space for low-dimensional spectral color management

Steven Le Moan[a] and Philipp Urban[b]

[a]Technische Universität Darmstadt, Germany
[b]Fraunhofer-Institut für Graphische Datenverarbeitung, Darmstadt, Germany

ABSTRACT

Multi- or hyper-spectral pixels are usually represented as vectors with high dimensionality. For many applications, not all of these dimensions are actually necessary, and a few values are enough to measure and/or process the pixel with a very good accuracy. In this work, we introduce a new strategy to reduce the dimensionality of spectral images ranging in the visible wavelengths, for purposes of color management. We define a new Interim Connection Space (ICS) that contains only five dimensions, and show that it has numerous advantages over state-of-the-art ICS such as LabPQR. In particular, it allows for a better spectral reconstruction accuracy.

1. INTRODUCTION

Spectral color management consists of extending the traditional color reproduction techniques to being independent from viewing conditions (illuminant, standard observer). Multi- and hyper-spectral pixels are typically described by several dozens of reflectance values, allowing to analyze their color renderings under various illuminants with great accuracy. Nevertheless, not only does a high-dimensional image create huge memory requirements, raw spectral data often lack of perceptual meaning. Indeed, color appearance can only be estimated in low-dimensional spaces such as CIELAB or CIECAM02, which require to specify certain viewing conditions. In other words, what we can refer to as the *spectral space* contains information aplenty, but is memory-costly and does not allow for direct perceptual analysis, whereas *colorimetric spaces* are perceptually meaningful, computationally efficient, but limited to certain viewing conditions, e.g., one particular illuminant.

The whole challenge when it comes to spectral color management lies in finding a tradeoff between these two conditions. In recent years, there have been several attempts at creating low-dimensional *Interim Connection Spaces* (ICS), to represent the most important features of multi- or hyper-spectral pixels in only a few dimensions. A good ICS should have no more than *a few components* (typically 6), it should span an entropy large enough to allow for an *accurate spectral reconstruction*, but small enough for *limited memory requirements* (e.g. for building look-up tables). Also, in order to be useful for applications such as spectral gamut mapping, it should be*perceptually meaningful*. For example, the Euclidean distance should have a good correlation with a metric like CIEDE2000 for various viewing conditions. Finally, a spectral reproduction should not only be better than a colorimetric reproduction on average over several illuminants, it should be at least as good under one common light such as CIED65 (daylight), for acceptability reasons. Therefore, a good ICS should as well allow to be *competitive with colorimetric workflows* under some specific viewing conditions.

Derhak and Rosen[1] introduced LabPQR, an ICS with three colorimetric dimensions (CIELAB components), optimized for a certain illuminant, as well as 3 spectral dimensions (PQR). The latter convey the dominant structure of the difference between original and reconstructed spectra from colorimetric values (also referred to as metameric black). Although it has been reported that LabPQR can be used successfully in several applications, it struggles to meet all of the aforementioned criteria in that its spectral dimensions (PQR) lack of perceptual meaning. Moreover, it has been shown more recently by Zhang *et al.*[2] that a multiple-XYZ space can outperform LabPQR when it comes to spectral reconstruction accuracy. The authors proposed indeed to concatenate several colorimetric spaces (XYZ) from different illuminants, the latter being computed as the principal components from a set of dozens of real illuminants' spectral power distributions. Such approach introduces however redundancy, due to the fact that some perceptual attributes do not vary much from one illuminant to another.[3,4] Moreover,

Send correspondence to steven.lemoan@gmail.com or philipp.urban@igd.fraunhofer.de

the multiple-XYZ ICS described by the authors lacks of an actual strategy to weight the various illuminants into consideration, with respect to their relative importance in a given application.

Based on these remarks, we propose an alternative ICS which has the advantage of being simple, meaningful, and – more importantly – with only five dimensions. We performed experiments over the Munsell spectra from the Vrhel collection,[5] as well as over a database of 16 multispectral images of natural scenes. A total of 74 illuminants were considered. Our results indicate that the proposed ICS allows for an overall better tradeoff between the aforementioned criteria: good overall accuracy of the reconstructed spectra, low computational burden, meaningful Euclidean distance and competitiveness with colorimetric workflows.

2. A NEW CONNECTION SPACE

2.1 Dimensionality reduction

The goal of the proposed ICS is to represent – with only 5 dimensions – high-dimensional pixels of reflectance spectra ranging in the visible wavelengths (roughly 380nm to 740nm). As in LabPQR, we use actual CIELAB values from a common illuminant (CIED65) as the first three dimensions. Only, in our case, we use the hue-linear LAB2000HL[6] space for a better perceptual uniformity. In that way, we make sure to have an accuracy at least as good as in a metameric workflow for this illuminant.

According to the other aforementioned criteria, the remaining dimensions of the proposed ICS must have three main characteristics:

- To be as de-correlated as possible to the first three coordinates, in order to avoid redundancy.
- To represent a large variety of viewing conditions, so as to convey as much spectral information as possible and therefore allow for an accurate spectral reconstruction.
- To be perceptually meaningful.

Therefore, we suggest to compute LAB2000HL coordinates for a representative illuminant that is as de-correlated as possible from CIED65. For this, we use a set of illuminants' Spectral Power Distributions (SPDs), denoted Θ, that we artificially de-correlate to the SPD of CIED65 by orthogonal subspace projection[7] (see Section 3.1.2 for an example). The orthogonal subspace of an SPD Υ is computed by a linear transformation defined by the following matrix:

$$\mathbf{P} = \mathbf{I} - \Upsilon(\Upsilon^T\Upsilon)^{-1}\Upsilon^T \tag{1}$$

where $\mathbf{I}$ is the identity matrix. By projecting an SPD υ by $\mathbf{P}$ such as $\upsilon_0 = \upsilon\mathbf{P}$, one ensures that the result υ_0 is de-correlated from Υ.

The set Θ can be built with regard to a specific application, i.e. all the illuminants under which the spectral reproduction would be observer, besides CIED65. Otherwise, Θ must contain a large variety of realistic SPDs (see Section 3.1.2).

We then extract the first principal component[8] from the de-correlated set $\Theta' = \{\upsilon\mathbf{P}|\upsilon \in \Theta\}$ and use it to compute the required LAB2000HL values. In a previous study[4] we observed that achromatic components from renderings under various illuminants are usually very correlated. Therefore, only a_{00HL} and b_{00HL} are eventually used to finish building the proposed ICS, which we will refer to as *LabAB* because of its structure.

2.2 Implementation and spectral reconstruction

The conversion from reflectance to LabAB is straightforward, as illustrated on Figure 1.

For the reconstruction, we use a pseudo-inverse strategy on a training set of spectra. The idea is to obtain a linear transformation matrix from ICS back to reflectance. However, the conversion from LAB2000HL not being linear, an intermediate transformation to XYZ coordinates is necessary (see e.g.[9] on the linearity of XYZ). Figure 2 illustrates the reconstruction procedure.

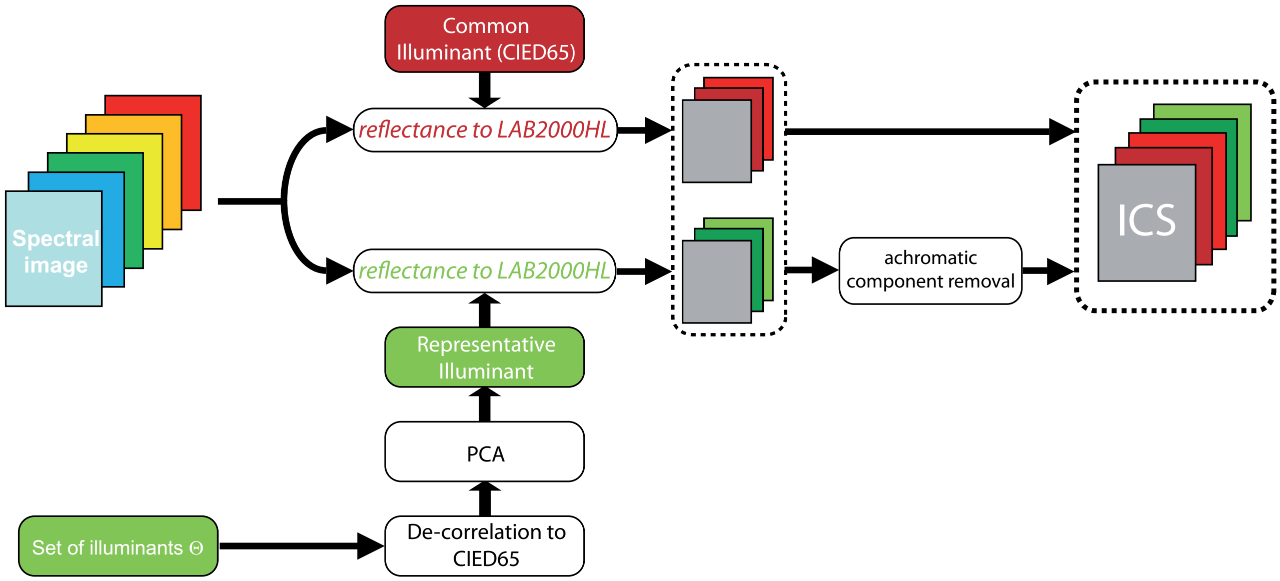


Figure 1. Conversion of a spectral image to the LabAB ICS.

3. EXPERIMENTS AND RESULTS

3.1 Setup

3.1.1 Benchmark

We compared LabAB with the state-of-the-art ICS LabPQR[1] and the synthetic-illuminants-based XYZXYZ by Zhang *et al.*[2] In order to ensure a fair comparison, the ICS-to-Reflectance reconstructions for each space were trained on a same dataset and an intermediate CIELAB to XYZ conversion was used for LabPQR (for linearity). The whole LabPQR dimensionality reduction and reconstruction was otherwise implemented according to the original paper by Derhak and Rosen.[1] In case of reconstructed spectral values falling outside the range $[0 \ldots 1]$, they were clipped.

3.1.2 Data

For training the spectral reconstruction, we used the Dupont set of spectra from the Vrhel collection.[5] Testing was done over the Munsell set from the same collection, as well as the 16 images from Foster's 2002 and 2004 databases[10] – outdoor pictures of natural scenes with 30 to 32 channels in the visible range.

We used a total of 74 illuminants' spectral power distributions in Θ: four CIE daylights (D50, D65, D80 and D100), the CIE A and Fluorescent Series as well as the full collection made available by the National Gallery of London,[11] which includes LED, fluorescent and tungsten-based lights. All illuminants were scaled to the range $[0 \ldots 1]$. An example of de-correlated illuminants is shown on Figure 3a and the whole set and its principal component are shown on Figure 3b. CIED65 was used to compute the first coordinates in both LabPQR and LabAB and the same Θ was used for both XYZXYZ and LabAB.

3.1.3 Evaluation

In this study, we focus mainly on the spectral reconstruction abilities. Therefore, we evaluated the reconstruction error for each ICS with the CIEDE2000 color difference,[12] on average over all illuminants but also under CIED65 only.

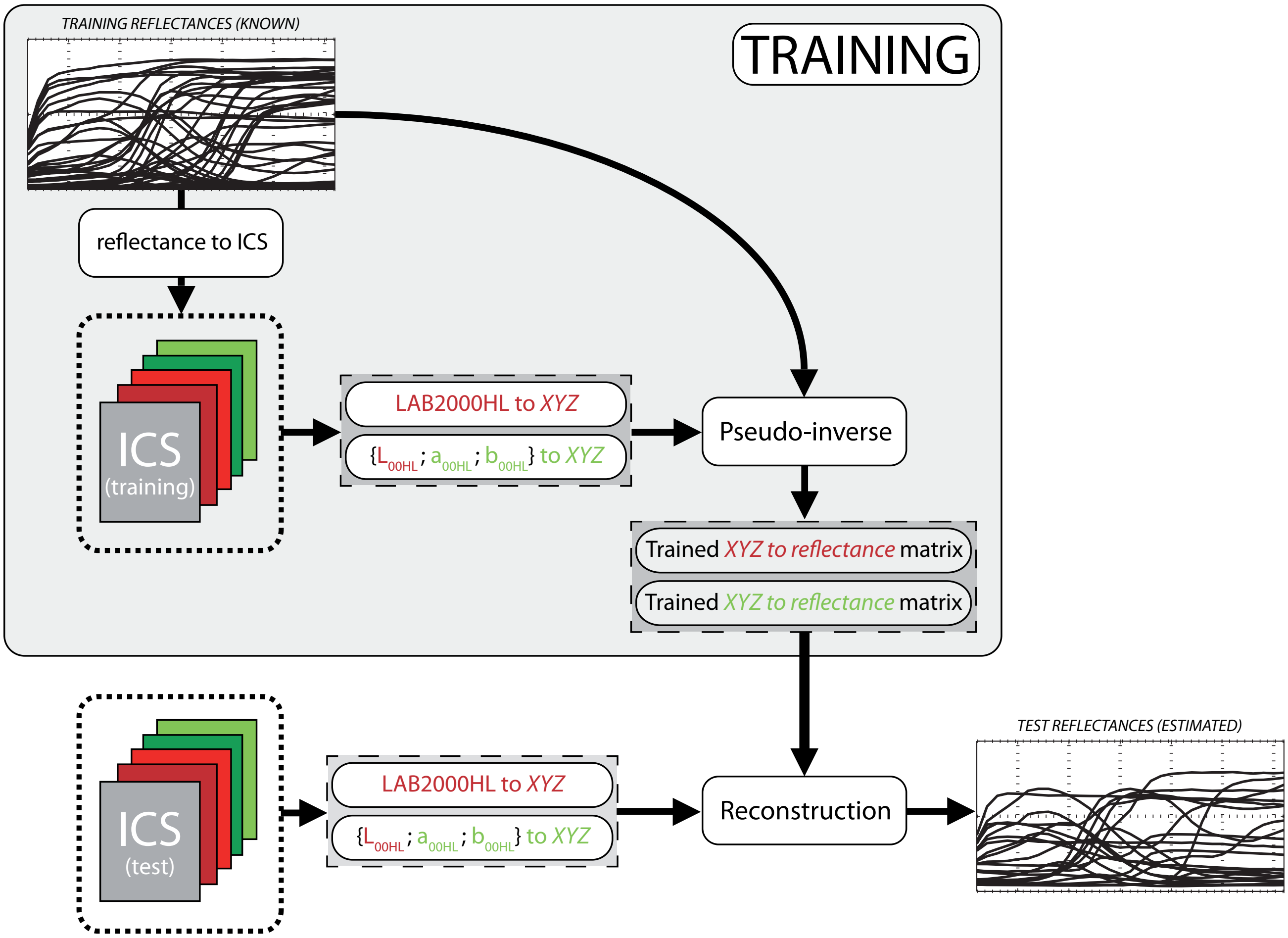
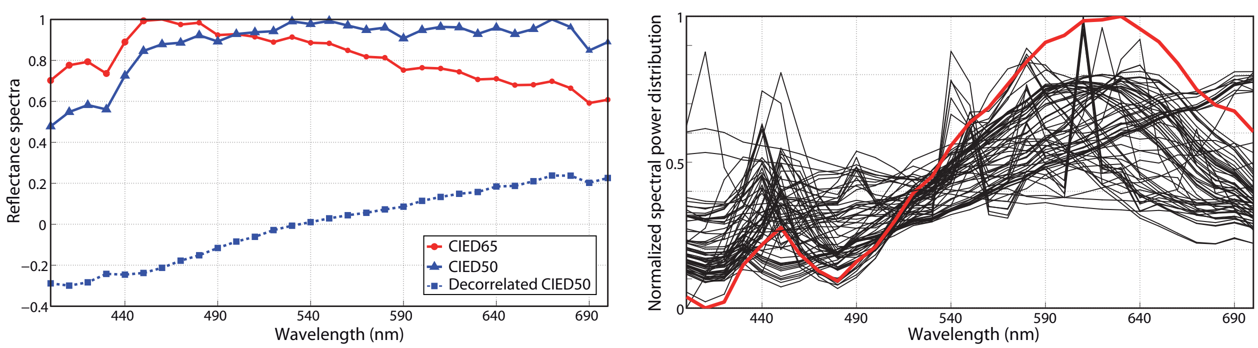


Figure 2. Spectral reconstruction. The top part represents the training stage.



(a) (b)

Figure 3. (a) De-correlating the spectral power distribution of the CIED50 illuminant, with respect to CIED65. Note that a scaling is necessary to avoid negative values. (b) Set of de-correlated illuminants. In red: first principal component (scaled).

3.2 Results

Figure 4 gives examples of reconstructed spectra and ICS coordinates. Tables 1-2 give the colorimetric errors for the reconstructions from each ICS, on average and for CIED65.

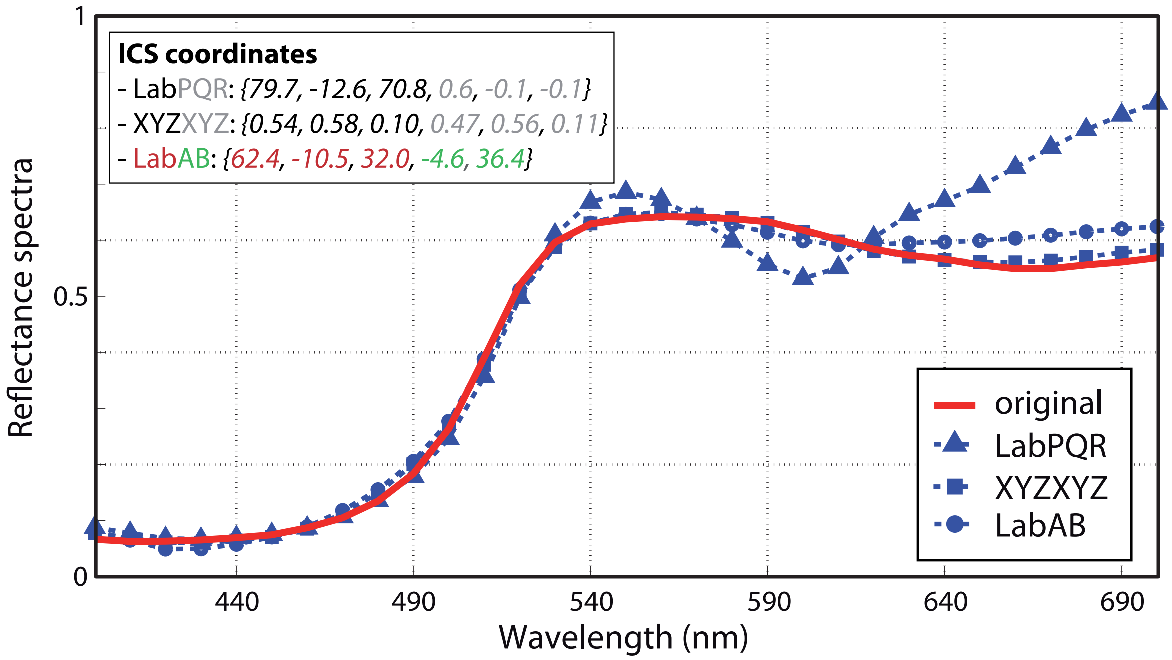


Figure 4. Examples of reconstructed spectra and ICS coordinates. Note that the coordinates are not shown here in full precision (number of digits after decimal point), for the sake of readability. The respective average CIEDE2000 colorimetric errors for LabPQR, XYZXYZ and LabAB are: **0.69**, **0.11** and **0.29**.

Table 1. Colorimetric errors in the reconstructed Munsell spectra: statistics over 74 illuminants.

	Overall average	Overall max.	D65 average	D65 max.
LabPQR	3.19	18.18	1.63	13.45
XYZXYZ	**0.20**	**6.01**	0.09	**0.48**
LabAB	0.93	8.46	**0.05**	2.03

Table 2. Colorimetric errors in the reconstructed images: statistics over 74 illuminants.

	Overall average	Overall max.	D65 average	D65 max.
LabPQR	3.25	37.43	1.08	33.67
XYZXYZ	**0.41**	40.12	0.23	**7.34**
LabAB	0.84	**33.51**	**0.04**	8.33

These results indicate that, although the multiple-XYZ strategy permits a slightly better spectral reconstruction accuracy on the overall average, the loss of accuracy engendered by our ICS is still within the range of the Just-Noticeable Distance (0.73 for the Munsell spectra and 0.43 for the images). Moreover, this does not counterweight the advantages of using 5 dimensions rather than 6 (computational cost). Our strategy yields better results – on average – than multiple-XYZ for its main illuminant (CIED65) and better results than LabPQR in most cases. The latter yields globally the worst results. In the end it is clear that, on this experimental setup, LabAB offers the best tradeoff between all the aforementioned criteria:

- It is meaningful in terms of perception as it is built out of LAB2000HL values.
- It yields a low computational burden as it contains only 5 dimensions.
- It allows for a high overall accuracy of the reconstructed spectra, particularly for its main illuminant.
- It is competitive with colorimetric workflows under a common illuminant, which can be modified at will.

4. CONCLUSIONS

We introduced a new strategy to reduce the dimensionality of spectral images ranging in the visible wavelengths, for purposes of color management. We defined a new 5-dimensional Interim Connection Space (ICS) called LabAB. We demonstrated its good performances in terms of spectral reconstruction and showed that it has numerous advantages over state-of-the-art ICSs such as LabPQR.

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