Emulation of one Camera by another Camera

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Introduction

The goal of this package colorSpec vignette is to reproduce the findings of [1] and [2], where a camera with Foveon X3 sensor is modified to closely emulate the spectral responses of the human eye. The two modifications are:

• a prefilter in front of the camera; this modification is optical and classical, see [3]
• a 3x3 matrix applied to the camera output; this modification is in hardware or in software

The figures below are best viewed on a display calibrated for sRGB. Featured functions in this vignette are: emulate().

library( colorSpec )
library( spacesRGB )  # for function plotPatchesRGB()

1 BT.709.RGB and Foveon X3

The camera BT.709.RGB is not real; it is a theoretical camera whose spectral responses are linear combinations of the responses of the human eye (the standard observer). See the man page of BT.709.RGB for details. Create a fixed wavelength vector, and resample both the Foveon camera, and the reference (the ideal) camera to the same wavelengths. Calibrate and plot both cameras.

wave = 380:720
# read the Macbeth ColorCheck target
path = system.file( 'extdata/cameras/FoveonX3.txt', package='colorSpec' )
foven = radiometric( readSpectra( path, wave=wave ) )
reference = resample( BT.709.RGB, wave=wave )
# calibrate so that both have the same response RGB=(1,1,1) to Illuminant E
illum = illuminantE(wave=wave)
foven = calibrate( foveon, stimulus=illum )
reference = calibrate( reference, stimulus=illum )
# plot both for comparison
par( omi=c(0,0,0,0), mai=c(0.5,0.9,0.1,0) )
plot( foveon, lty=2, add=TRUE, legend=FALSE, color=c('red','green','blue') )

See Figure 1. These spectral responses are obviously quite different; although the area under all 6 curves is 1. To visualize the difference we will use the ever-popular ColorChecker target. The data for this target has been kindly provided in CGATS format by [4]. ColorChecker is a Registered Trademark of X-Rite, and X-Rite is a Trademark.
Figure 1: Reference camera BT.709.RGB (solid) vs Foveon X3 camera (dashed)

```
# read the Macbeth ColorCheck target
path = system.file( 'exdata/targets/CC_Avg30_spectrum_CGATS.txt', package='colorSpec')
MacbethCC = readSpectra( path, wave=wave )  # MacbethCC is a 'colorSpec' object
MacbethCC = MacbethCC[ order(MacbethCC$SAMPLE_ID), ]  # still class 'colorSpec'
print( extradata(MacbethCC), row.names=F )

<table>
<thead>
<tr>
<th>SAMPLE_ID</th>
<th>SAMPLE_NAME</th>
<th>Munsell</th>
<th>ISCC-NBS_Name</th>
<th>LEFT</th>
<th>TOP</th>
<th>WIDTH</th>
<th>HEIGHT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>dark skin</td>
<td>3YR 3.7/3.2</td>
<td>moderate brown</td>
<td>7</td>
<td>9</td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td>2</td>
<td>light skin</td>
<td>2.2YR 6.47/4.1</td>
<td>light reddish brown</td>
<td>40</td>
<td>9</td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td>3</td>
<td>blue sky</td>
<td>4.3PB 4.95/5.5</td>
<td>moderate blue</td>
<td>73</td>
<td>9</td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td>4</td>
<td>foliage</td>
<td>6.7GY 4.2/4.1</td>
<td>moderate olive green</td>
<td>106</td>
<td>9</td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td>5</td>
<td>blue flower</td>
<td>9.7PB 5.47/6.7</td>
<td>light violet</td>
<td>139</td>
<td>9</td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td>6</td>
<td>bluish green</td>
<td>2.5BG 7/6</td>
<td>light bluish green</td>
<td>172</td>
<td>9</td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td>7</td>
<td>orange</td>
<td>5YR 6/11</td>
<td>strong orange</td>
<td>7</td>
<td>42</td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td>8</td>
<td>purplish blue</td>
<td>7.5PB 4/10.7</td>
<td>strong purplish blue</td>
<td>40</td>
<td>42</td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td>9</td>
<td>moderate red</td>
<td>2.5R 5/10</td>
<td>moderate red</td>
<td>73</td>
<td>42</td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td>10</td>
<td>purple</td>
<td>5P 3/7</td>
<td>deep purple</td>
<td>106</td>
<td>42</td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td>11</td>
<td>yellow green</td>
<td>5GY 7.1/9.1</td>
<td>strong yellow green</td>
<td>139</td>
<td>42</td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td>12</td>
<td>orange yellow</td>
<td>10YR 7/10.5</td>
<td>strong orange yellow</td>
<td>172</td>
<td>42</td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td>13</td>
<td>Blue</td>
<td>7.5PB 2.9/12.7</td>
<td>vivid purplish blue</td>
<td>7</td>
<td>75</td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td>14</td>
<td>Green</td>
<td>0.25G 5.4/8.65</td>
<td>strong yellowish green</td>
<td>40</td>
<td>75</td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td>15</td>
<td>Red</td>
<td>5R 4/12</td>
<td>strong red</td>
<td>73</td>
<td>75</td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td>16</td>
<td>Yellow</td>
<td>5Y 8/11.1</td>
<td>vivid yellow</td>
<td>106</td>
<td>75</td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td>17</td>
<td>Magenta</td>
<td>2.5RP 5/12</td>
<td>strong reddish purple</td>
<td>139</td>
<td>75</td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td>18</td>
<td>Cyan</td>
<td>5B 5/8</td>
<td>strong greenish blue</td>
<td>172</td>
<td>75</td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td>19</td>
<td>white</td>
<td>N9.5/</td>
<td>white</td>
<td>7</td>
<td>108</td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td>20</td>
<td>neutral 8</td>
<td>N8/</td>
<td>light gray</td>
<td>40</td>
<td>108</td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td>21</td>
<td>neutral 6.5</td>
<td>N6.5/</td>
<td>light medium gray</td>
<td>73</td>
<td>108</td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td>22</td>
<td>neutral 5</td>
<td>N5/</td>
<td>medium gray</td>
<td>106</td>
<td>108</td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td>23</td>
<td>neutral 3.5</td>
<td>N3.5/</td>
<td>dark gray</td>
<td>139</td>
<td>108</td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td>24</td>
<td>black</td>
<td>N2/</td>
<td>black</td>
<td>172</td>
<td>108</td>
<td>29</td>
<td>29</td>
</tr>
</tbody>
</table>
```
Note that `MacbethCC` is organized as 'df.row' and contains extra data for each spectrum, most importantly the coordinates of the patch rectangles.

Calculate the RGB responses to both cameras and display them.

```r
RGB.ref = product( illum, MacbethCC, reference)  # this is *linear scene* sRGB
# add the rectangle data to RGB.ref, so the patches are plotted in proper places
df.ref = extradata(MacbethCC)
df.ref$RGB.ref = RGB.ref
# display in proper location, and use the sRGB display transfer function
par( omi=c(0,0,0,0), mai=c(0,0,0,0) )
plotPatchesRGB( df.ref, space='sRGB', which='scene', back='gray20', labels=FALSE )
# repeat with foveon camera, and add to existing plot
RGB.foveon = product( illum, MacbethCC, foveon )
df.foveon = extradata(MacbethCC)
df.foveon$RGB.foveon = RGB.foveon
plotPatchesRGB( df.foveon, space='sRGB', which='scene', shape='bottomright', add=T )
```

![Figure 2: Rendering with Illuminant E, with Foveon RGB in bottom right half](image)

There is only agreement for the neutral patches, as might be expected.
Now modify the Foveon camera, using both a pre-filter and a matrix, to emulate the reference.
foveon.mod = emulate( foveon, reference, filter=TRUE, matrix=TRUE )
par( omi=c(0,0,0,0), mai=c(0.5,0.9,0.2,0) )
plot( reference, main='' )
plot( foveon.mod, lty=2, add=TRUE, legend=FALSE )

Figure 3: Reference camera (solid) vs the modified Foveon camera (dashed)

The agreement is now much better. Replot the ColorChecker to visualize the improvement.

par( omi=c(0,0,0,0), mai=c(0,0,0,0) )
plotPatchesRGB( df.ref, space='sRGB', which='scene', back='gray20', labels=FALSE )
# repeat with modified foveon camera, and add to existing plot
df.foveon.mod = extradata(MacbethCC)
df.foveon.mod$RGB.foveon.mod = product( illum, MacbethCC, foveon.mod )
plotPatchesRGB( df.foveon.mod, space='sRGB', which='scene', shape='bottomright', add=T )
The agreement in the RGBs is now much better, c.f. Figure 2. There is a noticeable difference in the Red and Magenta patches, and minor differences in some others. However, the neutrals are now worse; the green is low so they have a purple tint. A new feature - white-point preservation - might be added to a future version of `emulate()`, using the techniques in [5]. Alternatively, one could also re-calibrate (white-balance) `foveon.mod`.

The computed pre-filter and matrix are attached to `foveon.mod`, and are easy to print and plot.

```r
attr(foveon.mod,"emulate")$A

<table>
<thead>
<tr>
<th></th>
<th>r</th>
<th>g</th>
<th>b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red</td>
<td>13.054064</td>
<td>-7.362972</td>
<td>5.627526</td>
</tr>
<tr>
<td>Green</td>
<td>-10.008693</td>
<td>10.482482</td>
<td>-13.407764</td>
</tr>
<tr>
<td>Blue</td>
<td>2.848111</td>
<td>-3.419678</td>
<td>11.254107</td>
</tr>
</tbody>
</table>
```

```r
par( oma=c(0,0,0,0), mai=c(0.5,0.9,0.2,0) )
prefilter = attr(foveon.mod,"emulate")$filter
specnames(prefilter) = "prefilter for modified Foveon"
plot( prefilter, main='', ylim=c(0,1.1) )
```
This curve is broadly similar to those in [1] and [2]. All are bimodal and have a valley near 500 nm. But the peaks are in different locations, shaped differently, and both of their peaks have a maximum of 1. I suspect that they are different because of different optimization criteria. The function `emulate()` uses a simple least-squares criterion with the same weight at every wavelength. [1] uses a "Metamerism Index" defined in [4]. This index uses color targets which might be the same as those in the ColorChecker. [2] uses a criterion based on principal angles between subspaces. These optional criteria might be added to `emulate()` in the future. For a good comparison of the other 2 prefilters, see Figure 6 in [2].

A real engineering implementation of these modifications would have to include a noise and sensitivity analysis. We will not pursue that here, except to observe the condition number of the matrix.

```r
A = attr(foveon.mod,"emulate")$A  # A is the 3x3 matrix already printed above
kappa( A, exact=TRUE, norm='2' )  # kappa() returns the condition number of A
```

```
[1] 14.27221
```

This is quite large so that is not a good sign.

## 2 Red Epic Dragon and Plumbicon

The plumbicon, introduced in 1965, is a graylevel television camera tube. The Red Epic Dragon, announced in 2013, is a modern high-speed cinema RGB camera with 19.4 Megapixel CMOS sensor. We will find a good linear combination of the RGB responsivities of the Dragon to emulate the graylevel responsivity of the plumbicon.

Create a fixed wavelength vector, and resample both cameras to the same wavelengths. Then calibrate and plot both cameras.
The integral of all 4 curves is 1. Now matrix the Dragon camera to emulate the plumbicon. A filter is not used here, since the plumbicon has only one output channel, the problem is underdetermined and we could get an "exact" match with a filter.

```r
wave = 400:700
# read the 2 cameras
path = system.file( 'extdata/cameras/Plumbicon30mm.txt', package='colorSpec' )
plumbicon = readSpectra( path, wave=wave )
path = system.file( 'extdata/cameras/Red-Epic-Dragon.txt', package='colorSpec' )
dragon = readSpectra( path, wave=wave )
# calibrate to normalize the response to Illuminant E
illum = illuminantE(wave=wave)
plumbicon = calibrate( plumbicon, stimulus=illum )
dragon = calibrate( dragon, stimulus=illum )
# plot both for comparison
par( omi=c(0,0,0,0), mai=c(0.5,0.9,0.1,0) )
plot( dragon, main='', lty=2, legend=FALSE )
plot( plumbicon, col='black', lty=1, add=TRUE, legend='topleft' )
dragon.mod = emulate( dragon, plumbicon, filter=FALSE, matrix=TRUE )
specnames( dragon.mod ) = "Dragon, matrixed"
combo = bind( plumbicon, dragon.mod )
par( omi=c(0,0,0,0), mai=c(0.5,0.9,0.2,0) )
plot( combo, main='', lty=c(1,2), col='black' )
```
Figure 7: Plumbicon camera (solid) vs the modified Dragon camera (dashed)

The match on the interval [400,500] is not good. The RGB weights are attached to `dragon.mod` and easy to display. Note that the red weight is small.

```
t( attr(dragon.mod,"emulate")$A )
```

```
R  G  B
Plumbicon30mm.Gray   -0.06454983 0.3641843 0.6736629
```

Calculate the `ColorChecker` graylevel responses from both cameras and display them.

```r
MacbethCC = resample(MacbethCC, wave=wave)
graylevel = product( illum, MacbethCC, plumbicon)
RGB.plumbicon = matrix( graylevel, length(graylevel), 3 )
df.plumbicon = extradata(MacbethCC)
df.plumbicon$RGB = RGB.plumbicon
par( omi=c(0,0,0,0), mai=c(0,0,0,0) )
plotPatchesRGB( df.plumbicon, space='sRGB', which='scene', back='black' )
# repeat with dragon.mod camera, and add to existing plot, as triangles
graylevel = product( illum, MacbethCC, dragon.mod)
df.dragon = extradata(MacbethCC)
df.dragon$RGB = matrix( graylevel, length(graylevel), 3 )
plotPatchesRGB( df.dragon, space='sRGB', which='scene', add=T, shape='bottomright' )
```
Despite the mismatch on the interval $[400,500]$, the visual agreement is pretty good.

References


Appendix

This document was prepared December 7, 2019, with the following configuration:
R Under development (unstable) (2019-12-03 r77513), i386-w64-mingw32

Running under: Windows 7 (build 7601) Service Pack 1

Matrix products: default

Base packages: base, datasets, grDevices, graphics, methods, stats, utils

Other packages: colorSpec 1.1-1, knitr 1.26, spacesRGB 1.2-2

Loaded via a namespace (and not attached): MASS 7.3-51.4, Rcpp 1.0.3, compiler 4.0.0, digest 0.6.22, evaluate 0.14, highr 0.8, htmltools 0.4.0, magrittr 1.5, microbenchmark 1.4-7, rlang 0.4.1, rmarkdown 1.18, spacesXYZ 1.0-4, stringi 1.4.3, stringr 1.4.0, tools 4.0.0, xfun 0.11, yaml 2.2.0