Designing Robust Perceptual Colormaps for Internet Visualization

Alan D. Kalvin
IBM TJ Watson Research Center, Yorktown Heights, New York
kalvin@us.ibm.com

Abstract

Perceptual colormaps are colormaps that are designed using principles of human color perception. The importance of perceptual colormaps in visualization is that they provide a way to faithfully map data to colors without producing perceptual artifacts.

Typically, a perceptual colormap is specified as path in a perceptual color space. To visualize the colormapped data on a display monitor, this path first needs to be converted to device RGB space of the specific display monitor.

There are two problems that arise from the need to convert from device-independent to device-dependent color space. The first is that it limits the usefulness of perceptual colormaps to viewing environments in which we have control over the viewing factors that influence color perception. This excludes basically all Internet-based visualizations, since these are usually displayed on uncalibrated monitors under uncontrolled ambient lighting.

The second problem is that the color space conversion methods are designed to achieve *color fidelity*, not *perceptual fidelity*, and therefore they are not particularly suited to creating perceptual colormaps.

In this paper we consider the problem of designing perceptual colormaps that are suitable for the Internet-based visualization. We show that there are significant advantages in designing colormaps directly in device RGB space, rather than in a perceptual color space. In particular, this approach allows us to easily design “perceptually robust” colormaps, which maintain their perceptual properties over a wide range of viewing environments.

Introduction

In designing colormaps for visualization, it is critical to take into account principles of human color perception. Ignoring these perceptual aspects can result in poorly constructed colormaps that produce perceptual artifacts and lead to misinterpretations of the data. Despite the extensive literature on this subject[1,3,4,6-8,11-15,17,18] perceptual colormaps are not widely used, largely because most existing methods for constructing perceptual colormaps require difficult and labor-intensive calibration of display monitors. Furthermore for remote, networked-based displays, calibration is often impossible.

In this paper we present a new method for creating *perceptually robust colormaps*, that is, colormaps having perceptual properties that are stable, and are preserved over a wide range of viewing conditions. Therefore these colormaps are well suited to Internet-based visualization. The value of this method is that it defines a simple, systematic methodology for enumerating perceptual colormaps. This method greatly simplifies the task of designing perceptual colormaps for uncalibrated displays.

Perceptual Colormaps

Two important classes of perceptual colormaps are *perceptually ordered* colormaps, and *perceptually uniform* colormaps. In a perceptually ordered colormap, the positional ordering of the colors in the colormap corresponds to a perceived ordering of these colors. In a perceptually uniform colormap, the distance between the colormap positions of any pair of colors is proportional to the perceived distance between these two colors.

A number of researchers have discussed the importance of luminance in designing perceptually ordered colormaps. Because of the sensitivity to luminance variations in the human visual system, colormaps with monotonically increasing (or decreasing) luminance are good candidates for perceptual colormaps.[3,6-8,11-15,17,18]

In this paper, we focus on perceptually ordered colormaps that have monotonic luminance, and on their application visualizing continuous scalar data.

Perceived Color Variation of Across Viewing Environments

A problem that is often overlooked or ignored when using colormaps to visualize data, is the fact that the perception of the colors in the colormap is influenced by variations in the local viewing conditions. These variations can result in inconsistent (possibly contradictory) interpretations and conclusions drawn from visual analysis of the colormapped data. The local viewing conditions influenced by the following factors:

- Variations in the physical and electrical characteristics of different color displays.

- Variations in ambient lighting in the vicinity of the display.
- Variations in color vision among individuals.

We refer to the combination of color display, local ambient lighting, and individual observer's color vision as the "viewing environment".

It is clear that the same colormap may be perceptually ordered in one viewing environment, but not a second, different viewing environment. This situation leads us to the problem that is the focus of this paper, which is the problem of designing colormaps that maintain the property of perceptually ordering across many different viewing environments.

The standard methods for constructing perceptual colormaps usually involve a two-step process. In the first step, a device-independent colormap is created in a perceptual color space (also called a uniform color space), typically by specifying a path in this space. In the second step, this colormap is converted to device-dependent RGB space.

To converting from a device-independent to a device-dependent color space requires that we solve the general *display calibration problem.*[2,5,9,10] This introduces the following difficulties. In the first place, display calibration is extremely time-consuming, and needs to be repeated frequently to maintain reliability. Secondly, measuring devices like colorimeters are expensive, and they usually require some training to operate. Thirdly this approach solves only those problems relating to one component of the viewing environment, that is, the display characteristics. It does not deal with issues arising from variations in ambient lighting, and variations in human color vision. Finally, the need for display calibration makes this approach impractical for Internet visualization.

In addition to the practical difficulties associated with display calibration, the standard methods of color space conversion are designed to achieve *color fidelity* across color spaces, rather than *perceptual fidelity*, which is our real goal. Even if we make the optimistic assumption that color fidelity implies perceptual fidelity, that is, that perceptual fidelity is a special case of color fidelity, solving the larger problem involves unnecessary constraints on the space of valid solutions.

The first problem we now need to confront is the issue of out-of-gamut colors, and are faced with one of two options of dealing with this. The first option is to allow the remapping of out-of-gamut colors after color space conversion. However, this defeats the idea of using a perceptual color space, since the modified colormap may no longer be a perceptual one. The second option is to take a "lowest-common-denominator", and design the colormap based on a very limited gamut that lies inside the gamuts of all displays that we expect to be used for viewing the colormaps we are designing. Unfortunately, the result of this approach is that we are restricted to producing colormaps with very dull, insipid colors, which are not only unappealing visually, but have very limited dynamic range in luminance.

The second problem relates to the issue of colormap resolution, and the interpolation of colormap values. The resolution of a colormap can be increased by interpolation between existing colormap values. In order to ensure that the new (higher-resolution) version of the colormap is still a *perceptual* colormap, it is necessary to interpolate within the perceptual colorspace associated with the colormap. For a colormap designed in a *device-independent* (perceptual) colorspace, this requires the interpolation to be done *before* conversion to the device-dependent RGB colorspace. In other words colormap resolution has to be fixed in advance. On the other hand, for a colormap designed directly in a *device-dependent* RGB colorspace, interpolation can be done-on-the-fly, and thus the end-user can dynamically modify the colormap resolution. This provides not only greater flexibility, but also more compact colormap representation

Therefore it is impractical to base the design of perceptually ordered colormaps on the idea of solving the general color fidelity problem. At best, it would be difficult to profile all the displays within the set of viewing environments that we wish to consider. At worst it may be impossible, since we may not know in advance what type of the displays will be used -- in fact, the set of viewing environments, can change over time, and at some future time it may contain displays that didn't yet exist when the colormaps were created.

Nevertheless we can use the general concept of display profiling to design perceptual colormaps..

Robust Colormaps

Our method for producing perceptually robust colormaps is based on the idea of "graduated profiling" (or partial profiling), in which we make use of any available partial display profile data.

As we shall show, we can deduce a lot of very useful. All the perceptually robust colormaps produced by graduated profiling have luminance components that increase monotonically as a function of colormap position. In the case of chromatic colormaps, we shall also restrict ourselves to those colormaps consisting entirely of colors that lie on display gamut boundaries (or equivalently those colors that lie on the outer surface of the device-RGB cube). This ensures that we produce attractive colormaps containing only bright, vivid colors.

The basic idea behind graduated profiling is to build a hierarchy of perceptual colormaps corresponding to a hierarchy of display profile information. The lowest level of the profile hierarchy contains only the most basic profile information, information that that is common to the widest range of displays. The lowest level of the perceptual colormap hierarchy will in turn contain a relatively small number of colormaps. These colormaps will be the most robust colormaps, preserving perceptual ordering over the broadest range of viewing environments. As we ascend these hierarchies, the amount of profile information increases, and consequently the number of colormaps increases, while perceptual robustness decreases.

Level 1: Luminance Increases Monotonically with RGB Channel Values

At the lowest level of the partial profile hierarchy, we assume only the flowing basic display properties:

- each color produced by the display is specified by an RGB triple (r,g,b), where each component of the triple is an integer on the range 0 through N. Here N is a positive integer, and is typically 255.
- A positive increment in any of the RGB components produces a positive increment in color luminance. In other words, the luminance of any color (r,g,b) is always less than the luminance of each of the 3 colors (r+1,g,b), (r,g+1,b) and (r,g,b+1).

These are fundamental properties of RGB displays, directly related to the design of displays. As far as we know, all RGB displays have this property. Therefore all colormaps at the bottom level of the colormap hierarchy are perceptually ordered in all viewing environments. We call this set of colormaps the *universal set of perceptually ordered colormaps*.

Figure 1 shows an acyclic directed graph that is based on this simple partial profile. Here **R**, **G**, and **B** are the maximum values of the RGB components, i.e. **R** = (N, 0, 0), **G** = (0, N, 0), and **B** = (0, 0, N). The colors black and white are represented by **K** = (0,0,0), and **W** = (N, N, N), and **Y** = (**R** + **G**), **M** = (**R** + **B**), and **C** = (**G** + **B**).

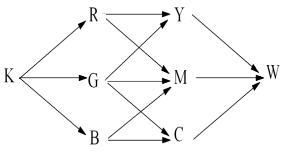


Figure 1. Directed graph representing all valid colormaps at level 1

This graph represents a partial ordering of the luminances of the eight colors **R**, **G**, **B**, **C**, **M**, **Y**, **K** and **W,** where **p→ q** means color **p** has lower luminance than color **q**. The set of all paths in the transitive closure of this graph corresponds to the set of all perceptually ordered colormaps at level 1 of the hierarchy.

Note that 12 arcs in this graph correspond to the 12 edges of the RGB color cube. Figure 3 shows the 43 perceptually ordered colormaps in the universal set. (See the colorplates for the colored versions of Figures 3-5. In the grayscale versions of Figures 3-5, the colormaps are specified by a sequence of letters, e.g. KR is the colormap from black to red.)

As shown in Figure 3, the region of the color cube that is traversed by the universal set, consists of all 12 edges of the cube, six of the 12 face diagonals, and one of the four cube diagonals.

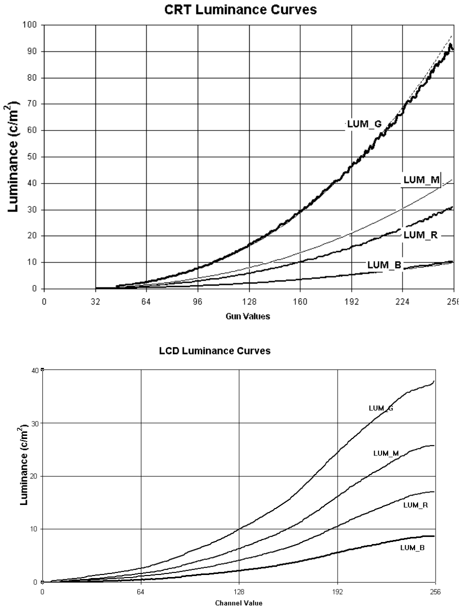


Figure 2. Typical examples of consistent channel ordering in a CRT display (top) and an LCD display (bottom).

Level 2 Consistent Channel Ordering

The second level of the profile information hierarchy contains the additional information that the channels are consistently ordered with reference to the size of luminance increments. That is, if $\mathbf{L_1}$, $\mathbf{L_2}$, and $\mathbf{L_3}$ are the luminance functions (or transfer functions) of the three channels, then for **k=1,..N**

$$\mathbf{L_1(1) < L_2(1) < L_3(1) \Rightarrow L_1(k) < L_2(k) < L_3(k)}.$$

In general the blue channel has lowest luminance, and the green channel has the highest, which gives the following ordering:

$$\mathbf{L_B(k) < L_R(k) < L_G(k), \text{ for } k = 1, 2, \ldots, N} \qquad (1)$$

Figure 2 shows examples of consistent channel ordering for typical CRT and LCD displays.

A broad class of displays that satisfies this condition consists of displays in which the three luminance curves are weighted versions of one common function. In other words,

$$\mathbf{L_{COMMON} = L_B/W_B = L_R/W_R = L_G/W_G}$$

The level 2 perceptual colormaps defined by this additional information are "pseudo grayscale" colormaps. They are useful for approximating high-resolution grayscale colormaps, by the process of "color bit-stealing".[16] This is achieved by extending the standard grayscale colormap that consists of the N+1 achromatic colors:

$$\mathbf{[(0,0,0), (1,1,1), (2,2,2), \ldots(N, N, N)]}$$

by inserting between the consecutive colors **(k,k,k)** and **(k+1,k+1,k+1)**, a sequence of five additional "almost achromatic" colors. This sequence can be either one of the following (i.e. it can include green or magenta, but not both):

[(k,k,k+1), (k+1,k,k), (k,k+1,k), (k,k+1,k+1), (k+1,k+1,k)]
[(k,k,k+1), (k+1,k,k), (k,k+1,k), (k+1,k,k+1), (k+1,k+1,k)]

For **N**=255, this method produces colormap with a total of 1531 colors.

As far as we can establish, this consistent channel ordering property, i.e. **$L_B(k) < L_B(k) < L_G(k)$**, is true for all RGB displays, and therefore, like the level 1 colormaps, these pseudo grayscale colormaps are in the set of universal perceptually ordered colormaps, and can be used in all possible viewing environments.

If in addition magenta luminance **$L_M(k) = (L_B(k)+ L_R(k))$** satisfies the condition **$L_M(k) < L_G(k)$**, then a more generalized channel ordering exists, and property (5.1) above can be extended to

$$\mathbf{L_B(k) < L_R(k) < L_M(k) < L_G(k)} \qquad (2)$$

In this case the sequence of six additional colors

[(k,k,k+1),(k+1,k,k),(k+1,k,k+1),
(k,k+1,k),(k,k+1,k+1),(k+1,k+1,k)]

can be inserted between the consecutive colors **(k,k,k)** and **(k+1,k+1,k+1)**. For **N**=255, this method produces colormap with a total of 1786 colors.

Level 3

At the third level of the profile information hierarchy, we assume that we have complete information about the normalized luminance functions L_B, L_R, and L_G. We now discuss the nature of the corresponding set of perceptually ordered colormaps that we can produce with this additional information.

In this section, we will not consider pseudo grayscale colormaps of the type discussed in the section on level 2 colormaps, since this is a very specialized type of perceptually ordered colormap. Instead, we will consider colormaps that lie either on the outer surface of the RGB color cube, or on one of the major cube diagonals As we discussed previously, the set of 43 universal level 1 colormaps, also lie in this region. However, within this region, the 43 universal colormaps are further constrained to paths that lie on the 12 edges of the RGB color cube, six of the 12 face diagonals, and one of the four cube diagonals. The additional profile information provided in level 3 allows us to create perceptually ordered colormaps with paths that lie on all 12 face diagonals, and all four of the major cube diagonals.

Note that information in the normalized luminance functions is not sufficient to determine the total display luminance. What is still missing is information the relative weighting factors of these luminances, . Now suppose that we do not know these weights, but know only the ratio of these weights. This is a very common situation when considering CRTs and LCDs, where we can assume that the following condition holds (for k=1,..,N):

$$L_B(k)*W_B < L_R(k)*W_R < L_G(k)*W_G \qquad (3)$$

The corresponding set of 183 perceptually ordered colormaps are shown in Figure 4.

As in level 2, suppose that the magenta luminance **$L_M(k) = (L_B(k)+ L_R(k))$** satisfies the condition **$L_M(k) < L_G(k)$.** Then property (5.3) above can be extended to

$$\mathbf{L_B(k)*W_B < L_R(k)*W_R < (L_R(k)*W_R + L_B(k)*W_B) < L_G(k)*W_{G,}} \qquad (4)$$

In this case we get a corresponding set of 247 perceptually ordered colormaps, as shown in Figure 5.

Discussion

We have discussed the problem of how to design perceptually ordered colormaps that are intended for use over a range of different viewing environments. We have shown that we can create a large selection of such colormaps even using partial display profile information. As shown in the figures, at each level of the perceptual colormap hierarchy, we have a large number of candidate perceptual colormaps. When the partial profile information is accurate, any of these candidates will be a valid choice, and will be perceptually correct in the corresponding viewing environments.

It is important to bear in mind that although all candidate colormaps will be valid perceptual colormaps, on any given display monitor, the may be big differences in other desirable colormap properties (for example the perceived smoothness in the transition between colors) within the set of candidate colormaps. Therefore, in is important to presenting viewers with a selection of valid colormaps, rather than just a single one.

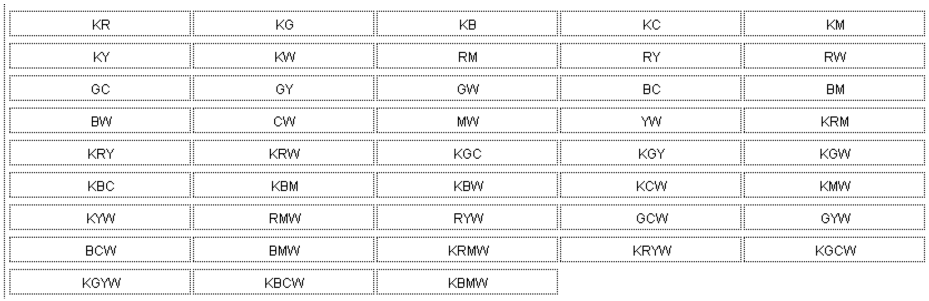
References

1. M. J. Bailey (1995), "The Use of Color in Scientific Visualization", *Circuit Cellar INK: The Computer Applications Journal*, vol. **60**, pp. 14-23.
2. D. H. Brainhard (1989), "Calibration of a Computer Controlled Monitor", *Col. Res. & Appl.* vol **14**, pp.23-34.
3. C. A. Brewer (1994), "Guidelines for Use of the Perceptual Dimensions of Color for Mapping and Visualization", *Proc. SPIE*, vol. **2171**, pp. 54-63.
4. R. Buckley and G. Beretta (2001), "Color Imaging on the Internet", *www.inventoland.net/imaging/cii/nip01.pdf.*
5. W. B. Cowan (1983), "An Inexpensive Scheme for the Calibration of Colour Monitors in Terms of CIE Standard Coordinates", *Computer Graphics*, vol **17**, pp. 315-321.
6. M. Green (1992), "Toward a Perceptual Science of Multidimensional Data Visualization: Bertin and Beyond", *http://www.ergogero.com/dataviz/dviz0.html.*
7. C. G. Healey (1996), "Choosing Effective Colours for Data Visualization", Proc. *IEEE Visualization 96*, pp. 263-270.

8. H. Levkowitz and G.T. Herman (1992), "The Design and Evaluation of Color Scales for Image Data," *IEEE Computer Graphics and Applications,* **12** (1): 72-80.
9. L. W. MacDonald (1995). "Calibrating Colour Displays", *Proc. Intl Conf. On Color Communication*, pp. 167-174.
10. D. L. Post (1992), "Colorimetric Measurement, Calibration and Characterization of Self-Luminous Displays", in *Color in Electronic Displays*, Ed. H. Widdel and D. L. Post. Plenum Press, New York, pp. 229-312.
11. S. Pizer (1981), "Intensity Mappings to Linearize Display Devices", *Comp. Graph. Img Proc.*, **17**(3): 262-268.
12. P. Rheingans (1999). "Task-based Color Scale Design", *Proceedings of Applied Image and Pattern Recognition '99, SPIE*, pp. 35-43.
13. P.K. Robertson, "Visualizing Color Gamuts: A User Interface for the Effective Use of Perceptual Color Spaces in Data Displays", *IEEE Computer Graphics and Applications*, 50-63, 1988.
14. B.E. Rogowitz and L.A. Treinish (1988), "Data Visualization: The End of the Rainbow," *IEEE Spectrum*, 52-59.
15. B. E. Rogowitz, A. D. Kalvin, A. Pelah, A. Cohen (1999), "Which Trajectories through which Perceptually Uniform Color Spaces Produce Appropriate Color Scales for Interval Data?" *IS&T Color Imaging Conf. 7, Scottsdale, AZ.*
16. C.W. Tyler (1997), "Colour bit-stealing to enhance the luminance resolution of digital displays on a single pixel basis", *Spatial Vision*, **10**(4): 369-300.
17. C. Ware (1988), "Color Sequences for Univariate Maps: Theory, Experiments, and Principles," *IEEE Computer Graphics and Applications,* **8**: 41-49.
18. C. Ware (2000), *Information Visualization: Perception for Design,* Academic Press, San Diego, CA, USA.

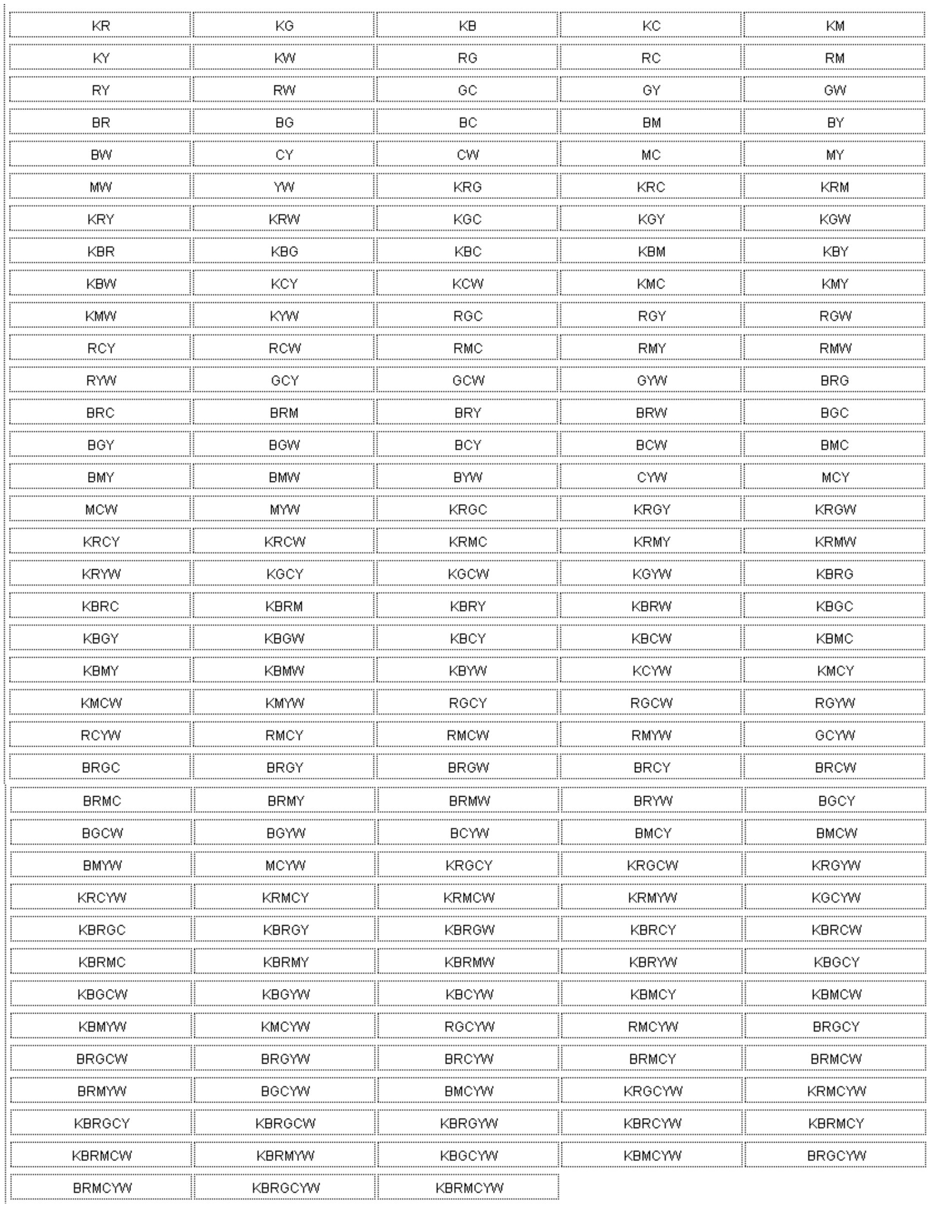
Biography

Alan Kalvin is a Research Staff Member in the Visual Analysis Group at the IBM TJ Watson Research Center.



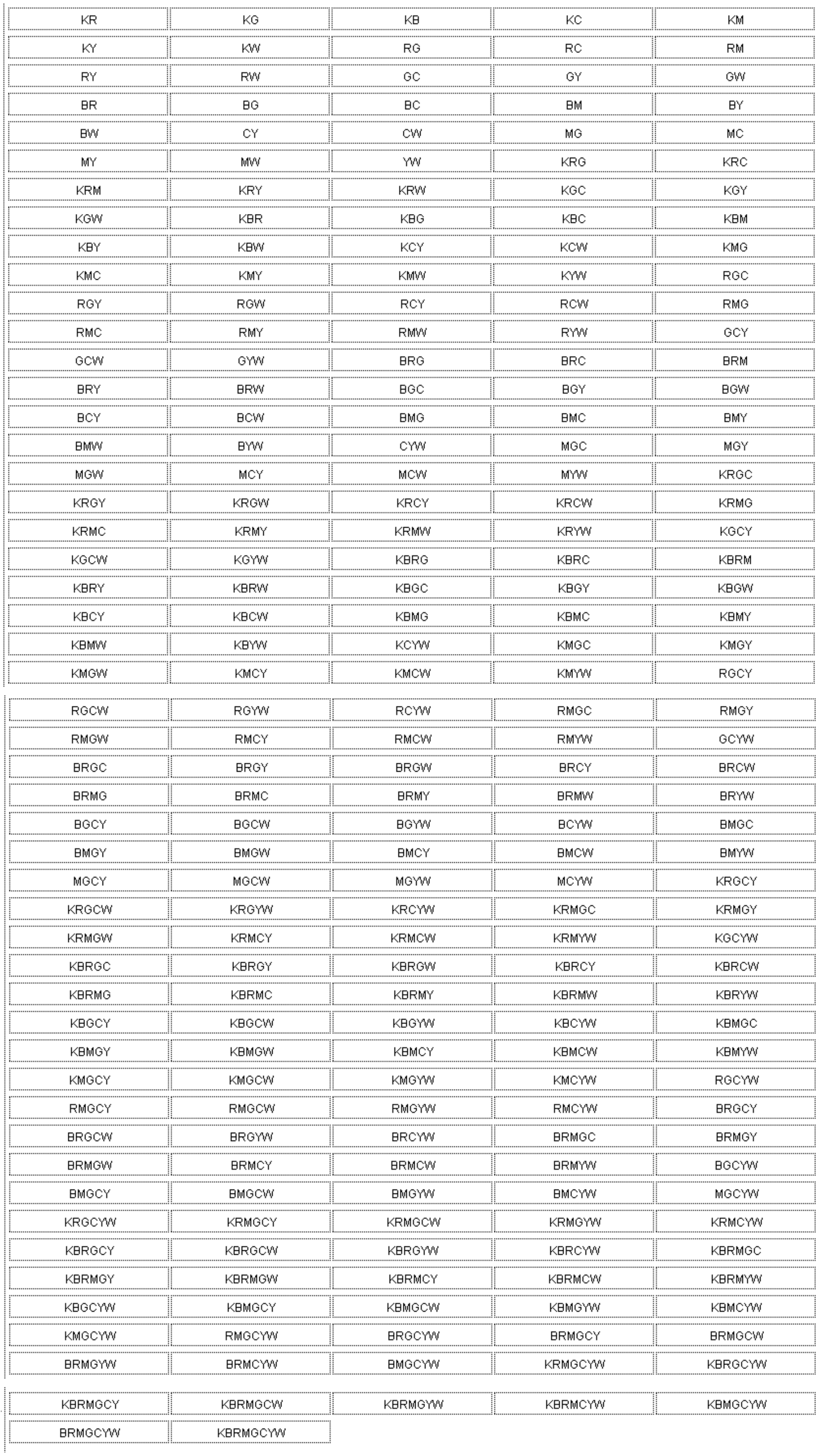
KR	KG	KB	KC	KM
KY	KW	RM	RY	RW
GC	GY	GW	BC	BM
BW	CW	MW	YW	KRM
KRY	KRW	KGC	KGY	KGW
KBC	KBM	KBW	KCW	KMW
KYW	RMW	RYW	GCW	GYW
BCW	BMW	KRMW	KRYW	KGCW
KGYW	KBCW	KBMW		

Figure 3. The 43 "universal" perceptually ordered colormaps



KR	KG	KB	KC	KM
KY	KW	RG	RC	RM
RY	RW	GC	GY	GW
BR	BG	BC	BM	BY
BW	CY	CW	MC	MY
MW	YW	KRG	KRC	KRM
KRY	KRW	KGC	KGY	KGW
KBR	KBG	KBC	KBM	KBY
KBW	KCY	KCW	KMC	KMY
KMW	KYW	RGC	RGY	RGW
RCY	RCW	RMC	RMY	RMW
RYW	GCY	GCW	GYW	BRG
BRC	BRM	BRY	BRW	BGC
BGY	BGW	BCY	BCW	BMC
BMY	BMW	BYW	CYW	MCY
MCW	MYW	KRGC	KRGY	KRGW
KRCY	KRCW	KRMC	KRMY	KRMW
KRYW	KGCY	KGCW	KGYW	KBRG
KBRC	KBRM	KBRY	KBRW	KBGC
KBGY	KBGW	KBCY	KBCW	KBMC
KBMY	KBMW	KBYW	KCYW	KMCY
KMCW	KMYW	RGCY	RGCW	RGYW
RCYW	RMCY	RMCW	RMYW	GCYW
BRGC	BRGY	BRGW	BRCY	BRCW
BRMC	BRMY	BRMW	BRYW	BGCY
BGCW	BGYW	BCYW	BMCY	BMCW
BMYW	MCYW	KRGCY	KRGCW	KRGYW
KRCYW	KRMCY	KRMCW	KRMYW	KGCYW
KBRGC	KBRGY	KBRGW	KBRCY	KBRCW
KBRMC	KBRMY	KBRMW	KBRYW	KBGCY
KBGCW	KBGYW	KBCYW	KBMCY	KBMCW
KBMYW	KMCYW	RGCYW	RMCYW	BRGCY
BRGCW	BRGYW	BRCYW	BRMCY	BRMCW
BRMYW	BGCYW	BMCYW	KRGCYW	KRMCYW
KBRGCY	KBRGCW	KBRGYW	KBRCYW	KBRMCY
KBRMCW	KBRMYW	KBGCYW	KBMCYW	BRGCYW
BRMCYW	KBRGCYW	KBRMCYW		

Figure 4. The 183 colormaps in level 3 corresponding to the condition $L_B(k)*W_B < L_R(k)*W_R < L_G(k)*W_G$



KR	KG	KB	KC	KM
KY	KW	RG	RC	RM
RY	RW	GC	GY	GW
BR	BG	BC	BM	BY
BW	CY	CW	MG	MC
MY	MW	YW	KRG	KRC
KRM	KRY	KRW	KGC	KGY
KGW	KBR	KBG	KBC	KBM
KBY	KBW	KCY	KCW	KMG
KMC	KMY	KMW	KYW	RGC
RGY	RGW	RCY	RCW	RMG
RMC	RMY	RMW	RYW	GCY
GCW	GYW	BRG	BRC	BRM
BRY	BRW	BGC	BGY	BGW
BCY	BCW	BMG	BMC	BMY
BMW	BYW	CYW	MGC	MGY
MGW	MCY	MCW	MYW	KRGC
KRGY	KRGW	KRCY	KRCW	KRMG
KRMC	KRMY	KRMW	KRYW	KGCY
KGCW	KGYW	KBRG	KBRC	KBRM
KBRY	KBRW	KBGC	KBGY	KBGW
KBCY	KBCW	KBMG	KBMC	KBMY
KBMW	KBYW	KCYW	KMGC	KMGY
KMGW	KMCY	KMCW	KMYW	RGCY
RGCW	RGYW	RCYW	RMGC	RMGY
RMGW	RMCY	RMCW	RMYW	GCYW
BRGC	BRGY	BRGW	BRCY	BRCW
BRMG	BRMC	BRMY	BRMW	BRYW
BGCY	BGCW	BGYW	BCYW	BMGC
BMGY	BMGW	BMCY	BMCW	BMYW
MGCY	MGCW	MGYW	MCYW	KRGCY
KRGCW	KRGYW	KRCYW	KRMGC	KRMGY
KRMGW	KRMCY	KRMCW	KRMYW	KGCYW
KBRGC	KBRGY	KBRGW	KBRCY	KBRCW
KBRMG	KBRMC	KBRMY	KBRMW	KBRYW
KBGCY	KBGCW	KBGYW	KBCYW	KBMGC
KBMGY	KBMGW	KBMCY	KBMCW	KBMYW
KMGCY	KMGCW	KMGYW	KMCYW	RGCYW
RMGCY	RMGCW	RMGYW	RMCYW	BRGCY
BRGCW	BRGYW	BRCYW	BRMGC	BRMGY
BRMGW	BRMCY	BRMCW	BRMYW	BGCYW
BMGCY	BMGCW	BMGYW	BMCYW	MGCYW
KRGCYW	KRMGCY	KRMGCW	KRMGYW	KRMCYW
KBRGCY	KBRGCW	KBRGYW	KBRCYW	KBRMGC
KBRMGY	KBRMGW	KBRMCY	KBRMCW	KBRMYW
KBGCYW	KBMGCY	KBMGCW	KBMGYW	KBMCYW
KMGCYW	RMGCYW	BRGCYW	BRMGCY	BRMGCW
BRMGYW	BRMCYW	BMGCYW	KRMGCYW	KBRGCYW
KBRMGCY	KBRMGCW	KBRMGYW	KBRMCYW	KBMGCYW
BRMGCYW	KBRMGCYW			

Figure 5. The 247 colormaps in level 3 corresponding to the condition $L_B(k)*W_B < L_R(k)*W_R < (L_R(k)*W_R+L_B(k)*W_B) < L_G(k) *W_G$