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RESEARCH ARTICLE

COLOR RESEARCH AND APPLICATION WILEY

Virtual Colour Atlas

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Abstract

A web application (Virtual Colour Atlas) has been developed that implements seven of the leading color order systems: *Colorcurve*, *Coloroid*, *DIN 6164*, *Munsell*, *OSA-UCS*, *NCS*, and *Swiss Colour Atlas 2541*, three color spaces: *CIE xyY*, *CIELAB, and CIELUV*, and three colour ranges: *BS:5252*, *RAL 840-HR*, and *RAL 841-GL*—allowing the user to view any of the core planes in the color space of each of these systems. The Virtual Colour Atlas is freely available at (www.vcsconsulting.uk) and provides visual interaction with these systems using any modern browser hosted on a device with a sufficiently large physical display including: windows PCs, Macs, iPads, Linux devices, and smart televisions (HD to 8 K). This paper provides a brief background on the systems, describes the Virtual Colour Atlas software and history, and discusses example applications of the Virtual Colour Atlas.

KEYWORDS

Colorcurve, DIN-6164, Munsell, Natural Color System, Optical Society of America—Uniform Color scales

1 | INTRODUCTION

Over the course of the last century some of the most widely respected practitioners of color science endeavored to develop systems that represent the human perception of color. This resulted in a range of color order systems—often based on widely different and incompatible principles and aims. Kuehni and Schwarz[1] have provided a detailed and comprehensive review of the systems described in this paper and many more. Although these systems share a common basis of perceptual spacing, research investigating the spacing of these systems has shown them to be fundamentally and radically different from one other.[2,3]

The Virtual Colour Atlas software (version 3.x) described in this paper provides online, interactive embodiments of seven color order systems developed in the 20th century: *Colorcurve*, *Coloroid*, *DIN 6164*, *Munsell*, *OSA-UCS*, *NCS*, and *SCA2541*, together with the *CIE xyY*, *CIELAB*, and *CIELUV* color spaces and the *BS:5252*, *RAL 840-HR*, and *RAL 841-GL* color ranges.

The Virtual Colour Atlas software was first developed in 2005 using the algorithms described in Neville Smith's PhD thesis on the development of the Colour Notation Conversion program (developed in the late 1980s on an IBM PC and written in Turbo Pascal, this software had no color rendering capability or graphical user interface [GUI]). The thesis details the algorithms, their development and testing, and their conversion accuracy.[4]

Version 1 of the Virtual Colour Atlas (2005) was written in C# with a winforms GUI and had a rudimentary color rendering engine—there was no support for RGB color spaces or chromatic adaption. Version 1 was limited to running on desktop PCs using the windows operating system; it was not released to the public due to the limited platform support and complexity of distribution (the world was moving to the internet for software solutions and away from operating system dependent applications but the internet at that time did not support complex applications).

Version 2 (released in September 2010) featured support for RGB color spaces and chromatic adaption, the

GUI was recoded in extensible application markup language (XAML) and used the proprietary Microsoft Silverlight run-time engine allowing the application to be executed on the client within a browser (IE, Chrome, Safari, etc.) using the windows, mac or Linux operating systems. The Virtual Colour Atlas application was downloaded to the client by the browser where it was executed in a browser hosted sandbox using the plug-in Silverlight runtime engine; this resulted in a fast and highly responsive web-hosted application that executed all the complex compiled code on the client device using the client's CPU and GPU.

In 2015, Microsoft indicated that the company would no longer be developing Silverlight, and support for the Silverlight run-time engine within the various browsers was withdrawn in subsequent years with the last supported browser, Internet Explorer, losing support in October 2021. At the start of 2021, client-side Blazor using web assembly (wasm) became a viable alternative to Silverlight and the application's GUI front-end was recoded to use HTML5; Virtual Colour Atlas v3.0 was released in August 2021. The main aim of wasm is to enable high-performance applications on web pages—it was designed by the World Wide Web Consortium (W3C) and is an open standard. The standard is maintained by the W3C and as such is not dependent on the support of a commercial company in the way Silverlight was with Microsoft, guaranteeing a longer support life. Wasm received the programing Languages Support Award from ACM SIGPLAN in 2021. Unlike Silverlight, where the run-time engine is a browser extension, a wasm application is fully self-contained and therefore generates a significantly larger deployment package than was the case with Silverlight as an application needs to ship with everything it needs contained within the package. Consequently, a complex wasm application is large and needs to unbox on the client device resulting in slow initial load times of 20–30 seconds on a desktop PC to around 2 minutes on the 65″ LG OLED smart TV used as a test platform during development. However, as the code is entirely self-contained, it will execute on any hardware running a modern browser with a sufficiently large enough screen size (the larger the screen size and resolution the better); the application is highly performant as the code is executed using the client device's CPU (typically employing ahead-of-time [AOT] or just-in-time [JIT] compilation). Although a wasm application can operate on a smart phone, the GUI of Virtual Colour Atlas does not currently support these devices as the screen size is too small.

A brief conceptual overview of each of the supported systems is provided here.

2 | COLOR ORDER SYSTEMS

2.1 | Colorcurve

The Colorcurve system was developed by Ralph Stanziola as a system for color communication between designers and manufacturers of colored materials.[5] It is specified by sampling in the CIELAB color space that is a hybrid of uniform CIELAB lightness-hue-chroma sampling and additive mixtures in between anchor points. This hybrid design was felt to be more intuitive to designers. The system used the same metric attributes as CIELAB, namely lightness (L) and the reddish/greenish and yellowish/bluish chromatic dimensions a and b. A unique feature of Colorcurve was that each color in the atlas was also specified by a spectral reflectance curve such that they could be used in colorant formulation systems to produce matching color samples via spectral, not just tristimulus, matching.

2.2 | Coloroid

Antal Nemcsics developed the Coloroid system in the latter half of the 20th century.[6] It was based on large numbers of esthetic judgments and organized around principles designed to explore harmonious color combinations. Its three attributes are hue (A), saturation (T), and lightness (V). Hue is defined as hue angle in the CIE 1931 chromaticity diagram, Coloroid saturation is a unique index of chromatic intensity defined relative to the highest-chroma color of each hue, and lightness is defined by a square-root compression of CIE luminance (Y). Conceptually, Coloroid is a cylindrical color space.

2.3 | DIN 6164

DIN 6164 was designed to show equal perceptual differences across three dimensions of hue (T), saturation (S), and darkness (D).[7] Uniquely, samples of constant hue and saturation, but varying in darkness, all have the same chromaticity coordinates. They thus represent a shadow series, that is often considered a most intuitive definition of chromatic dimensions and has often been defined as constant perceived saturation (as well as representing constant ratios of cone excitation). Another interesting feature is that the darkness dimension incorporates the Helmholtz-Kohlrausch effect rather than being unidimensionally dependent on luminance.

2.4 | Munsell

The Munsell system was developed early in the 20th century by Albert Munsell and the Munsell Color Company as a means to specify, communicate, and teach color appearance in an intuitive, systematic way, and was thoroughly revised and integrated with CIE colorimetry in the Munsell "renotation" published in 1943.[8] It is based on perceptually uniform scales of Munsell Value (lightness), Munsell Hue, and Munsell Chroma. Each dimension is scaled to have perceptually uniform increments in a given attribute, but the dimensions are independent and no relationship among the three scales is specified. Uniquely, Munsell included five principal hues (rather than the four suggested by opponent-colors theory) because five were required to produce a hue circle with uniform perceptual steps for all hues. The Munsell system remains widely used and commercially available to this day.

2.5 | Natural Color System

The Swedish Natural Color System (NCS) is another color appearance system that is still widely used and commercially available.[9] While it also scales appearance in a uniform perceptual manner, it uses dimensions quite different from those selected by Munsell. The system is based on Hering's opponent colors theory and color samples are arranged in a double-cone space with white at the top, black at the bottom, and maximally chromatic colors of each hue on the perimeter. Hering's opponent dimensions are light-dark, red-green, and yellow-blue. The NCS hue circle is designed such that the unitary hues red, green, yellow, and blue fall on orthogonal axes. Thus, hue differences can only be perceptually uniform in one quadrant at a time and the four quadrants have different perceived-hue spacing. (Recall Munsell inserted purple in his hue circle to allow uniform hue spacing across the full hue circle). For a given hue, the system is represented by a triangle with trilinear sampling of whiteness, blackness, and chromaticness. Zero blackness in the NCS system corresponds to Evans' concept of zero gray content, G_0, and like the DIN 6164 system, the blackness dimension automatically incorporates the Helmholtz-Kohlrausch effect.

2.6 | Optical Society of America—Uniform Color Scales

The Optical Society of America—Uniform Color scales (OSA-UCS) color system attempts to address the limitation of independent scales in the Munsell system by creating a perceptually uniform three-dimensional sampling of color space using a regular rhombohedral lattice.[10] Each nonboundary color is surrounded by 12 equidistant nearest neighbors (a cuboctahedron where the 12 vertices are the nearest neighbors to the center point) that are designed to be equal in color differences from the starting point. The system is specified with a lightness dimension, L, that is computed from CIE 1964 luminance, Y_{10}, and two opponent dimensions, j and g, that are computed from CIE 1964 tristimulus values, X_{10},Y_{10},Z_{10}. The 12 different possible cleavage planes of the regular rhombohedral sampling provide unique and beautiful perspectives on color harmony and relationships.

2.7 | Swiss Colour Atlas 2541

Aemilius Müller described the Swiss Colour Atlas (SCA2541) in the middle of the 20th century.[11] It was based on Ostwald's double-cone color order system (similar to NCS) but was refined to improve perceptual uniformity. Each of its 60 constant hue pages were also sampled trilinearly in terms of whiteness, blackness, and chromaticness.

3 | COLOR SPACES

3.1 | CIE xyY

The CIE colorimetric system is a method of numerically specifying the physical attributes of colors and is primarily of use in the instrumental measurement of color.[12] The basis of the system is that a color stimulus can be matched by an additive mixture of three primary color stimuli of variable proportions. A primary color stimulus is a color that cannot be color matched by a mixture of the other primary color stimuli. The CIE colorimetric system is only incidentally associated with collections of physical samples, and as such no CIE atlas exists. Additionally, as the CIE colorimetric system is not based on perceptual qualities of color any such atlas would be of little use to designers or architects. The CIE system is a method of specifying colors solely by their physical attributes, and by general consensus the CIE colorimetric system, CIE standard observers, and CIE standard illuminants are the global standards of specification. Luminance (Y) forms the central axis of the system with the x and y axes perpendicular to the luminance axis and each other. Planes of constant lightness form xy chromaticity planes.

3.2 | CIELAB (L*a*b*)

The CIELAB system is derived from Adams's (1942) system, the color difference formula being a cube root version of the Adams-Nickerson formula.[13,14] The rectangular coordinates L*,a*,b* of this system are calculated from the CIE X,Y,Z tristimulus values by equations. Lightness (L*) forms the central axis of the system with the a* and b* axes perpendicular to the lightness axis and each other. Planes of constant lightness form ab chromaticity planes. CIELAB was one of two color spaces adopted by the CIE in 1976 (the other being CIELUV) that attempted perceptual uniformity.

3.3 | CIELUV (L*u*v*)

The CIE 1976 (L*,u*,v*) system, abbreviated to CIELUV, is an improvement of the CIE 1964 (U*,V*,W*) system that it supersedes.[13,15] The rectangular coordinates L*,u*, v* of this system are calculated from the CIE X,Y,Z tristimulus values by equations. Lightness (L*) forms the central axis of the system with the u* and v* axes perpendicular to the lightness axis and each other. Planes of constant lightness form uv chromaticity planes.

4 | COLOR RANGES

4.1 | BS:5252

BS 5252F:1976 is the British Standard framework for color co-ordination for building purposes and contains 237 colors divided over five values of gray (A-E) and then by Hue and Light.[16] The Virtual Colour Atlas displays the 237 samples on five charts, one for each plane of gray, by Hue and Light with the gray planes containing: A: 24 samples, B: 48 samples, C: 66 samples, D: 44 samples, and E: 55 samples.

4.2 | RAL 840-HR

RAL 840-HR is a collection of 213 semimatt RAL CLASSIC colors designated by a 4-digit number.[17] The first digit is the system code number: 1-yellow, 2-orange, 3-red, 4-violet, 5-blue, 6-green, 7-gray, 8-brown, and 9-black and white, the remaining three digits are sequentially assigned. This is presented in the Virtual Colour Atlas as a single page of 152 colors split by the system code number into nine rows. The dataset is old (circa 1990) and lacks some of the new core colors together with all of the pearlescent (15), daylight luminous (5), and micaceous iron (2) colors.

4.3 | RAL 841-GL

RAL 841-GL contains 196 RAL CLASSIC colors in high-gloss using the same designation mechanism as RAL 840-HR.[17] The Virtual Colour Atlas has colorimetric data on 183 of the colors, and these are displayed on a single page of nine rows, one row for each system code.

5 | VIRTUALIZATION

There are a number of problems commonly associated with color order systems: the lack of a universal standard, the appropriateness of applying a particular notational structure to differing problems, the cost of producing the physical color atlas coupled with a limited audience size, the color accuracy of the samples in the atlas to their intended aim points, and limitations in their physical representations: primarily sample range and size. From their peak in the 70s and 80s, the use of color atlases has declined both for the reasons mentioned and due to technological advancements, and most have become unavailable.

This article attempts to address these issues by presenting virtual models of the color spaces of seven color order systems and the potential development of new systems without the inherent limitations of the existing models. This freely available software tool is described in the following sections. It is composed of notation conversion, display, and graphics engines.

6 | NOTATION CONVERSION ENGINES

A software tool—The Colour Notation Conversion Program—was developed that enabled the interconversion between various color order systems by using the CIE system as an intermediary.[18,19] All of the color systems implemented in the original application and in Virtual Colour Atlas are defined by a range of points in their unique color space, and corresponding coordinates in CIE space exist for these points either by their defined aim points and/or by measuring the colored samples in the associated atlas (actual points). The notation conversion engines are custom algorithms implemented for each color system that: (a) convert from the notation of the source system to CIE space, and (b) convert from CIE coordinates to the notation of the target color system (color ranges can only be source systems not targets). As there are only an often-small number of points the algorithms employ various interpolation and extrapolation algorithms to enable conversion from and to any point within the defined limit of the 3D color space of the color system (not applicable to color ranges that cannot be interpolated). A conversion request will result in one of three outcomes: (a) if the target color is within the color space of the target system the conversion is undertaken, (b) for target colors just beyond the color space system-specific algorithms are employed to expand the base color space to enable the conversion and a warning is issued: "Warning: possible significant error in conversion," or (3) if the target color lies beyond the boundary of the algorithmically expanded color space an error is returned "Error: could not convert coordinates." If a color cannot be converted to RGB the "Gamut failure" warning is issued. Table 1 lists the supported datasets and their sources. The software only allows conversions between points in the datasets defined (in the case of aim points) or measured (in the case of physical atlas samples) using the same CIE illuminant and CIE standard observer. No adjustment is made for differences between datasets that were defined or measured using different conditions, for example: spectrophotometer geometry or specular inclusion/exclusion.

7 | DISPLAY ENGINES

Given the CIE coordinates calculated by the notation conversion engines, that are specific to a given CIE illuminant and standard observer, two engines have been developed to convert the points to displayable RGB values.

The RGB engine converts the CIE tristimulus values to RGB using a mapping matrix and any required corrections for nonlinearities. Table 2 lists the supported RGB color spaces.

Any differences in white point between the illuminant specified in the color system and the white point of the selected RGB display color space should be corrected using a chromatic adaptation transform. For such corrections between the source illuminant and the illuminant of the selected RGB color space, the chromatic adaption algorithms listed in Table 3 are supported. By default, selecting a chromatic adaption algorithm will convert the colors from the CIE illuminant of the source system to that of the RGB space—unless the two are the same in which case no chromatic adaption transformation is required.

TABLE 1 Datasets supported by Virtual Colour Atlas

System	Available datasets: CIE illuminant/CIE standard observer
CIELAB[13,14]	Aim points for all (by equation)
CIELUV[13,15]	Aim points for all (by equation)
Colorcurve[20]	Aim: D65/1964, Actual: D65/1964
Coloroid[21]	Aim: C/1931, D65/1931, D65/1964
DIN 6164[22,23,a]	Aim & Actual: C/1931, D65/1931, D65/1964
Munsell[24]	Aim: C/1931
NCS[25,26,b]	Aim: C/1931, D65/1931, Actual: C/1931, D65/1931, D65/1964
OSA-UCS[9,27]	Aim: D65/1964, Actual C/1931. D65/1964
SCA2541[28]	Actual: C/1931, D65/1931
BS:5252[29]	Actual: C/1931, D65/1931, D65/1964
RAL 840-HR[c]	Actual: D65/1931
RAL 841-GL[d]	Actual: D65/1964

[a]Klaus Witt, personal communication, measured DIN 6164 sample data for C/1931, D65/1931 and D65/1964

[b]Tomas Hård, personal communication, measured NCS sample data for C/1931 and D65/1931

[c]Klaus Witt. personal communication, measured RAL 840-HR D65/1931 sample data

[d]Klaus Witt. personal communication, measured RAL 841-GL D65/1964 sample data

8 | GRAPHICS ENGINES

The relevant notation conversion engine converts the source notations to CIE and the display engine calculates the corresponding RGB notations based on the selected RGB color space and the chromatic adaption algorithm (if applicable); a graphics engine is then used to generate the chart. There are three graphics engines: RALViewer (for RAL 840-HR and RAL 841-GL), TriangularViewer (NCS and SCA2541), and PlaneViewer (standard x/y axes

TABLE 2 RGB color spaces supported by Virtual Colour Atlas

RGB color space	CIE illuminant
Adobe RGB (1998)	D65
Apple RGB	D65
Best RGB	D50
Beta RGB	D50
Bruce RGB	D65
CIE RGB	E
ColorMatch	D50
Don RGB 4	D50
ECI	D50
Ekta Space PS5	D50
NTSC	C
PAL/SECAM	D65
ProPhoto	D50
SMPTE-C	D65
sRGB	D65
Wide Gamut RGB	D50

grid layout used by the remaining systems) that take as input the required plane to be generated and the GUI specified configuration settings, returning a virtual canvas containing the components of the image.

Returning a virtual canvas achieves separation between the logic that draws the image and the logic that renders the image, so the notation conversion and display engines are not dependent on the rendering mechanism used by the front-end. The front-end implements a rendering engine that converts the virtual canvas into native graphic primitives: in the case of Virtual Colour Atlas (version 3.x) this is HTML5. With appropriate selection of RGB color space and a properly calibrated display, the displayed colorimetry is accurate. In other situations, the displayed colors are representative of the systems and their interrelationships and the viewing experience can be considered similar to viewing the original atlases under slightly incorrect illumination.

TABLE 3 Chromatic adaption algorithms supported by Virtual Colour Atlas

Chromatic adaption algorithm
None [own reference white][a]
XYZ scaling
Von Kries
Bradford
Bradford [D50][b]

[a]"None [own reference white]"—does not apply any chromatic adaption.
[b]"Bradford [D50]" applies Bradford algorithm chromatic adaption to the RGB space to convert it to D50 (unless it already is D50), so for example sRGB [D65] is converted to sRGB [D50], and then Bradford algorithm chromatic adaption is applied to the source system illuminant to D50.

9 | VIRTUAL COLOUR ATLAS

The Virtual Colour Atlas application is free to use, available at www.vcsconsulting.uk and is compatible with windows, MacOS, iPadOS, ChromeOS, Linux, and smart televisions using modern browsers (including Chrome, Edge, and Safari). Please note that the application is large and it may take up to 30 seconds on a desktop device or 2 minutes on a smart TV (on first execution) before the application is fully loaded.

The application allows the user to display a plane of colored samples for any dimension in the selected system; for example, any plane in the Munsell system: Hue, Chroma, and Value for any constant level of one of the dimensions. Plane selection is not limited to the steps used in the underlying atlas, so for example a plane of constant Chroma at 4.5 can be specified (see Figure 1), as can the Hue 5.35GY.

Interpolation and extrapolation algorithms are applied, where required, to determine missing points. For example: the SCA2541 atlas does not include any samples of chroma 1 or 2 for hue 23 and the software employs algorithms to calculate these missing values (Figure 2). The display of these calculated points can be suppressed to show only the original atlas dataset if desired (see online help).

A zoom option (not color ranges) expands the default dataset to include interpolated/extrapolated values at the selected zoom setting and has four options: 100%

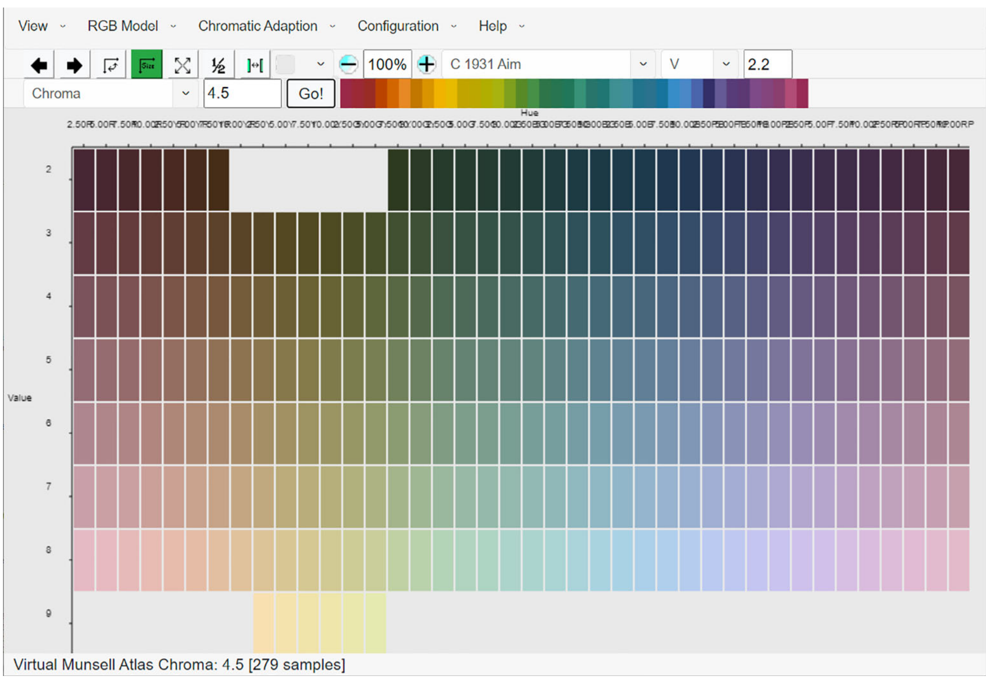

FIGURE 1 Munsell Chroma 4.5

(default), 200%, 400%, and 800%. For example: a standard NCS hue is laid out in the NCS atlas as a triangular structure from 0 chromaticness to 100 in steps of 10, and the same for blackness, producing 66 possible sample points. Activating the zoom setting for NCS changes this step (in all displayed axes) from 10 to: 5 (200%) generating 231 samples, 2.5 (400%) generating 861 samples, and 1.25 (800%) generating 3321 samples. Figure 3 displays the DIN 6164 constant saturation plane $S = 2$ at 400% zoom (increments of 0.25 in T [hue] and D [darkness] producing 1849 colored samples.

Displayed planes can be presented in two ways: sized to fit the screen and unlimited size based on the display sample size and the number of samples. For the former, the entire sample set will be autosized to fit the application window including any screen resizing. When autosizing is not enabled, the underlying display area may be many times larger than the viewing area, and in this case, scroll bars are activated allowing the user to scroll the view over the display area (Figure 4).

Left-clicking on a display sample opens a moveable and resizable window displaying a larger version of the selected color together with its system notation, color name (applicable to Munsell [as ISCC-NBS color name], BS:5252 and RAL), CIE tristimulus values, and RGB values. Right-clicking on a chart allows the chart to be saved as a PNG.

Colors that exceed the gamut limit of the RGB space are, by default, not displayed—the number of excluded sample points due to gamut failures is displayed on the status bar. For example: a color with the calculated RGB value 100, 200, 260 would exceed the gamut limit (maximum of 255) and would, with the gamut limiter enabled, not be displayed. The gamut limiter can be disabled in which case colors with RGB values in excess of 255 will be clipped to 255 (for each RGB value that exceeds 255) and those less than zero will be clipped to zero.

10 | COLOR NOTATION CONVERSION

A front-end to the underlying color notation conversion algorithms and datasets is available within the application. This supports conversion from BS:5252, CIE, CIELAB, CIELUV, Colorcurve, Coloroid, DIN 6164, Munsell, OSA-UCS, NCS, SCA2541, and the RAL color ranges to any of the systems that are not fixed ranges (BS:5252 and RAL) as the fixed ranges cannot be interpolated. Notations can be processed individually or as a batch and the data exported as CSV, TSV, HTML, or XML files. Optionally, one of nine color difference formulas can be specified to locate the nearest physical atlas sample to the calculated target notation; both the target and nearest atlas sample colors are displayed side by side.

11 | EXAMPLE APPLICATIONS

In addition to the obvious application of the Virtual Colour Atlas to teach, compare, and contrast various color systems,

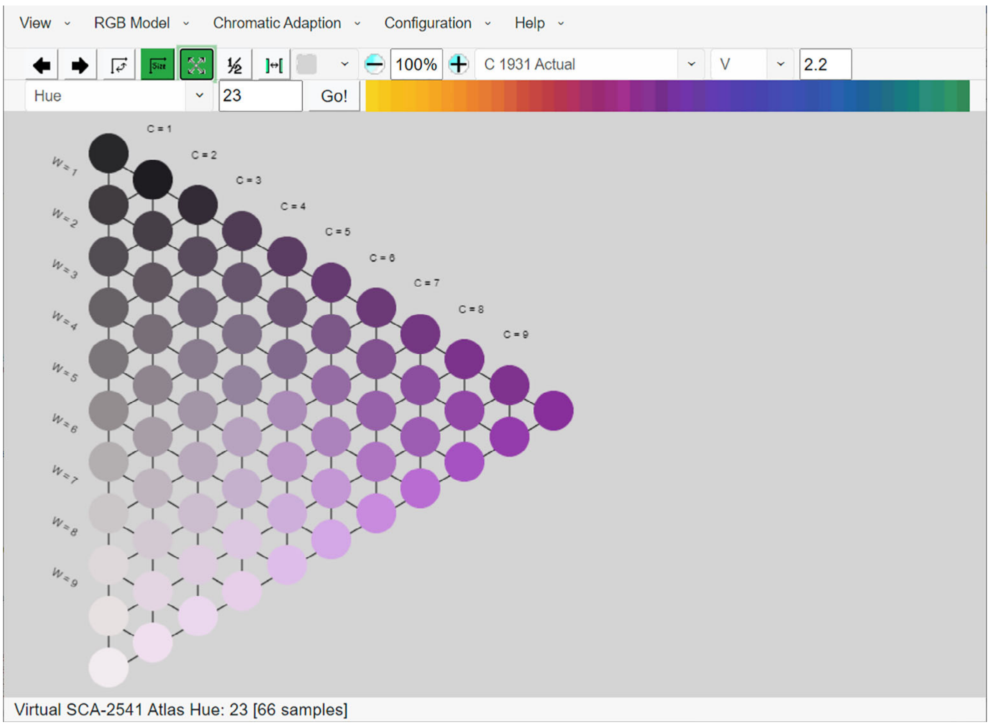

FIGURE 2 SCA2541 Hue 23 (extrapolated)

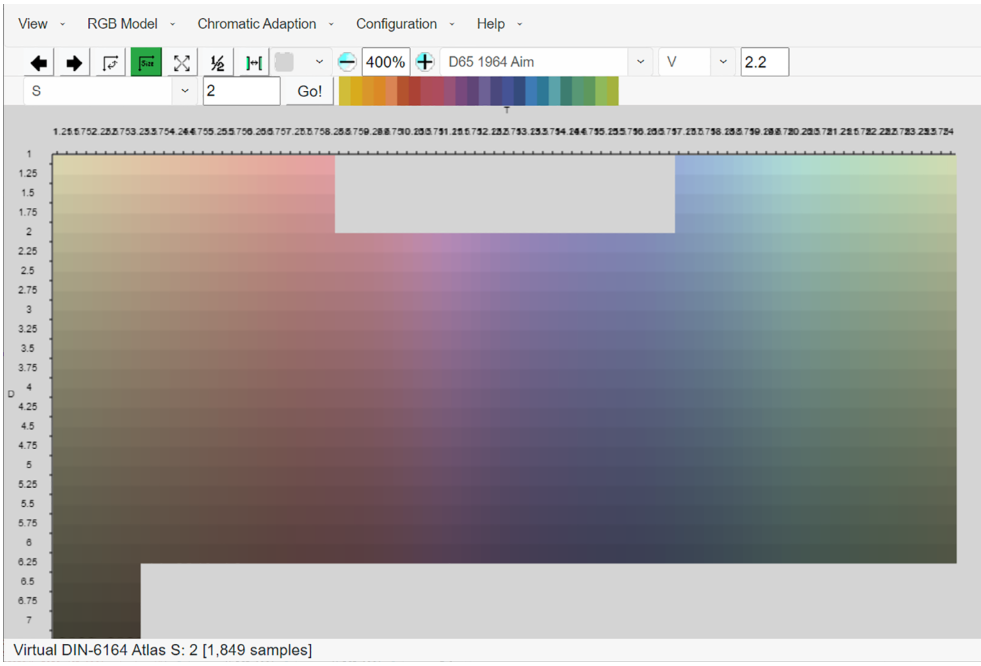

FIGURE 3 DIN 6164 Saturation 2, zoom 400%

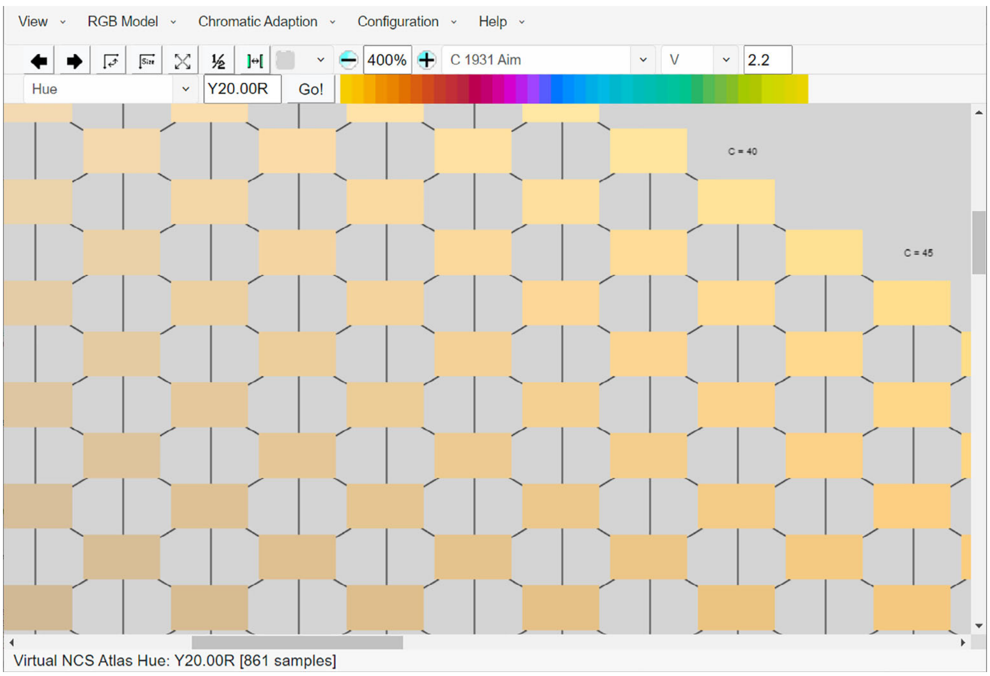

FIGURE 4 NCS Hue Y20R, zoom 400%, autosize disabled

it has also been applied in various experimental paradigms at the RIT Munsell Color Science Laboratory. Examples of the variety of educational and research settings in which the system has been successfully utilized include:

- Using the Munsell system to create scales of constant Value and Chroma for the full hue circle to enable hue scaling of afterimages in a classroom experiment. Students concentrate on a color sample for an adaptation period and then project the afterimage adjacent to the high Value, low Chroma hue scale to select a hue that matched the afterimage.
- Planes of constant Chroma (or Value) are used in both classroom and research experiments on categorical color naming, similar to the world color survey that sought to better understand categorical and lexical color boundaries. The arrays of samples presented in the Virtual Colour Atlas and the included conversion to other color specifications allows students to set up, perform, and analyze experiments without the need for other display software.

- In research on color tolerancing and/or chromatic adaptation, various systems within the Virtual Colour Atlas have been used to provide stimuli for memory-matching tasks. This can be applied directly on display or the system can be used to generate color samples for printing. (It should be noted that careful calibration of displays or printers is required to generate samples accurate to the color systems, but even slightly inaccurate samples are often useful as long as they are separately measured or characterized.)
- The Virtual Colour Atlas has been recently used to aid research on the perceptions of brilliance, zero-grayness, and saturation using the unique sampling of the DIN 6164 system.[30] This has been particularly helpful since DIN 6164 atlases are long out of print and very difficult to obtain.

12 | CALL FOR DATA

The Virtual Colour Atlas is missing some key datasets including:

- Measurements of the Munsell atlas samples for any combination of CIE illuminant and standard observer, that is, spectral reflectance measurements of Munsell samples that could be used for arbitrary colorimetric computations.
- The supported RAL datasets date from 1990 and are incomplete.
- The software is extensible by design, so datasets from color order systems, color systems, or fixed ranges not already implemented in the software can be incorporated.

Anyone having one of these missing datasets and amenable to including the data in the Virtual Colour Atlas application is encouraged to contact the lead author.

13 | CONCLUSIONS

Virtual Colour Atlas provides a powerful tool for educational, research, and industrial application. It can be used to support the teaching of color order systems, color perception research, color difference formula, as well as the history and evolution of color order systems. The freely available software, along with recent advancements in display capability, stability, and color management in consumer computer systems, allow these virtual presentations of historical color atlases to be viable and useful reproductions of the original. Modern reference displays make it possible to use the Virtual Colour Atlas to directly generate desired color samples for research purposes with little or no additional characterization or calibration. The authors hope that many future generations of students and researchers will find this tool helpful.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy restrictions.

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