An Alternative Color Space for Color Selection and Image Manipulation with Improved Brightness Component

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Abstract. An alternative color space for color selection and image manipulation is described using a cylindrical variant of YIQ color space. The classical color spaces HSL and HSV do not take human perception into account and produce incorrect results in terms of perceived brightness. Perceptually uniform color spaces such as CIELAB and CIELUV are computationally expensive for real-time interactive applications and are difficult to implement. The color space *YCH* proposed in this work provides a reasonable balance between perceptual uniformity, performance and calculation simplicity. It models the colors in terms of perceived brightness more closely and is fast to compute for real-time applications. Experimental results are described, where the classical color spaces are compared to the proposed one in terms of perceptual uniformity, color richness and the performance, showing that the proposed color space is a viable alternative for the applications that use the classical color spaces HSV and HSL.

Keywords: color space, perceived brightness, color selection, image manipulation

1 Introduction

In image editing and manipulation software it is common to use HSV and HSL color spaces based on hue and lightness for image manipulation and intuitive color selection. These color spaces are so popular that they made their way into CSS3 specification [1]. The HSV and HSL color spaces were originally proposed by A. R. Smith back in 1978 [2]. They have an elegant way of color specification – using hue, saturation and lightness (or value in HSV). This specification makes it easy to define colors both numerically and visually using sliders, rings and so on. The values of hue, saturation and lightness can be directly calculated from the red, green and blue components. The conversion process was initially described by A. R. Smith [2] and can be found in popular books [3], [4].

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However, the main drawback of the HSV and HSL color spaces is that they do not model colors as they are seen by the human eye. According to Charles Poynton [5], these color spaces are "useless for conveyance of accurate color information", suggesting that they should be abandoned. In his works [5], [6], Charles Poynton describes HSV and HSL models as flawed in respect to color vision and that they do not define the color objectively. The major drawback of the HSL color space is the lightness (or similarly value in HSV) component does not take into account the perception of the color brightness as it is perceived by the human eye.

In the context of color perception more uniform color spaces have been proposed such as CIE XYZ, CIELAB and CIELUV [7]. Several formal definitions are necessary to compute the color components in these spaces from the red, green and blue values, such as the primaries specifying the RGB color space and white point coordinates [6], [7]. Other candidates for perceptually uniform color spaces include Guth's ATD95 Color Model [8] and DIN99 color space [9], [10]. All these color spaces share several characteristics – having the advantage of being more perceptually uniform with the major drawback of being cumbersome to compute and difficult to implement. The mathematical complexity of the aforementioned color spaces makes them an expensive alternative for real-time image manipulation, especially in mobile applications such as those running in a web browser, and for interactive color selection when a relatively large color palette is available. Another drawback is that the chroma component in the aforementioned models has range of values that varies depending on other values. This makes it difficult, if not impossible, to display the color wheel given a specific value of brightness because some areas of the color wheel will have invalid colors, being either out of range or not visible by the human eye at all.

An alternative color space inspired by HSV and HSL called HCL Color Space has been recently introduced by M. Sarifuddin and R. Missaoui [11]. The authors have taken into account the fact that the human eye reacts in a logarithmic manner to color intensity, making the color model more closely related to color perception. However, the HCL color space shares the drawbacks with the HSL and CIELAB color spaces and none of their advantages. The "luminance" (marked in quotes because according to Poynton the term luminance is commonly misused [6]) component L in the HCL color space is calculated using minimum and maximum RGB values, similarly to how it is done in HSL color space, making it inherently perceptually incorrect. The chroma component C has a non-normalized variable range, depending on the given "luminance" L, making its selection unintuitive. Last but not least, the conversion between RGB and HCL is cumbersome with some parameters not explained in sufficient detail (such as the origin of Y0 parameter and the tuning of parameter γ).

The colors in the HCL color space plotted at constant values of L, namely 25%, 50% and 75% of maximum value, are illustrated on Fig. 1. The chroma at each position is calculated as $C = \sqrt{x^2 + y^2}$ and the hue is calculated as $H = \operatorname{atan2}(y, x)$. The atan2 function is an arctangent of y/x with the resulting angle in range of $[-\pi, \pi]$ [12].

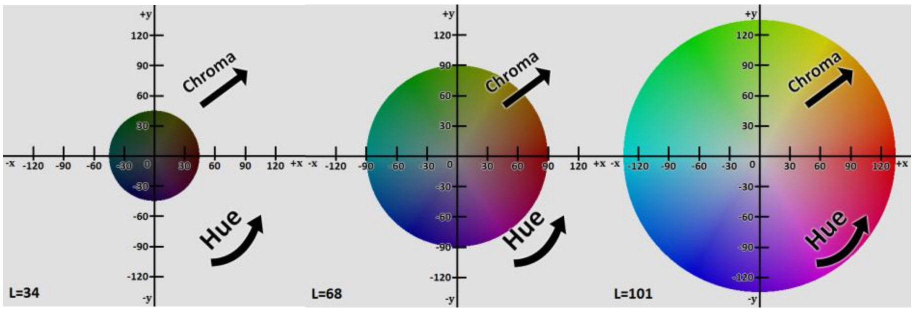

Fig. 1. Colors plotted in the HCL color space with *L*=34 (a), *L*=68 (b) and *L*=101 (c). Bright gray indicates that the resulting RGB values are out of the valid range.

It can be seen on the Fig. 1 that HCL color space looks similar to HSV, where different hue shades have different perceived brightness. That is, green appears brighter than red and blue appears darker. For a reference, the colors in the CIELUV space [7], [13] are displayed in Fig. 2 for the same percentages of the maximum value of luminance L*.

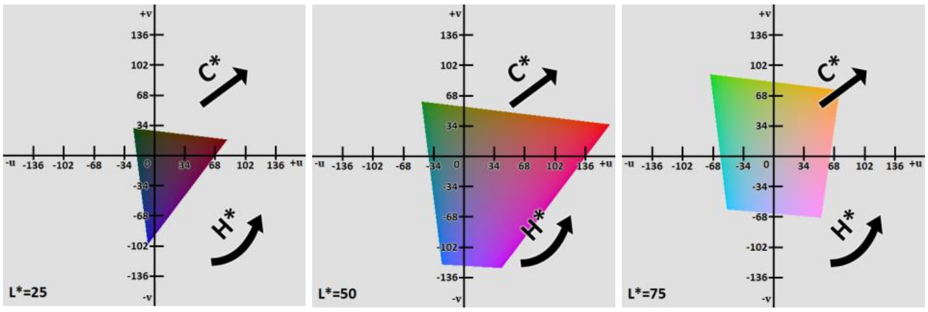

Fig. 2. Colors plotted in the CIELUV color space with *L**=25 (a), *L**=50 (b) and *L**=75 (c). Bright gray indicates that the resulting color is outside of sRGB color gamut.

The above figures show that different shades of color like green versus blue produce colors with similar perceived brightness (note that the printed version may slightly differ depending on the color space used by the printer). Comparing the figures of HCL and CIELUV color spaces it is evident that colors with the same L value in HCL color space do not appear with the same brightness. This problem occurs also in HSV and HSL color spaces, but not in CIELAB, CIELUV and DIN99, and their cylindrical variants. However, the range of chroma C* in these color spaces (the distance from the center to any point on diagram) varies a lot – that is, with the specific values of chroma C* and luminance L*, different values of H* may produce colors either inside or outside the sRGB color gamut [14].

2 The proposed coordinate system

One of the several color television standards is the YIQ color space, introduced by the National Television System Committee (NTSC) [3], [15]. The particularities of this color space are that its Y, I and Q components can be calculated quickly right from RGB color values, and that the component Y called luma is proportional to the gamma-corrected luminance of a color [5], [6], [15]. That is, the luma models the perceived brightness more precisely than the “brightness” component in color models such as HSV, HSL and HCL.

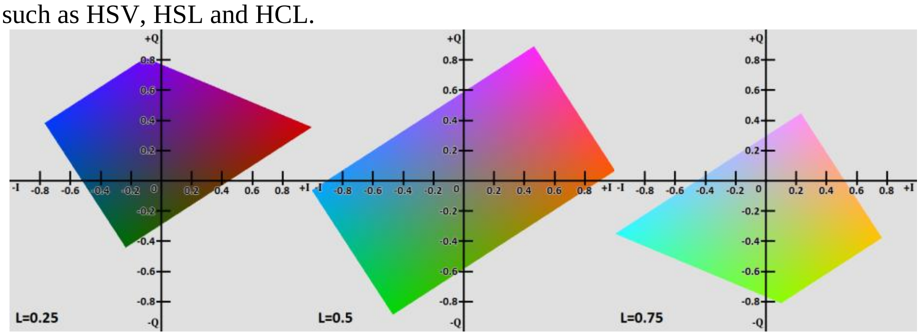

Fig. 3. Colors plotted in the YIQ color space with *Y*=0.25 (a), *Y*=0.5 (b) and *Y*=0.75 (c). The bright gray indicates that the resulting RGB values are outside of valid range.

Fig. 3 shows colors plotted in the YIQ color space with different values of the luma. The colors on each diagram have roughly the same perceived brightness, looking similar to the results obtained with perceptually uniform spaces such as CIELUV and CIELAB. In terms of hue, the diagram shows that a wide palette of colors is available; the question is how a user can choose a color in the YIQ color space using common terms such as hue and saturation.

As shown previously on Fig. 2, the cylindrical version of CIELUV uses terms of chroma and hue based on the angle between u and v. A similar approach can be applied to YIQ, introducing the terms Y’, C’ and H’:

$$Y' = Y \tag{1}$$

$$C' = \sqrt{I^2 + Q^2} \tag{2}$$

$$H' = \operatorname{atan2}(Q, I) \tag{3}$$

The parameters described by the equations (1), (2) and (3) form a new color space denoted YCH, with a cylindrical coordinate system. The parameter Y’ is defined in the range [0, 1], H’ is defined in the range [-π, π] and C’ values range from 0 to 0.7925 in typical applications. The reverse transformation from YCH to YIQ color spaces is the following:

$$Y = Y' \tag{4}$$

$$I = C' \cdot \cos(H') \tag{5}$$

$$Q = C' \cdot \sin(H') \tag{6}$$

However, as mentioned previously, the YCH color space suffers similar drawback as other color spaces such as cylindrical variants of CIELAB and CIELUV. Different values of hue with constant values of luma and chroma may produce both valid and invalid RGB colors. This is illustrated on Fig. 4.

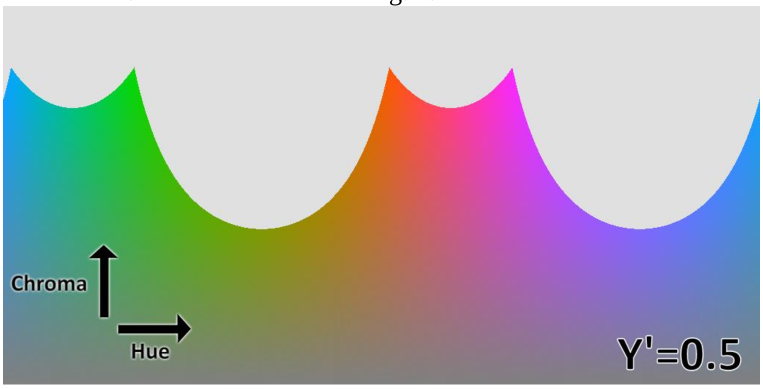

Fig. 4. Colors plotted in the *YCH* color space showing the dynamic range of chroma for a constant value of luma and different values of the hue.

Note that the shape shown on Fig. 4 looks different with other values of Y'. In order to display the color wheel or speak in terms of saturation, it would be convenient for the chroma to be normalized within a fixed range for different values of hue and luma. This way, the saturation will range from 0 to 1, for all the values of the hue and the luma, eliminating the area of invalid RGB colors. This issue is further discussed in the next section.

3 The Valid Chroma Algorithm

The normalization of valid chroma values, so that they fall within a fixed range, requires calculating the valid lower and upper bounds of the chroma values for the given set of luma and hue values. The lower chroma bound is zero, while the upper bound needs to be determined. This can be solved either analytically or numerically. Due to the fact that every color space is calculated differently, it is difficult to develop an algorithm that can be used in each scenario. It is possible to calculate the bounds using a brute force approach, but it would be too slow to be considered for practical applications. An alternative described in this work is an algorithm that is more efficient than the pure brute force search, but can still work with any given color space. It is based on the popular branch and bound algorithm [16], [17]. This algorithm can quickly determine the approximated upper chroma limit by continuously dividing the space in half until the reasonable precision is achieved. The algorithm can be described as a series of steps:

1. Set *L* to zero (lower bound), set *R* to one (upper bound).
2. Set *Result* to zero.

3. If (*R*-*L*)<*ε*, then go to step 9.
4. Set *M* to (*L*+*R*)/2.
5. If Valid(*L*) and not Valid(*M*) and not Valid(*R*), then set *R* to *M*, set *Result* to *Left*, go to step 3.
6. If not Valid(*L*) and not Valid(*M*) and Valid(*R*), then set *L* to *M*, set *Result* to *Right*, go to step 3.
7. If Valid(*L*) and Valid(*M*) and Valid(*R*), then set *L* to *M*, set *Result* to *Middle*, go to step 3.
8. If not Valid(*L*) and Valid(*M*) and Valid(*R*), then set *R* to *M*, set *Result* to *Middle*, go to step 3.
9. Return *Result*.

In the algorithm described above, L, R and M are variables of floating-point type, the function Valid(x) returns true if the color with the chroma x and constant values of hue and luma has a valid RGB entry, and false otherwise; ε is the desired precision factor. For the image resolution of 1024 by 512 pixels shown on Fig. 4, the color curve is seamlessly predicted with ε equal to 0.0079, requiring at most 7 cycles from step 3 to 8 in the worst case. The returning value, denoted as Cmax, is the maximum value of chroma that in combination with hue and luma can be properly displayed within the sRGB color gamut or has valid RGB values if formal RGB color space is not defined. It is evident that the algorithm does not only work for the YCH color space, but can also be applied to other cylindrical coordinate variants such as those based on CIELAB, CIELUV and DIN99, although the function Valid(x) in these color spaces might be quite computationally expensive, making the algorithm less attractive in terms of performance.

The saturation of color defined in the range of [0, 1] can be calculated once Cmax is known:

$$S_c = \frac{C'}{C'_{\max}} \tag{7}$$

Where C' is the chroma of the given color in the YCH color space and $C'_{\max}$ is the value calculated using the valid chroma algorithm. If the value of saturation is given, the chroma can also be calculated as:

$$C' = S_c \cdot C'_{\max} \tag{8}$$

The equations (7) and (8) allow the color to be defined using the values of Y', H' and Sc, which always produce valid RGB values, assuming that values of Y', H' and Sc are within the proper ranges. In the context of this work, the color space with Y', H' and Sc coordinates is referred to as YScH.

The pseudo code for the

Proposed algorithm when applied to YCH color space is the following:

Table 1. **The pseudo code for the valid chroma algorithm**

```
Left  = 0;
Right = 1;
```

```
while (Right - Left > Epsilon) do
 begin
  Middle = (Left + Right) / 2;

  IsLeft   = ChromaValid(Y, Left, H);
  IsRight  = ChromaValid(Y, Right, H);
  IsMiddle = ChromaValid(Y, Middle, H);

  if (IsLeft)and(not IsMiddle)and(not IsRight) then
   begin
    Right  = Middle;
    Result = Left;
   end;

  if (not IsLeft)and(not IsMiddle)and(IsRight) then
   begin
    Left   = Middle;
    Result = Right;
   end;

  if (IsLeft)and(IsMiddle)and(not IsRight) then
   begin
    Left   = Middle;
    Result = Middle;
   end;

  if (not IsLeft)and(IsMiddle)and(IsRight) then
   begin
    Right  = Middle;
    Result = Middle;
   end;
end;
```

In the pseudo code in Table 1 the function ChromaValid determines whether the color specified using the coordinates Y, C and H is a valid color. This can be achieved, for instance, by converting the color back to RGB coordinates and then verifying whether these coordinates are within the valid range. In the pseudo code it is assumed that the Y and H color components are valid, and remain constant.

4 Visual Characteristics

The color specification using Y', H' and S' coordinates provides an alternative way for color selection or image modification. The classical color wheel can easily be displayed with the variable hue at constant saturation and luma, as illustrated in Fig.

5. Note that, depending on the printing device and/or the monitor, the image may have different perceptual uniformity in hue – some areas appear smoother on paper while other look smoother on a computer monitor. This is due to the fact that different output devices using different color spaces to display images may reduce the visible palette, which is already limited, since all the colors visible by humans cannot be represented using valid RGB coordinates.

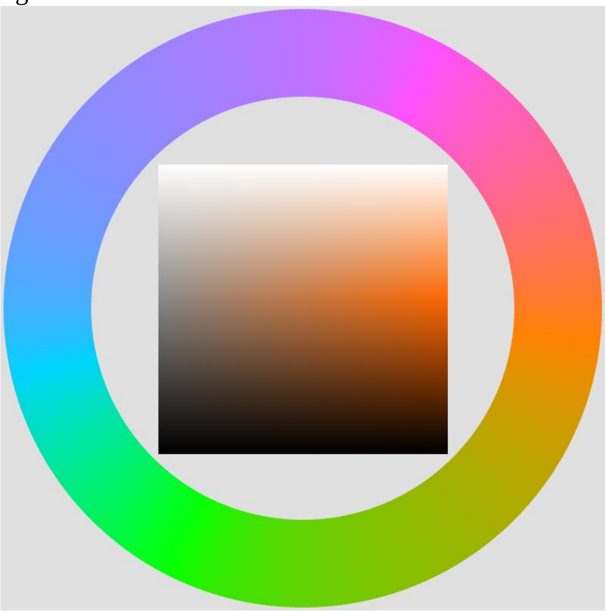

Fig. 5. Color wheel displayed using the YScH color space where Y'=0.6 and S_c=1.0. The rectangle in the middle has H'=0.

In Fig. 5 it can be seen that the blue and red shades have their perceived brightness closer to the green one as opposed to the classical color wheels of HSV and HSL. These color wheels are not shown in this work, but can be easily found in many popular image editing applications. The rectangle in the middle shows that given a certain color and saturation, changing the luma coordinate gives more perceptually uniform results than HSV and HSL color spaces.

In Fig. 4, a diagram illustrating the variations of C and H at constant Y was characterized by areas of invalid RGB color values. A similar diagram for the YScH color space is shown in Fig. 6.

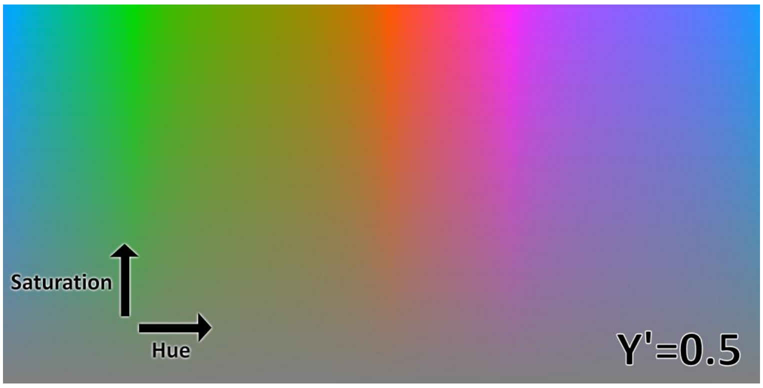

Fig. 6. Colors plotted in the YScH color space with variable hue and saturation, and constant luma.

It is evident in the Fig. 6 that all colors specified in YScH are valid and, with a constant value of luma, have similar perceived brightness (something that does not happen with HSV and HSL color spaces, as can be seen in the next section). In addition, a more detailed color disks are shown in the next section, which display the same shades as those on Fig. 5 and Fig. 6 in a different arrangement, where it can be compared to HSV and HSL more interactively.

5 Analysis of Perceptual Uniformity

It was mentioned previously that the valid chroma algorithm can be also applied to other color spaces that use cylindrical coordinate system for specifying the color hue, the chroma and the brightness. The newly introduced color spaces YCH and YScH are fast to compute but their perceptual uniformity still remains to be established. Therefore, it is necessary to compare the results obtained with the proposed color spaces and with the classical ones. One experiment consists in drawing color circles divided into segments of the same size, each filled with a unique color. The hue is chosen by means of the radial angle of the segment and the brightness (luma, luminance or similar component depending on the color space used) is chosen as the distance of the color block to the center. Two images are displayed for each color space, one with a full saturation, the other with the half saturation. The evaluation is made by considering the perceived changes in brightness in the circle from the outside to the center, as well as the changes in hue between individual blocks. The smoother the change, the better is the result. In the color spaces such as CIELUV and DIN99 the valid chroma algorithm was used. In order to properly display the color disks for these color spaces, the white point D65 is assumed and the final color is represented in sRGB color gamut.

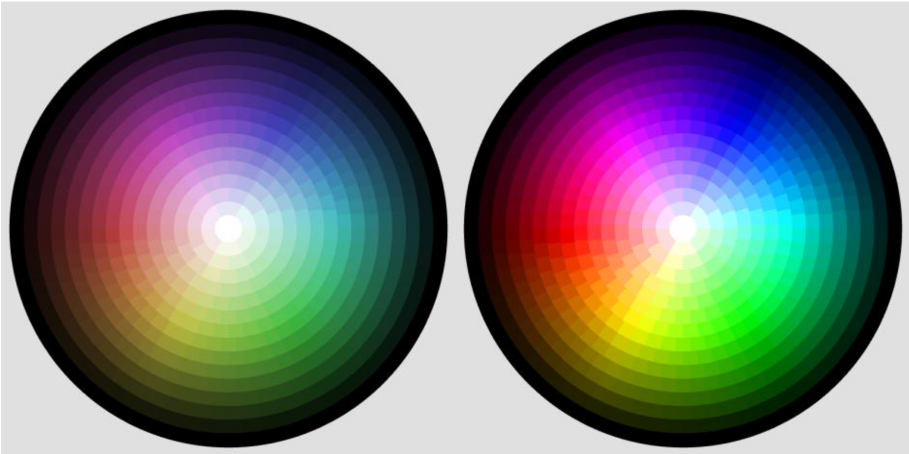

Fig. 7. The color disks plotted using the HSL color space with S=0.5 and S=1.0 respectively.

The first set of images shown in Fig. 7 shows the color disks using the HSL color space. The fully saturated image shows that the change in brightness and even in hue is quite non-uniform – there are three large spots of perceptually the same color (red, blue and green) where both the brightness and hue don't change much. There are noticeable jumps in hue, especially near the blue area.

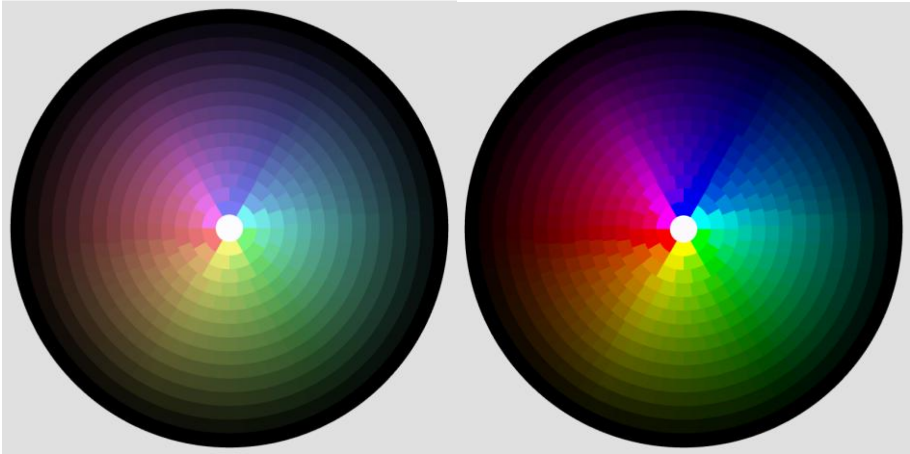

Fig. 8. The color disks plotted using the HCL color space with S_c=0.5 and S_c=1.0 respectively.

The images in Fig. 8 show the disks obtained with the recently introduced HCL space. They are very similar to those obtained with the HSV color space, not shown here, with the same problems as those pointed for the HSL color space.

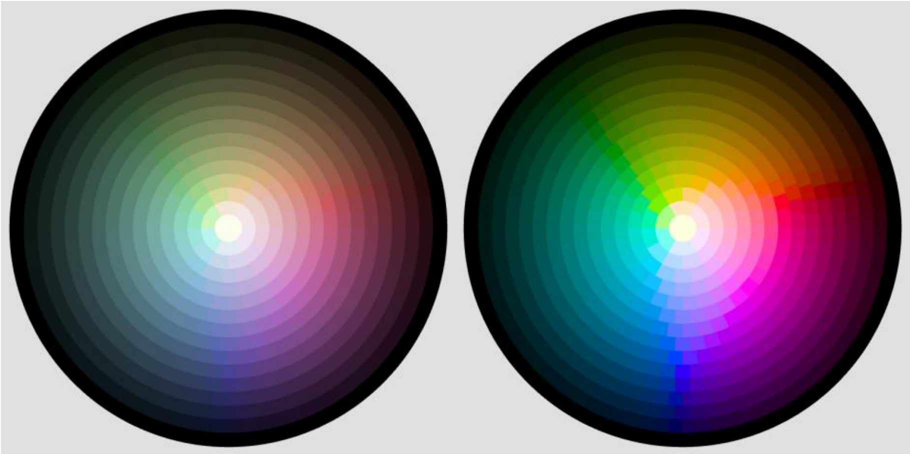

Fig. 9. The color disks plotted using the CIELUV color space with S_c=0.5 and S_c=1.0 respectively.

The disks obtained when using the CIELUV and DIN99 color spaces are shown on Fig. 9 and Fig. 10 respectively. The disk obtained with the CIELAB is not shown as appears quite similar. The images make it evident that both color spaces handle the perceived brightness very well, and better than the HSL and HCL color spaces. The change in hue is smoother too, although a large area on the disk is dedicated to blue, making the cylindrical variants of CIELUV and DIN99 (CIELAB is also included in this list) not suitable for showing color wheels as it dedicates too much space on the color wheel for a specific color, being, for this reason, insufficient.

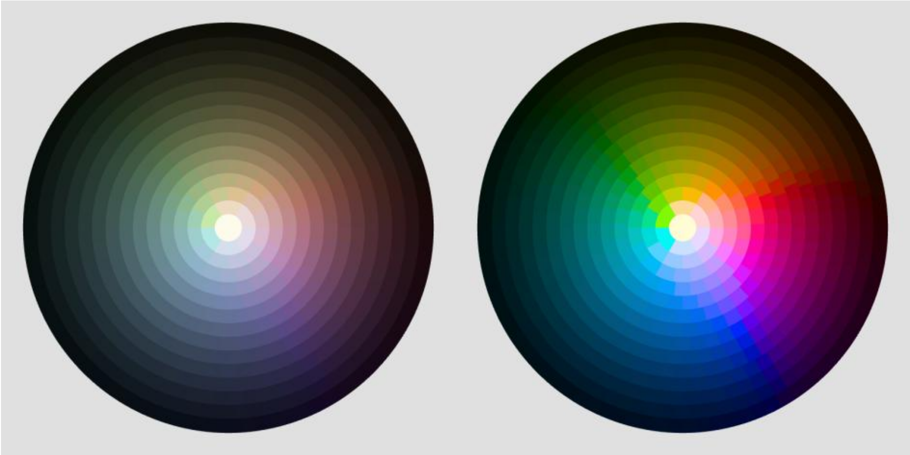

Fig. 10. The color disks plotted using the DIN99 color space with S_c=0.5 and S_c=1.0 respectively.

Finally, the color disks obtained with the proposed YCH (YScH) color space are shown in Fig. 11. The images show a good balance between the perceived brightness and the changes in hue, although an apparent rotation of red and blue shades can be seen in the darker areas.

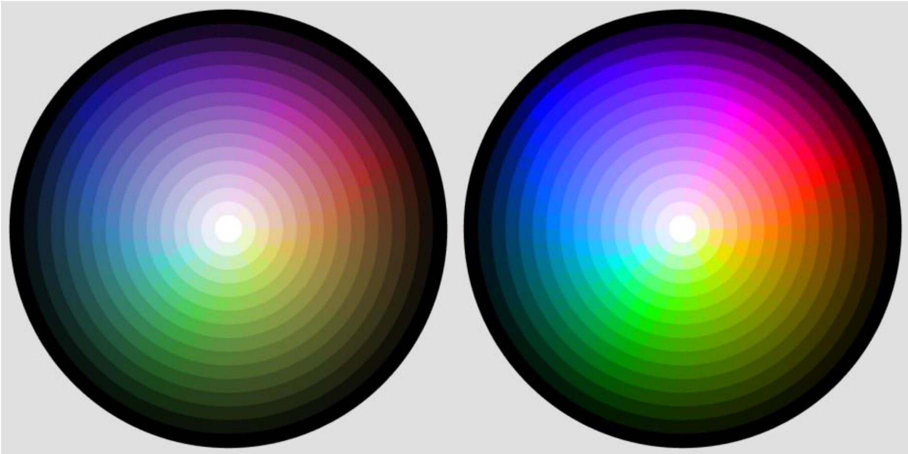

Fig. 11. The color disks plotted using *YCH* color space with S_c=0.5 and S_c=1.0.

If the above figures are viewed on a monitor that conforms to sRGB standard, a troubling observation can be made: the blue area in color spaces such as CIELAB, CIELUV, DIN99, and even YCH, appears to be actually brighter than the rest of hues with the same brightness component and saturation. This observation suggests that the discrimination of the blue in Rec. 709 [14] for the calculation of perceived brightness is too high, in other words, the blue does not appear as dark as red and green.

The observation of the HSL color disk shows that the colors corresponding to representative points positioned on the same circle of the color disk have different perceived brightness, which varies even more on the HCL color disk. This does not happen in the CIELUV and DIN99 color disks. The problem is very apparent in the area of blue shades, but it appears to be reduced in the YCH color disk, where the blue colors appear to have a perceived brightness similar to that of the other colors corresponding to representative points positioned on the same circle in the color disk.

6 The User Study

The experiments described in the previous section were backed up with the user study, where the color disks were shown to each of the participants either on a large TFT LCD screen, a computer monitor or on a printed paper. The display and the printing devices were carefully chosen to be fully compliant with the sRGB color space (at least according to their manufacturers) to ensure that the colors are properly displayed and the discrepancy between the brightness and hue on the different media is minimal. Each participant observed the color disks shown in the previous section and had to answer 19 questions in the quiz, 4 of which were control questions to verify the consistency of the answers.

In the quiz there were 3 categories that are classified as color variety, color uniformity and general category. The color variety category is mainly about the richness of the colors on the given color disk: the score depends on the number of colors that the participant can differentiate, so the disks with more perceived colors scored higher. The color uniformity category is used to determine which of the color disks appears more uniform in perceptual terms to each participant. The final general category is used to determine how well each of the color disks can be used for the color selection, being the source color palette for picking up colors.

In the user study a total of 52 people participated with the age ranging from 11 to 48 years old, with an average age of 25.7 and the standard deviation of 9.16. According to the people who specified their sex in the quiz, 23 were females and 22 males. The specialization that was specified by each participant included but not limited to administration, agriculture, arts, business, chemistry, commerce, computer science, education, electronics, foreign languages, history, industrial engineering, information technology, psychology and robotics.

Table 2. The average scores given by the participants in the quiz in the scale of 1 to 10, with 1 being the worst and 10 being the best.

	HSL	**HCL**	**CIELUV**	**DIN99**	**YCH**
Variety	8.34	5.17	7.15	5.54	8.38
Uniformity	7.19	4.25	6.89	6.17	8.70
Selection	8.18	5.57	7.24	5.75	8.53
Overall	7.90	4.99	7.09	5.82	8.53

The results are shown in the Table 2. It is important to note that although there was general consensus in the answers of the participants, there were few with the controversial results, where people gave higher scores to the HCL color space and lower scores to the rest. The participants did not know what color space was shown on each color disk, in the quiz they were marked by letters from A to E in the order as they appear in the table.

It is evident from the results that the YCH color space proposed in this work received higher scores on average in every category, with the HSL color space being in the second place. An interesting observation is that although the color spaces CIELUV and DIN99 were developed to be perceptually uniform, the human observers gave higher scores in the uniformity category to the HSL and the YCH color spaces.

7 Performance Benchmarking

The classical color spaces were compared to the proposed YCH color space in terms of performance on different computers. In the experiments it was assumed that the source pixel of an arbitrary image is given using the RGB components. The conversion from the RGB components to the given color space was made; the valid chroma algorithm was applied whenever possible. The resulting color was then converted back to the RGB components.

Table 3. The benchmarking results for different color spaces on a variety of computers

	HSL	HCL	CIELUV	DIN99	YCH
	Frame rate (frames per second) when processing 640x480 pixel image				
Intel Q6600 2.4 GHz, 1066 MHz BUS, 4 Gb RAM DDR2 800 MHz	14.86	4.64	0.14	0.08	0.56
Intel Q8300 2.5 GHz, 1333 MHz BUS, 4 Gb RAM DDR2 800 MHz	17.31	5.80	0.18	0.09	0.80
Intel Atom N280 1.66 GHz, 667 MHz BUS, 2 Gb RAM DDR2 533 MHz	3.66	1.58	0.04	0.02	0.16
Intel Atom D510 1.66 GHz, 553 MHz BUS, 2 Gb RAM DDR2 800 MHz	3.87	1.68	0.05	0.03	0.22
Intel T7700 2.4 GHz, 800 MHz BUS, 2 Gb RAM DDR2 667 MHz	16.04	4.97	0.14	0.08	0.56

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The results shown in Table 3 indicate that the YCH color space is significantly faster than the CIELUV and the DIN99; it cannot be compared reliably in terms of performance with the color spaces HSL and HCL because the valid chroma algorithm was not used in these tests. The valid chroma algorithm cannot be applied to the HSL color space because its saturation is always valid, and it was not used for the HCL color space as there is not enough information about the HCL color space for the proper implementation. It is important to note that the performance benchmarking was made in a single execution thread only and the frame rate can still be improved by using multiple execution threads.

Conclusions and Future Work

In this work, the new YCH color space is proposed as an alternative for the color selection and image manipulation applications. It is based on the YIQ transmission color space, using a cylindrical coordinate system. The advantage of this YCH color space over the HSV, HSL classical color spaces, and even the recent HCL color space, is that it models the color brightness closer to the human perception. Furthermore, working with YCH is substantially faster in computational terms than with perceptually uniform color spaces such as CIELAB, CIELUV and DIN99. The conversion process between *YCH* and RGB is trivial and requires little time for the developer.

The valid chroma algorithm described in this work uses a branch and bound technique to constrain the saturation value to stand within a predefined interval, making the color specification more user-friendly. Although the algorithm can work with other color spaces that use cylindrical coordinate system, it is particularly useful for the proposed YCH color space as the amount of calculations is relatively small when compared to well-known color models such as CIELUV and DIN99. Furthermore, it can be used with CIELAB, CIELUV, DIN99 and other color spaces where conversion back to RGB may produce some colors that are outside of valid RGB values.

The experiments described in this work show that the proposed color space models the human perception better than the classical HSV and HSL color spaces that are very popular in computer applications. The proposed YCH color space can be a better candidate for applications that currently use HSV or HSL for color specification, color selection or image manipulation. The low computation cost and better real-time performance of the YCH color space makes it also a good candidate for real-time applications and mobile devices where the mathematical capabilities of the CPU are lower than those on standard computers and workstations.

The color disks shown in this work and their user study suggest that the CIELUV and the DIN99 color spaces are not very well suited for the color selection since they received lower scores in almost every category in the quiz, being worse than the YCH and HSL color spaces. In addition, the CIELUV and the DIN99 color spaces apparently dedicate too much space for blue color shades. This can be a drawback when working with color selection disks, where a larger variety of colors is preferred. Further experiments are required to confirm this observation. The Guth's ADT color model and HSP color space informally proposed by Darel Rex Finley [18] should be also evaluated using the valid chroma algorithm to compare the results with the experiments described in this work.

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