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New software for comparing the color gamuts generated by printing technologies

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ABSTRACT

In the color industry, it is vital to know the color gamut of a given device. Several tools for visualizing and comparing color gamuts are available but they each have some drawbacks. Therefore, the aim of this work was to develop and validate new software for comparing the color gamuts generated by printing devices; we also developed an automated color measurement system. The software simultaneously represents the gamuts in the 3D CIELAB space. It also calculates the Gamut Comparison Index and the volume using two algorithms (Convex Hull and Alpha Shapes). To evaluate the performance of our software, we first compared the results it obtained for the color gamuts with those from other comparison methods such as representation in the CIE 1931 chromaticity diagram or other color spaces. Next, we used Interactive Color Correction in 3 Dimensions (ICC3D) software to compare the gamut representations and volumes. Our software allowed us to identify differences between color gamuts that were not discriminated by other methods. This new software will enable the study and comparison of gamuts generated by different printing technologies and using different printing substrates, International Color Consortium profiles, inks, and light sources, thereby helping to achieve high quality color images.

1. Introduction

The color gamut is the set of colors that can be captured or reproduced by devices such as printers, scanners, or display units [1] under certain observation conditions [2]; they are defined areas in the color space [3]. On printers, this gamut depends on the amount of CMYK (cyan, magenta, yellow, and black) used, the printing technology, ink and substrate characteristics [4], and default printing conditions [5]. The color gamut can be obtained in two ways: via an analytical method that generates models to describe the behavior of the printer, or by an empirical method, which measures printed samples and describes the limits of the resulting gamut [6,7].

In the color industry, it is crucial to know the color gamut of a device [8]. Gamuts have been compared to examine different paper types [9,10] or the optical properties of papers [11], printing systems [8], International Color Consortium (ICC) profiles [12], inks, or light sources [13]. Researchers must also know the color gamut of devices to understand what colors fall outside of this range and to study how these might be reproduced in order to optimize performance—a process termed gamut mapping [3,14]. Even when developing new printing technologies, it is important to evaluate the color gamut in order to choose the optimal inks for use [14].

When comparing color gamuts, they must be qualitatively and/or quantitatively analyzed [10], and different factors must be considered, including the color space used to represent them [15], their 2D or 3D graphic representation, and algorithms used to determine their limits. In this present work we created new software to compare the color gamuts generated by printing devices. Our

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main objectives were to analyze and select the most appropriate method to determine and compare color gamuts, develop an automated color measurement system for use with samples generated by printing devices, and create and implement software to compare these color gamuts by measuring a pattern with 1331 color samples.

Section 2 in this manuscript presents previous work on the visualization of color gamuts, the main mathematical algorithms used to determine their limits, and some previous programs developed for their representation. Section 3 establishes the methodology we used to obtain and compare gamuts and to develop the software. Section 4 describes the characteristics of the new software and summarizes the results we obtained when testing it. Finally, we summarize our findings in Section 5.

2. Background and related work

2.1. Color gamut visualization

The choice of the color space used to reproduce the gamut is important because different spaces provide different visual sensations when representing the same gamut [15]. The CIELAB color space is not perceptually uniform [16], but it resembles the way humans perceive color. For the average observer, equal distances between L*, a*, and b* correspond to roughly equal differences in color [14], but this color space will over-predict color differences in high-chroma regions [17]. Furthermore, CIELAB is independent of the device used [5].

The 2D space of the CIE-1931 chromaticity diagram is traditionally used to evaluate color gamuts [6]. These represent the primary (cyan, magenta, and yellow; CMY) and secondary colors (red, green, and blue) of subtractive mixtures and link them by straight lines. A similar alternative to measure the gamut volume also represents black and white to form a polygon [4]. Another option is the representation of the gamut in the CIELAB space with constant luminosity and chroma (L* and C_{ab}*), varying the tone (h_{ab}*) or observing the projection in different planes a*–b* [12,18]. However, these representations only give a general idea of the gamut and lose a lot of information [5,13].

The color gamut is a 3D volume [6,9,19] and so researchers have started to represent it as colored solids [20] or point clouds [12, 21]. Moreover, calculating the gamut volume provides important information as it expresses how much of color space it contains [10, 22]. Therefore, some authors combine the 3D representation of the gamut with the calculation of its volume [2,10,19,23]. This allows them to perform a qualitative analysis by studying the 3D figures and a quantitative analysis by using the volume [10]. Color gamuts can be compared by simultaneously representing them in the same coordinate system [7,15], with CIELAB being the space most often used for this purpose [11,24,25]. Thus, the solid obtained from the difference of two gamuts can be generated [20] or the volume remaining at their intersection calculated [2].

2.2. Algorithms for gamut boundary determination

To calculate the color gamut volume, we must first determine its limits. This can be achieved using different mathematical algorithms; some of the best known such algorithms are described below.

2.2.1. Convex hull algorithm

The convex hull of a set of points is the smallest convex polyhedron that contains all the points [26]. The structure it forms has no concave areas, which results in a volume overestimation of approximately 10% [27]. The convex solid algorithm can be used with any number of samples without needing to know the CMYK values used [4]. The main problem of this algorithm is that its gamut boundary descriptors (the points that define these boundaries) are not distributed uniformly on the surface, making the gamut mapping difficult [25,26].

2.2.2. Alpha shape algorithm

Cholewo and Love [3] proposed building color gamuts using the alpha shape—a generalization of the convex hull algorithm applicable to non-convex solids. The alpha shape builds the gamut based on Delaunay's triangulation [3] in which a parameter α is used to determine which tetrahedra will shape the final structure. In three-dimensions, a simplex belongs to the alpha shape of a set of points when there exists a sphere of radius α which does not contain any points of the set and which has the property that all vertices of this simplex lie on its boundary [3]. The major challenge with alpha shapes is the choice of α, as α value that is too large runs the risk of overestimation and a value that is too small can result in false concavities. Researchers must find the value of the parameter that connects the largest number of tetrahedra without leaving gaps in the final structure. Bakke et al. proposed that the best α would be the one with the highest value so that the final volume will be equal to or less than 90% of that obtained with the convex hull algorithm [27]. The disadvantage of this algorithm is that it can be difficult to implement, although it can be used to obtain optimal visualization and approximation of the gamut volume by interactively adjusting the value of α [27].

2.2.3. Segment maxima gamut boundary descriptors

In this method the color space is divided into different segments according to its hue and brightness. The points in each segment furthest from the center of the gamut are joined by triangulation [28]. The problem is that the error in determining the limits of the more saturated areas increases with respect to less saturated areas [26]. This method is widely used for gamut mapping, to build ICC profiles, and for other applications in the color industry [26].

2.2.4. Irregular segmentation algorithm

The irregular segmentation algorithm was developed to solve the problem of the segment maxima gamut boundary descriptors. This algorithm calculates more gamut descriptors in the high saturation areas, thereby increasing precision and creating a fast algorithm [26].

2.3. Programs for the 3D representation of color gamuts

Tools and techniques for the visualization of color gamuts have been under development for many years [14,18,29]. Several are implemented in C, Java3D [12], JavaScript [3], and MATLAB [30], with some of the most important being ColorThink (CHROMiX) [31], GamOpt (Hewlett Packard Enterprise) [14], Gamutvision (Imatest LLC) [32], Perfx 3D gamut viewer (TGLC Inc.) [33], and ICC3D (Interactive Color Correction in 3 Dimensions; NTNU) [7]. Most allow the representation and comparison of 3D gamuts [5,14,32,33], calculation of their volume [5], evaluation of ICC profiles [32–34], and even their manipulation for their optimization [14].

However, most of these programs are now quite old, which generates some problems for their use. For example, GamOpt is not available for public use and ColorThink is monetized, limiting its use. Gamutvision and Perfx 3D gamut viewer only allow the visualization of gamuts from ICC profiles and so are not useful for color measurement series. ICC3D is the only program capable of representing and comparing gamuts generated by printing technologies, but it is unintuitive, generates low resolution 3D figures, and its figure representation time is slow.

3. Materials and methods

3.1. Method for comparing color gamuts: color spaces and algorithms for determining color gamut boundaries and volumes

To thoroughly compare different gamuts, we simultaneously represented them in three dimensions in the CIELAB color space [6,9,19] and calculated their volumes [10]. That color space has limitations in terms of perceptual uniformity, but it is often used for gamut visualization [16]. We used nearest neighbor interpolation to generate the limits of the gamuts from the color measurements because this type of analysis enables 3D data interpolation and requires very little processing time [35]. This method assigns the value of the nearest point to the point we wish to interpolate, without varying the original values too much [36]. In addition, the interpolation is independent of the concavity or convexity of the figure [30]. Alternatively, both the convex hull and alpha shapes algorithms were used to calculate the limits of the gamuts and the volumes.

The gamut volume alone allows a comparison of the gamut size, but not whether the gamuts intersect sufficiently to meet the reproduction purposes. This can be achieved by visual comparison of the two gamut volumes in a 3D representation, but it is also useful to have a single-number value, which enables this comparison to be calculated from the volumes of the two gamuts. Deshpande et al. [37] proposed a number of metrics for comparing and analyzing two color gamuts. We have implemented this metrics in our software. The primary metric is the Gamut Comparison Index (GCI), which quantifies the similarity between gamuts. It can be calculated by the following equation:

$$GCI = \left(\frac{V_i}{V_x}\right)\left(\frac{V_i}{V_y}\right) \tag{1}$$

In Eq. (1), V_x and V_y are the volumes of two color gamuts, x and y respectively, and V_i is the volume of intersection of the two gamuts. This value ranges from 0 for no match to 1 for an exact match between the gamuts.

In addition to the GCI, the following metrics were calculated: the gamut volume ratio $[V_x/V_y]$, which compares the sizes of two gamuts without considering their intersection; and the out-of-gamut volume, which gives the fraction of one gamut volume lying

Fig. 1. Experimental set-up for obtaining the color gamuts. Automated displacement modules were used inside the light cabinet; a spectroradiometer, sample pattern, and computer used for these measurements.

outside another gamut: how much of gamut x is outside the gamut y [$(V_x - V_i)/V_x$], and how much of gamut y is outside the gamut x [$(V_y - V_i)/V_y$] [37].

3.2. Obtaining the color gamuts

Data for the printer color gamuts were obtained from a printed pattern with 1331 color samples using a spectroradiometer (PhotoResearch SpectraScan PR-670, Photo Research Inc., Los Angeles, USA). These samples were obtained by varying the CMY colors of the printer from 0 to 100 units in 10-unit steps, and were measured in a light cabinet (VeriVide CAC 120, VeriVide, Leicester, UK) with diffuse/0° geometry and a light source that simulates the CIE standard illuminant D65. The sample pattern was placed at 45° on a stand mounted on a linear displacement module which, in turn, was mounted on a second module (Zaber, Zaber Technologies, Vancouver, Canada), with a displacement axis perpendicular to the first one (Fig. 1). The aforementioned displacement modules and our in-house software were used to automatically measure the color of each of the 1331 samples.

The printed pattern was designed to include all possible samples on A4 size paper, using a sample size adapted to the aperture of the spectroradiometer (0.5°). The size of the aperture determines the exposure time of the detector: the smaller the aperture size, the longer the sample measurement time, which increases the uncertainty in the results. After several previous tests, the optimum sample size and number of color samples was selected in order to obtain the most chromatic information from the printer gamut in the shortest viable time (almost 8 h). The measurement geometry is similar to that used by an observer viewing printed samples (diffuse/0°). All the gamuts are compared using the same measurement geometry and light source.

We obtained the color gamut provided by both an inkjet printer (Epson XP-530, Seiko Epson Corporation, Nagano, Japan) and a laser printer (Canon iR-ADV C2020i, Canon Inc., Tokyo, Japan), using two brands of matte photo paper: 167 g/m^2 Epson (Seiko Epson Corporation, Nagano, Japan) and 190 g/m^2 Ice Professional (Paper Elements Ltd, Nottinghamshire, UK). Therefore, we obtained a total of four different color gamuts.

3.3. Development of the new software

We used MATLAB (MATLAB R2020a, The MathWorks, Inc., Natick, Massachusetts, USA) to develop the new software described in this work. First, we represented a color gamut in the CIELAB space. Next, we simultaneously generated two gamuts. We then created a graphical user interface that allowed interactive control of the gamuts and calculation of their volume. Finally, we optimized the interface by correcting errors and improving the code to increase the speed of the graphic representation. The input data for our program were the colorimetric coordinates L* , a* , and b* for each sample, which were calculated from the spectral radiances, and the quantities of CMY used to generate each one.

To test our software, we compared the color gamuts for each printing technology and paper used. To do this, first we compared the gamuts by representing them in 3D xyY color space and we then represented them in the CIE 1931 chromaticity diagram. Finally, we checked the colorimetric coordinates at various points on the gamuts and compared the results with the gamut comparison we obtained from our new software. We also used ICC3D (ICC3D 1.2.9) to compare the 3D representations of overlapping color gamuts and the volume values obtained with those obtained in our program. We used ICC3D because this is the only software that allows manual data entry and the generation of the gamut volumes with the two algorithms we used [7,38].

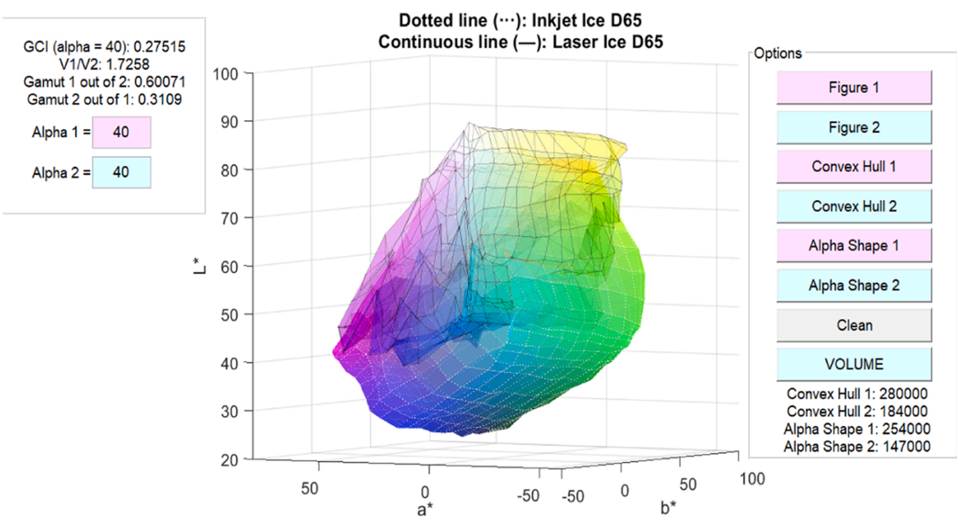

Fig. 2. Comparison of two color gamuts using the GamutLab_3D program. The dotted white line corresponds to the inkjet printer while the continuous black line represents the laser printer, in both cases when using Ice brand paper.

4. Experimental results and discussion

4.1. GamutLab_3D software

The interface of our GamutLab_3D software is divided into three zones: on the left we have a panel with the GCI value, the gamut volume ratio, the out-of-gamut volumes, and two editable text boxes to choose the α value used to represent each figure; on the right, a panel with the control buttons and volume values rounded to thousands [22] in cubic CIELAB units; and in the middle, the axes where the figures are represented. The buttons on the interface can be used to independently or simultaneously generate two color gamuts in the 3D CIELAB color space. These gamuts are generated by nearest neighbor interpolation, convex hull, and/or alpha shapes algorithms. An alpha shape radius α of 40 is used in this work to represent the figures and calculate de GCI value (and other metrics), as it is recommended by the ISO/TS 18621–11:2019 [16], but it is possible to adjust this value.

The simultaneous representation of the color gamuts obtained with our software for the two types of printers with the Ice brand paper is shown in Fig. 2. The gamuts had different degrees of transparency and the line styles forming the surfaces were different, with continuous black lines representing the laser printer and dotted white lines showing the inkjet printer. This allowed us to differentiate the two gamuts and see when one exceeded the other. In this case, the laser printer gamut was somewhat above the inkjet printer gamut for the yellow and yellow-green colors, while that of the inkjet printer was greater for the green and blue colors. This software also allows interactive 3D rotation of the gamuts so that they can be compared from different points of view. The gamut colors are distributed according to the area of the color space. Finally, a legend is shown at the top of the representation to indicate which figure corresponds to each data set.

4.2. Software testing

To test the GamutLab_3D software, we compared the results obtained by studying the color gamuts with those extracted by representing the gamuts individually in the 3D xyY space, in the CIE 1931 chromaticity diagram, and by studying the colorimetric coordinates at various points of the gamuts.

By comparing the 3D representation in the xyY space individually, we obtained the following analysis which showed that the gamut surface produced by the laser printer was rougher compared to the one from the inkjet printer (Fig. 3. A), especially in the dark blue-magenta area. Similar results were obtained with our software (Fig. 3. B), although we also saw these peaks in the green colors. The conclusions about the gamut surfaces were the same both for the xyY and CIELAB color spaces.

We then studied the colorimetric coordinates at some points in the gamut and compared the results for each type of paper and printing technology. Very similar results were obtained for the inkjet printer with the different papers, although the Epson paper provided the greatest gamut in the reds while the gamut in the blues was highest for Ice paper (Tables 1 and 2).

When comparing both gamuts with our program, we saw that the shapes of the figures were nearly identical, making them difficult to compare because their colors were the same. To avoid this, we modified the code slightly to change the color of the Epson paper gamut to make it red (Fig. 4). As shown, the blue-cyan-magenta gamut was greater for the Ice brand paper, while for the Epson paper it was wider for the other colors, although the differences between the two gamuts were minimal. In these cases, the comparison by

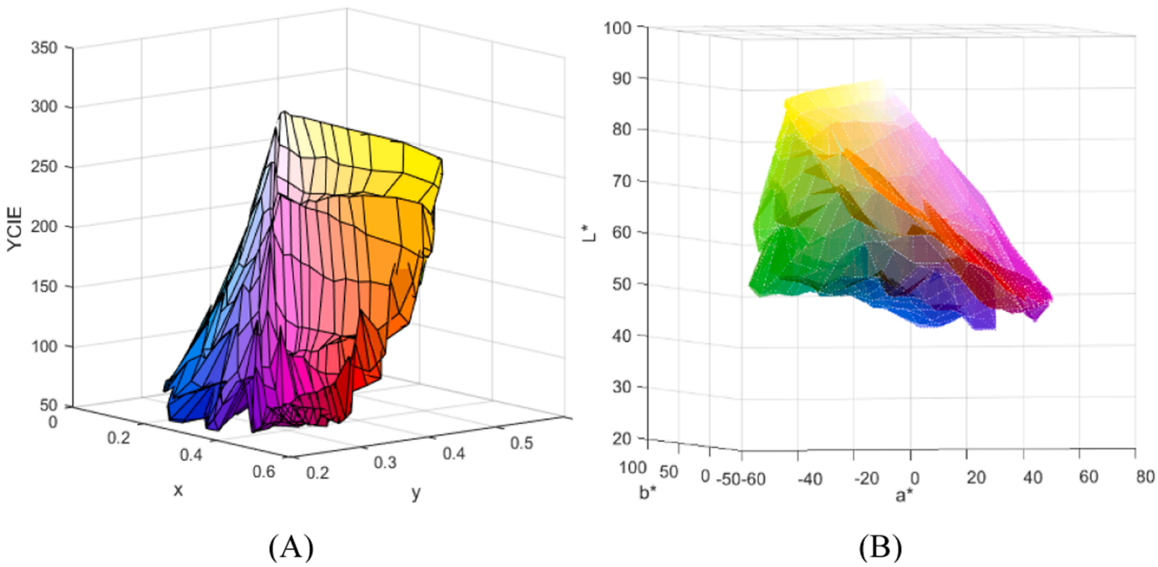

Fig. 3. Color gamut obtained in (A) the xyY color space and (B) the CIELAB space. Both were obtained using Epson brand paper and the laser printer.

Table 1
x and y coordinates for the primary colors of cyan (C), magenta (M), and yellow (Y) and for the extremes of the color gamut of the inkjet printer when using Epson brand paper.

Inkjet - Epson	x	y	C	M	Y
Magenta	0.5235 ± 0.0015	0.2673 ± 0.0015	0	100	0
Yellow	0.4862 ± 0.0015	0.4870 ± 0.0015	0	0	100
Cyan	0.1795 ± 0.0015	0.2635 ± 0.0015	100	0	0
Red (max. x)	0.5925 ± 0.0015	0.3406 ± 0.0015	0	80	100
Green (max. y)	0.3511 ± 0.0015	0.5573 ± 0.0015	60	0	100
Light blue (min. x)	0.1704 ± 0.0015	0.2413 ± 0.0015	100	30	0
Dark blue (min. y)	0.2438 ± 0.0015	0.1835 ± 0.0015	100	100	0

Table 2
x and y coordinates for the primary colors of cyan (C), magenta (M), and yellow (Y) and for the extremes of the color gamut of the inkjet printer when using Ice brand paper.

Inkjet - Ice	x	Y	C	M	Y
Magenta	0.4884 ± 0.0015	0.2532 ± 0.0015	0	100	0
Yellow	0.4817 ± 0.0015	0.4883 ± 0.0015	0	0	100
Cyan	0.1822 ± 0.0015	0.2617 ± 0.0015	100	0	0
Red (max. x)	0.5760 ± 0.0015	0.3408 ± 0.0015	0	80	100
Green (max. y)	0.3535 ± 0.0015	0.5547 ± 0.0015	60	0	100
Light blue (min. x)	0.1720 ± 0.0015	0.2436 ± 0.0015	100	30	0
Dark blue (min. y)	0.2344 ± 0.0015	0.1763 ± 0.0015	100	100	0

volume is particularly important. We can see that, with both algorithms, the color gamut obtained with Epson paper was greater than that from the Ice paper (Fig. 4). In addition, the GCI value shows that 81% of the two gamuts are identical. This metric provides an objective value that can be used to compare two color gamuts and quantify the difference between them [37].

Thus, our program helped to distinguish small differences between two color gamuts that other comparison methods, especially the individual study of color coordinates and gamuts in the 3D xyY space, did not perceive.

When comparing the colorimetric coordinates for the laser printer, the Ice brand paper had a greater gamut in magenta, blue, cyan, and green, and in this case a greater difference between the two types of paper was detected (Tables 3 and 4).

Thus, the two figures obtained by our program were remarkably similar. The Ice brand paper provided a greater gamut in the green, cyan, blue, and purple, while the Epson gamut was greater for yellow, orange, and magenta. In contrast to the outcome for the inkjet paper, comparison of the volumes obtained with the two algorithms showed that the gamut with the Ice paper was higher. In this case, the information obtained by using GamutLab_3D software was more complete than that obtained from studying the colorimetric coordinates and the individual representation of gamuts in the xyY space. This was because we were able to see exactly which areas of the color space of one gamut exceeded the other.

When using the colorimetric coordinates to compare the two devices for the same type of paper, the laser printer produced a smaller

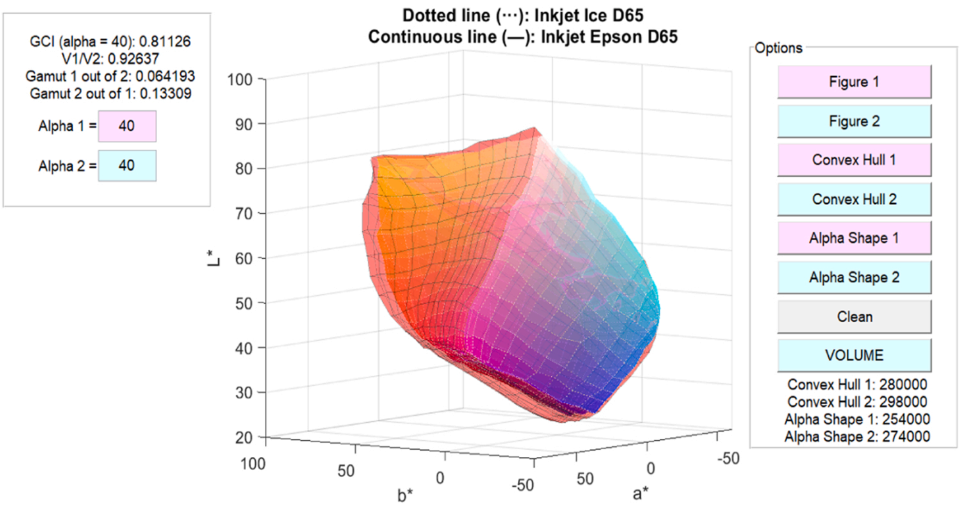

Fig. 4. Comparison of two color gamuts using the GamutLab_3D program. The gamut obtained using the inkjet printer with Epson paper is represented in red while the gamut obtained with Ice paper and the inkjet printer is shown in different colors.

Table 3
x and y coordinates for the primary colors of cyan (C), magenta (M), and yellow (Y) and for the extremes of the color gamut of the laser printer when using Epson brand paper.

Laser - Epson	x	y	C	M	Y
Magenta	0.4751 ± 0.0015	0.2754 ± 0.0015	0	100	0
Yellow	0.4420 ± 0.0015	0.5056 ± 0.0015	0	0	100
Cyan	0.2022 ± 0.0015	0.2440 ± 0.0015	100	0	0
Red (max. x)	0.5247 ± 0.0015	0.3198 ± 0.0015	20	100	100
Green (max. y)	0.4165 ± 0.0015	0.5067 ± 0.0015	30	0	100
Light blue (min. x)	0.1881 ± 0.0015	0.2352 ± 0.0015	100	30	20
Dark blue (min. y)	0.2260 ± 0.0015	0.2205 ± 0.0015	100	80	0

Table 4
x and y coordinates for the primary colors of cyan (C), magenta (M), and yellow (Y) and for the extremes of the color gamut of the laser printer when using Ice brand paper.

Laser - Ice	x	y	C	M	Y
Magenta	0.4806 ± 0.0015	0.2653 ± 0.0015	0	100	0
Yellow	0.4411 ± 0.0015	0.5093 ± 0.0015	0	0	100
Cyan	0.1900 ± 0.0015	0.2281 ± 0.0015	100	0	0
Red (max. x)	0.5224 ± 0.0015	0.3172 ± 0.0015	20	100	90
Green (max. y)	0.3919 ± 0.0015	0.5120 ± 0.0015	50	10	100
Light blue (min. x)	0.1755 ± 0.0015	0.2192 ± 0.0015	100	30	20
Dark blue (min. y)	0.2196 ± 0.0015	0.2037 ± 0.0015	100	80	0

gamut in magenta, blue, green, and red (Tables 1–4). Using our new software, we saw that the laser printer generated a wider color gamut for cyan, light green, and yellowish-green with Epson brand paper, while the inkjet printer generated a wider gamut in blues, greens, oranges, reds, and magentas (Fig. 5). When we compared the volumes, the gamut obtained with the inkjet printer was greater.

We reached the same conclusion regarding the distribution and volumes of the gamuts as we had as with the Epson brand paper when we compared the two printing systems with the Ice brand paper; the difference in volume of the two figures was greater in the former than for the Ice brand paper. Therefore, based on the analysis with our new GamutLab_3D software, we concluded that a larger color gamut was obtained with the inkjet printer compared to the laser printer. Finally, when we represented the CMY primary colors and the secondary colors (red, green, and blue) in the CIE 1931 chromaticity diagram and joined the points to form a hexagon (Fig. 6), we obtained near identical results to those from our analysis of the chromaticity coordinates.

In the second part of our software testing, we used the ICC3D program, which allowed us to represent gamuts not only in the CIELAB space, but also in many other color spaces, either individually or simultaneously. In addition to the alpha shapes and convex hull algorithms, ICC3D can also implement other algorithms to generate the gamut and calculate its volume.

First, we used the same data to represent the overlapping color gamuts in the CIELAB space. Because ICC3D does not use interpolation to calculate the surface of the gamut, we compared the figures it obtained with those from our program in a simple way by using the Quantized option for one of the figures to represent the points of the color space as spheres. We used alpha shapes in the other

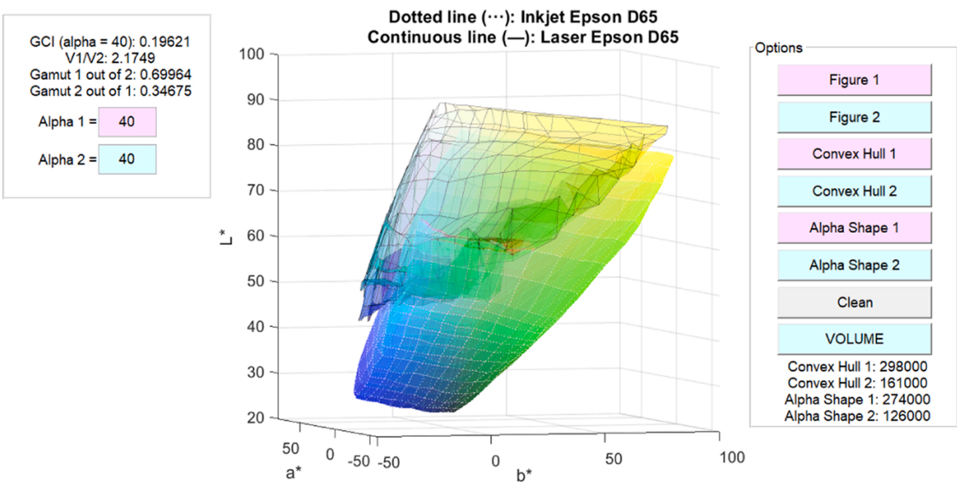

Fig. 5. Comparison of two color gamuts using the GamutLab_3D program. The white dotted line corresponds to the inkjet printer while the black continuous line represents the laser printer, both using Epson brand paper.

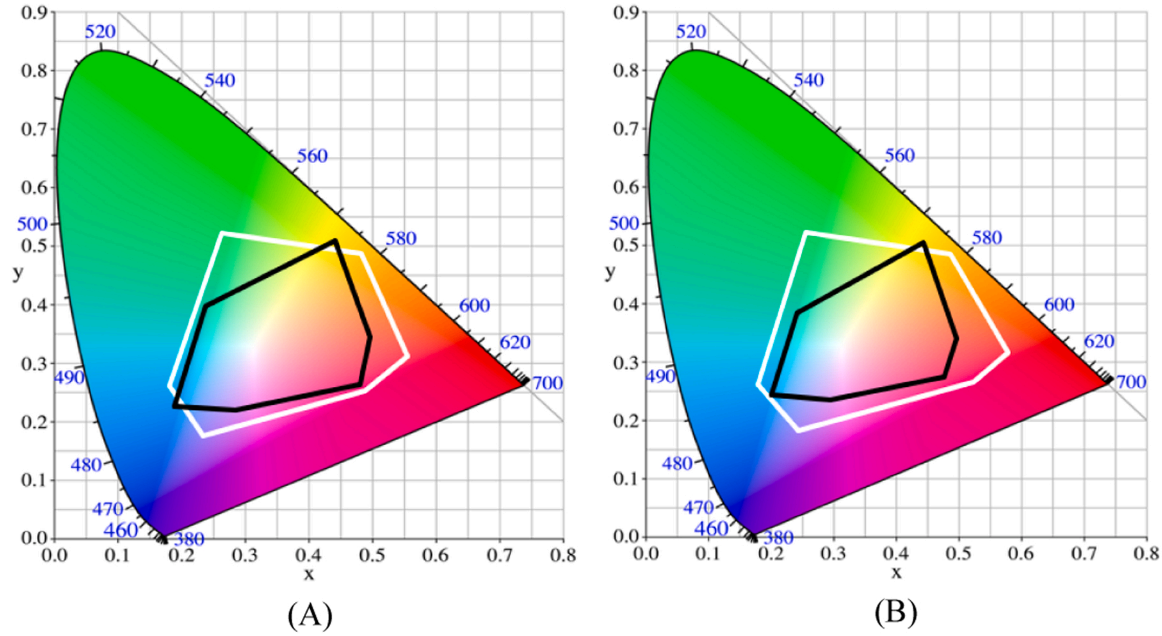

Fig. 6. Comparison of color gamuts in the CIE 1931 chromaticity diagram. The white line corresponds to the inkjet printer and the black line to the laser printer for (A) Ice and (B) Epson brand paper.

gamut because this is the most precise algorithm available in ICC3D [27,37]. Fig. 7.A shows the results obtained with ICC3D when comparing the gamuts produced with Ice photo paper on the inkjet printer (represented with alpha shapes) and the laser printer (shown as spheres). Fig. 7.B shows the same comparison generated by interpolation with our GamutLab_3D program. Both comparisons were remarkably like those previously noted for the Epson paper.

Second, we compared the volume and figures generated separately with the alpha shapes and convex hull algorithms. Comparing the volumes obtained with our software and the ICC3D program, the maximum difference was 0.012%, with an average difference of 0.00041%. Therefore, we can consider that with our software we obtain volume values similar to those obtained with the ICC3D program.

The figures generated with ICC3D were nearly identical to those obtained with our software, both for the alpha shapes and convex hull algorithms (Fig. 8).

Comparison of the color gamuts produced by the two programs highlighted some of their advantages and disadvantages. ICC3D is a fairly old program which therefore produces figures with a relatively poor resolution. In addition, the program is not intuitive and so it is quite hard to compare two color gamuts using it. Rendering the figure representations also takes too much time and they do not move well when rotated in 3D; indeed, sometimes the program does not even respond. Another disadvantage is that the representation in CIELAB does not have numbered axes, making it impossible to know the value of a* , b* , or L* . However, our program also has some limitations including the fact that it does not contain all the ICC3D display modes and it lacks the segment maxima method, although the latter is not a problem because the accuracy of this algorithm for saturated colors is low [26]. Finally, our program is not suitable for gamut mapping, although this was not our objective when developing this software.

5. Conclusions

The best way to determine and compare two color gamuts is their simultaneous representation in the 3D CIELAB space. In addition, comparison of their volumes is also vital when trying to select the largest gamut among several similar ones. We developed an automated color measurement system for use with samples generated by printing technologies. New software to compare gamuts generated by printing devices under the conditions described above was also programmed and tested. This software allows researchers to distinguish differences between gamuts that are not detectable by other methods, thereby obtaining more complete information. This new software will facilitate the study and comparison of gamuts generated by different printing technologies, and with different printing substrates, default printing conditions, ink characteristics, lighting conditions, and ICC profiles. It also allows the gamuts to be compared after ink undergoes an aging or drying process which may help researchers understand the conditions under which the best possible image can be obtained in terms of color.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to

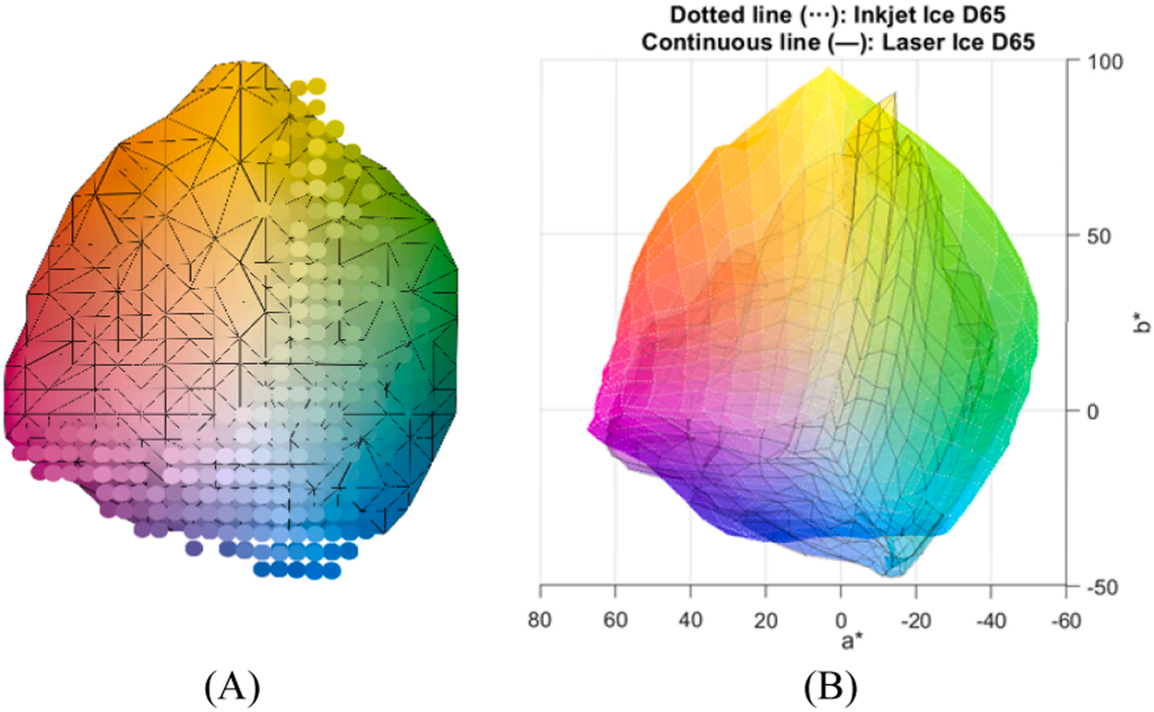

Fig. 7. Comparison of the gamuts obtained with the laser printer and the inkjet printer, using Ice brand paper, (A) with the ICC3D program and (B) with the GamutLab_3D software.

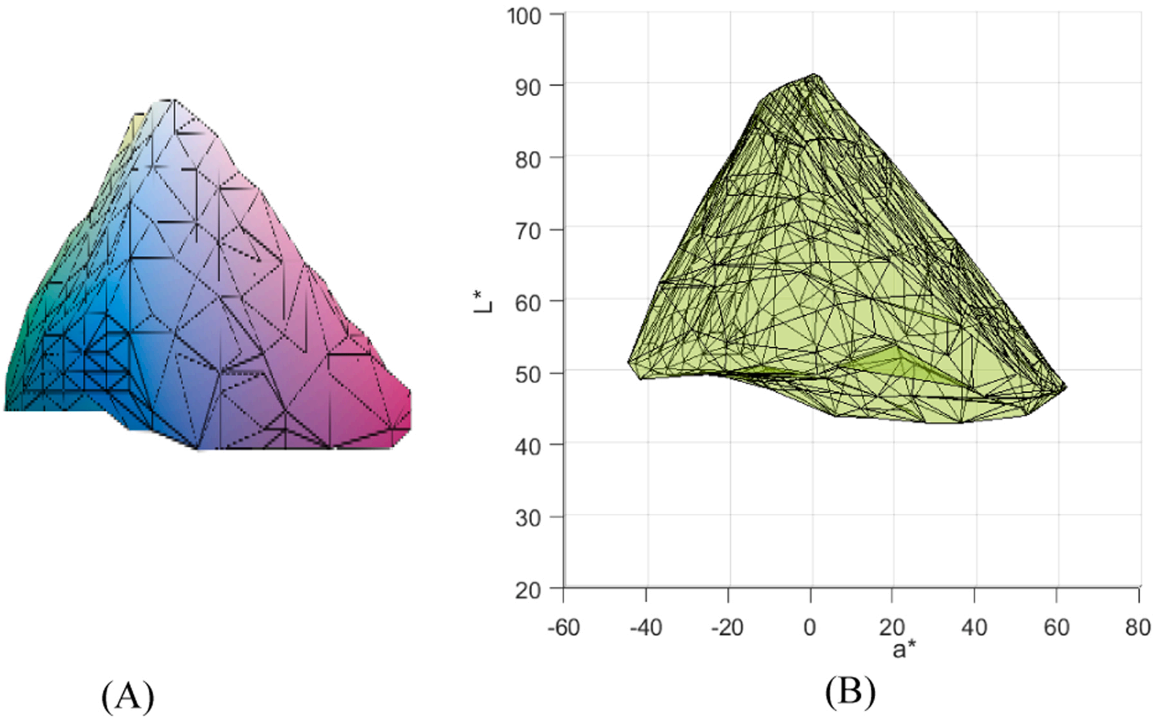

Fig. 8. Figures obtained with the alpha shapes algorithm (A) using the ICC3D program and (B) our GamutLab_3D software for the laser printer gamut using Epson brand paper and an alpha radius of 40 in both cases.

influence the work reported in this paper.

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