The gamuts of input and output colour imaging media

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ABSTRACT

The colour gamuts of colour imaging media are important parameters in the reproduction of colour images between them and their assumed magnitudes directly influence the degree to which colours are modified. In spite of this, the determination of gamut boundaries is often done in a way that ignores some basic implications that follow from the definition of colour gamuts. This is partly due to the fact that some of these implications are not understood and partly due to the fact that if they are understood their magnitude is underestimated. Hence, the approach that is taken in this paper is to first discuss the theoretical implications of what colour gamuts are and subsequently to illustrate them by experimental means.

Firstly, colour imaging media can be divided into two categories which have very different characteristics in terms of colour gamut. The determination of gamuts of input colour imaging media, for example, introduces a number of problems that do not arise for output media as it involves the determination of the range across which they can capture colour information. This results in significant difficulty from a practical point of view as it necessitates the availability of stimuli from a larger gamut than that of the input gamut to be determined. As this latter gamut is to be determined and hence as yet unknown, the former gamut needs to be very large so as to be usable in general. Secondly, the most crucial factor that is commonly ignored is that viewing conditions are intrinsic to colour gamuts – i.e. that one can only talk about the colour gamut of a set of stimuli if the corresponding viewing conditions are specified. The consequences of this will be shown by looking at the gamuts of commonly used output colour imaging media under a range of viewing conditions with the aim of establishing how the resulting gamuts change in terms of colour appearance. Amongst other things, this will show that the gamuts of different media can be affected to different degrees across the range of illumination levels used in this study. The magnitude of changes ranged from virtually no difference for some LCD displays up to a six–fold change for some projected media. Hence it will be shown that instead of a medium having a single gamut, it has a multitude of them. Describing a colour reproduction medium using a single gamut boundary inevitably leads to mismatches between what that gamut boundary suggests and how the gamut of the medium is seen under different conditions. While one solution to the problem is to generate a number of gamut boundaries for each medium – viewing condition combination, this would result in an explosion of gamut boundary descriptors and in some degree of inflexibility. Alternatively and preferably this relationship could be modelled and this would result in the possibility of having a single reference gamut per medium which could then be modified to suit particular viewing conditions.

Understanding the nature of colour gamuts is of significant practical as well as theoretical importance as it can often be the source of errors in cross–media colour reproduction applications.

Keywords: colour imaging media, gamut calculation, colour appearance, viewing conditions

1. INTRODUCTION

Before discussing the actual topic of this paper – the nature of colour gamuts – it is useful to first have a look at a context within which its understanding is of importance. Arguably where this is most important is cross–media colour reproduction.¹

Figure 1. Elements of cross–media colour reproduction.¹
**reproduction**, which will here be defined as “the process by which colour information from an original medium is transferred to a reproduction medium so as to achieve a predetermined relationship between them.” Such a definition entails that there are the following four elements that constitute colour reproduction (Figure 1): colour information, colour imaging media, cross–media transformation and the intended relationship between original and reproduction (i.e. rendering intent).

Of these elements, it is the imaging media that need to be understood in more detail for the purposes of this paper as it is their gamuts that we are concerned with here. A digital colour imaging medium here provides a link between digital data and colour stimuli and can be of two principal types depending on whether colour stimuli are its inputs or outputs. “Output colour imaging media (e.g. monitors, printers) produce colour stimuli on the basis of digital data sent to them whereas input media (e.g. digital cameras, scanners) produce digital data based on sensing colour stimuli” (Figure 2).

Considering the above view, colour gamuts are involved in the first two elements of cross–media colour reproduction – colour information and colour imaging media – whereby the colour gamut of the information (e.g. an image, a set of colours) of the medium in which that information is present can be considered. The presence of colour gamuts in these cross–media colour reproduction elements is in terms of them being their properties and it will be an aim of this paper to suggest in what way this is the case. Further, colour gamuts are also present in the transformation element, however, here they have a parametric rather than a characteristic role – i.e. they influence the nature of the transformation rather than being its property. Hence the accurate determination of colour gamuts will directly influence how colour information is transformed in the process of communicating it between original and reproduction media.

Now that the cross–media colour reproduction context, in which colour gamuts will be considered here, has been introduced, a more systemic approach to understanding what a colour gamut is can be attempted. The next section will aim to answer the questions of what a colour gamut is and what it is that has a colour gamut. Section 3 will look at an example of calculating input gamuts and Sections 4 and 5 will then contain details of work done for illustrating the characteristics of output gamuts. Finally, some general conclusions about the topic of this paper will be drawn.

### 2. DETERMINING GAMUT BOUNDARIES

**Figure 3.** CAM97s2 Gamut of print made with colour laser printer, illuminated by D50 with 100 cd/m² luminance of reference white and seen against mid–grey background by the CIE Standard Colorimetric Observer (2°).

#### 2.1. Terminology

As with any subject, there is a range of possible interpretations of the basic terms used in cross–media reproduction, and so as to avoid misunderstandings the definitions of key gamut–related terms will be given next:
Colour reproduction medium: a medium for displaying or capturing colour information, e.g. a CRT monitor, a digital camera or a scanner. Note, that in the case of printing, the colour reproduction medium is not the printer but the combination of printer, colorants and substrate.

Colour gamut: a range of colours achievable on a given colour reproduction medium (or present in an image on that medium) under a given set of viewing conditions – it is a volume in colour space.

Colour gamut boundary: a surface determined by a colour gamut’s extremes (e.g. Figure 3.).

Note, that the above terminology is that used by the CIE’s Technical Committee 8–03 on Gamut Mapping and hence represents the consensus of a number of researchers investigating the present subject. Two important implications of these definitions, which are often overlooked, will be discussed next.

2.2. Theoretical implications of definitions

The most crucial factor that is commonly ignored is that viewing conditions are intrinsic to colour gamuts – i.e. one can only talk about the colour gamut of a set of stimuli if the corresponding viewing conditions are specified. This follows directly from our general understanding of colour which is seen as a phenomenon that arises when the following are present: observer, stimulus and viewing conditions (illumination, geometry, surround, etc.). If this is the case for individual colours it necessarily is also the case for colour gamuts which are simply their ranges. Hence it is essential to specify the details of all three of these components when talking about a colour gamut and it also means that it is meaningless to talk about the colour gamut of a set of stimuli in general (e.g. the set of colours displayable on a given CRT). Such a set only has a colour gamut when seen by some specific observer under some specific viewing conditions. Considering that the colour gamut of a colour reproduction medium is nothing but the colour gamut of the set of stimuli it is capable of displaying/capturing, it is essential to specify viewing conditions and observer details so as to be able to talk about such colour gamuts. For example, talking about the colour gamut of a printed image is meaningless as it could assume a number of forms subject to viewing conditions and observers – i.e., a printed image has a set of possible colour gamuts rather than a single one. Looking at such an image in the dark gives a zero–volume gamut (to use an extreme example), different levels of illumination result in different gamut volumes, illumination chromaticity changes gamut shape as well as volume and viewing distance and flare in the environment make a difference too. Hence, the question “What is the gamut of this print?” cannot be answered and should instead be rephrased to “What is the gamut of this print under viewing conditions X for observer Y?” This point in particular will be illustrated in Sections 4 and 5 so as to show that understanding colour gamuts in this way is necessary rather than dismissable as being overly pedantic. In addition to these factors influencing colour gamuts, the colour space in which they are computed and visualised also plays a crucial and well recognised role.

2.3. Implications on characterisation and profiling

Both implications of the definitions given above have important practical reverberations that are habitually overlooked. Any system containing device characterisation must be interpreted as having medium characterisation and this must be determined for each individual observer – viewing condition (O–VC) combination. It is not possible to characterise a medium in general. A prominent example of systems where characterisation is used are colour management systems like those using the ICC framework. If in this context a device profile is determined for some medium then it needs to be ensured that the medium is characterised under the O–VC under which it will be used. Characterising a CRT in a dark, flare–free environment and then using the characterisation to predict appearance under usual office conditions is invalid and will result in substantial error and mistrust of the system used. This entails either the need for a large number of profiles for a single medium or for the possibility to transform a standard O–VC profile to predict appearance under a range of specific O–VCs. While it is not within the scope of the present paper to investigate the latter and more ideal of these options, the experimental data presented here is meant to be a motivation for embarking on a more systemic modelling of medium appearance as a function of O–VC change.

2.4. Gamut boundary calculation for given O–VC

Given particular O–VCs, the gamut of a set of colours, which could either be meant to represent a colour reproduction medium or an image on it, can be described using a number of methods. In this study the Segment Maxima method for calculating gamut boundary descriptors (SMGBD) was used and will be briefly introduced next. Using this method, the gamut boundary of a set of colours is described by a matrix containing the most extreme colours for each segment of colour space. Here the segmentation was carried out in terms of spherical coordinates calculated from orthogonal CAM97s coordinates using the following formulæ:
\[ r = \sqrt{(J-J_E)^2 + (a-a_E)^2 + (b-b_E)^2} \]  
\[ \alpha = \tan^{-1}\left(\frac{b-b_E}{a-a_E}\right) \]  
\[ \theta = \tan^{-1}\left(\frac{(J-J_E)}{(a-a_E)^2 + (b-b_E)^2}^{1/2}\right) \]

Here \( a \) and \( b \) are the orthogonal coordinates corresponding to CAM97s2’s cylindrical \( C \) and \( h \) coordinates, \( E \) is defined as a point inside the gamut to be described and can, for example, be obtained by averaging the coordinates of the points which will be used for calculating an SMGBD (here \( E=[50,0,0] \) in terms of \( Jab \)), \( r \) is the distance of a colour from \( E \), \( \alpha \) is an angle having a range of 360° and \( \theta \) is the angle in a plane of constant \( \alpha \) having a range of 180° (Figure 4.a).

![Figure 4. Overview of SMGBD in CAM97s2: (a) spherical coordinates, (b) sphere segmented in terms of \( \alpha \) and \( \theta \) (6\times6 segments used for illustration; one segment highlighted).](image)

The SMGBD matrix is calculated by first dividing colour space into \( n\times n \) segments \((n=16 \text{ was used here})\) in terms of \( \alpha \) and \( \theta \) (Figure 4.b). Then, the CAM97s2 coordinates of each of the given set of colours are transformed into spherical coordinates using formulae 1–3. From these, the colour with the largest \( r \) is stored for each of the \( n\times n \) segments whereby it is not only \( r \), that is stored for a given segment but the corresponding spherical angles as well. If in the end there are segments in which there are no colours, values for them are linearly interpolated on the basis of the nearest SMGBD matrix entries. The result of this method is a bi–linear surface describing the set of colours on which it is based without the constraint of convexity.

Given such a SMGBD, the gamut boundary for any hue angle can then be obtained using the Flexible Sequential Line Gamut Boundary method9 and gamut volumes can also be calculated by summing up the volumes of tetrahedra formed by \( E \) and sets of three points from the SMGBD forming triangles on the gamut boundary surface.

3. DETERMINING INPUT GAMUTS

Colour imaging media can be divided into two categories which have very different characteristics in terms of colour gamut. For media that capture colour information (e.g. scanners, digital cameras, etc.) and can hence be seen as input media, the determination of their colour gamuts involves the determination of the range across which they can capture variation in colour information. This results in significant difficulty from a practical point of view as it necessitates the availability of stimuli from a larger gamut than that of the input gamut to be determined. As this latter gamut is to be determined and hence as yet unknown, the former gamut needs to be very large so as to be usable in general. A further issue arises when input media are characterised based on a set of specific samples and their colour gamut is estimated on the basis of the characterisation model. In this case what one gets is not necessarily the gamut of the medium but that of the intersection of the medium’s gamut and the gamut of the samples on the basis of which the medium was characterised. (Note, however, that if the medium gamut is a subset of the characterisation set’s gamut then what one gets is the medium gamut.)

A way of determining the gamuts of input media has been proposed recently2 and is based on simulating the responses of an input medium to given spectral power distributions. The gamut of an input medium is then determined on the basis of having a set of spectra that cover the majority of all possible spectra, knowing a medium’s responses to them and then determining a boundary beyond which the medium does not produce variation in its responses. Such an approach consists in three principal parts: generation of a set of stimuli for determining the gamut boundaries of input media, modelling of the responses of input media and calculation of gamut boundaries of input media. The first of these is achieved by calculating the gamut of all possible surface reflectances in a colour appearance space (e.g. CIELAB), then evenly sampling that gamut and calculating spectra that correspond to these colours using a metamer set recovery method.11 Once these spectra are available, the responses of an input medium can be predicted and
for each of the evenly–sampled lines. The gamut boundary is then found by finding that sample along each of these lines for which the camera response is not significantly different from the response for the following sample along that line, starting from the centre of colour space. An illustration of using this technique can be seen in Figure 5 which shows the colour gamut of an Agfa Studiocam for two different f–stop settings. The gamut labelled ‘all spectra’ represents the gamut of spectra predictable using the metamer set recovery method.

![Image of CIELAB gamuts of input media.](image)

**Figure 5.** CIELAB gamuts of input media.

### 4. EXPERIMENTAL METHOD FOR DETERMINING OUTPUT GAMUTS

Table 1. Overview of media used in experiment (use of these mnemonics in the text will be indicated by using italics).

<table>
<thead>
<tr>
<th>Mnemonic</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Laser</strong></td>
<td>Prints made on plain paper using <em>HP Color LaserJet 5</em></td>
</tr>
<tr>
<td><strong>Thermal</strong></td>
<td>Prints made on glossy substrate using <em>Tektronix Phaser 440</em> with cyan, magenta and yellow colorants only</td>
</tr>
<tr>
<td><strong>CRT</strong></td>
<td><em>Apple 21&quot; Studio Display</em> with white point calibrated to D50</td>
</tr>
<tr>
<td><strong>LCD</strong></td>
<td>TFT LCD of <em>Acer Extensa 367T</em> notebook with white point set to D65</td>
</tr>
<tr>
<td><strong>Projector</strong></td>
<td>Images projected using a <em>Sanyo PLC–5605B</em> TFT LCD Projector</td>
</tr>
</tbody>
</table>

**Output media** do not suffer from the difficulties faced when calculating the gamuts of input media as their gamut can be determined if their input can be sampled in its entirety. And this certainly is not a problem for digital devices that necessarily have a finite and known range of possible inputs. However, a different issue arises in conjunction with output media whereby some **colour reproduction devices** are media while others are not. CRTs or other types of displays, for example, are directly colour imaging media as they themselves display colour information. Printers on the other hand are not colour imaging media – rather, they can give rise to a range of printed media often using a range of substrates and colorants. Hence, the question of a printer’s gamut cannot be answered even if viewing condition and observer details are supplied. Instead, it is only prints that can have colour gamuts.

The data gathered for the sake of illustrating how the theoretical points made in the Section 2 are manifest in output media are measurements of colours from a number of media taken under a number of viewing conditions. Observer differences and differences in the relative spectral power distributions of the illumination were not considered in this study (CIE
Standard Colorimetric Observer ($2^\circ$)\textsuperscript{12} was used throughout) and the background and surround were also kept constant at a reflectance of 20% for all setups. Table I shows the mnemonics and descriptions of the media used in the experiment.

Table 2. CAM97s2 parameters for medium, viewing technique and viewing condition combinations.

<table>
<thead>
<tr>
<th>Medium</th>
<th>Viewing technique</th>
<th>Perfect diffuser (cd/m²)</th>
<th>Background (% of adopted white)</th>
<th>Luminance of adapting field (% of adopted white)</th>
<th>Surround conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser</td>
<td>Isolated</td>
<td>350, 240, 130, 55</td>
<td>20</td>
<td>20</td>
<td>Average</td>
</tr>
<tr>
<td>Thermal</td>
<td>Isolated</td>
<td>350, 240, 130, 55</td>
<td>20</td>
<td>20</td>
<td>Average</td>
</tr>
<tr>
<td>Thermal and CRT</td>
<td>Simultaneous</td>
<td>350, 240, 130</td>
<td>20</td>
<td>20</td>
<td>Average</td>
</tr>
<tr>
<td>Thermal and CRT</td>
<td>Simultaneous</td>
<td>55</td>
<td>20</td>
<td>20</td>
<td>Dim</td>
</tr>
<tr>
<td>CRT</td>
<td>Isolated</td>
<td>350, 240, 130</td>
<td>20</td>
<td>20</td>
<td>Average</td>
</tr>
<tr>
<td>CRT</td>
<td>Isolated</td>
<td>55</td>
<td>20</td>
<td>20</td>
<td>Dim</td>
</tr>
<tr>
<td>CRT</td>
<td>Isolated</td>
<td>0</td>
<td>20</td>
<td>20</td>
<td>Dark</td>
</tr>
<tr>
<td>LCD</td>
<td>Isolated</td>
<td>350, 130</td>
<td>20</td>
<td>20</td>
<td>Average</td>
</tr>
<tr>
<td>LCD</td>
<td>Isolated</td>
<td>0</td>
<td>20</td>
<td>20</td>
<td>Dark</td>
</tr>
<tr>
<td>Projector</td>
<td>Isolated</td>
<td>350, 240, 130, 55</td>
<td>20</td>
<td>20</td>
<td>Average</td>
</tr>
<tr>
<td>Projector</td>
<td>Isolated</td>
<td>0</td>
<td>20</td>
<td>20</td>
<td>Dark</td>
</tr>
</tbody>
</table>

These media were measured using a Minolta CS–1000 telespectroradiometer (TSR) under a range of levels of illumination in terms of $X_L^*Y_L^*Z_L^*$ where $Y_L^*$ is luminance in cd/m². The Projector images were projected from a distance of 2 m and measured from a distance of 3 m under two levels of illumination resulting from having the diffuse ceiling lights on and off respectively in a room with blackened windows. For the other media a 1 m measuring distance was used under some of four levels of illumination resulting in the following luminances for the perfect diffuser at the location where colours were measured: 350, 240, 130 and 55 cd/m². The different levels of illumination were obtained by illuminating the various media using combinations of ceiling lights and an OHP projector as well as using filters to vary the output of the latter. Measurements were taken orthogonal to the media measured (i.e. at $0^\circ$) and the OHP projector was positioned at $45^\circ$ relative to the surface of the media so as to avoid specular reflection at the location from which measurements were taken. All illumination used here was diffuse. Note, that while care was taken to minimise white point differences between the media considered here, this was not completely possible. While having a set of data with identical white points for all media would be desirable, the present, less perfect, set exhibits the same nature of gamut differences as would be shown by the more optimal set.

To obtain SMGBDs for the above set of media under these viewing and measuring conditions, a set of 26 colours were generated and measured per medium–viewing condition. These colours were determined by those device–dependent coordinate combinations of the 0, 50 and 100% levels being on the gamut surface in device–dependent terms. CAM97s2 coordinates were then calculated from perfect diffuser normalised XYZ values obtained from measurements made under a number of conditions which will be described in the following section. Based on the 26 original colour samples, which cover the surface of the RGB gamut cube evenly, 3456 ($=12\times12\times4\times6$) simulated gamut boundary colours were generated for the gamut boundary calculation in CAM97s2 $Jab$ colour space. A bi–linear interpolation technique was used for simulating $12\times12$ colours within each square consisting of $2\times2$ original samples. RGB distances between the interpolated colour and the four original samples were regarded as the weights for the interpolation in $Jab$ space.

For all calculations the background (CAM97s2 $Y_b$) had a luminance which was 20% of the luminance of the adopted white. When colour appearance was calculated for media viewed in isolation, surround conditions were set to ‘average’ and adopted white was taken to be the medium white point (i.e. the substrate for Thermal and Laser and R=G=B=100% for CRT, LCD and Projector) as measured under actual viewing conditions. The luminance of the adapting field (CAM97s2 $L_A$) was set to 1/5 of the adopted white. When calculating appearance for media viewed simultaneously the adopted white was taken to be the medium white point with the higher luminance (i.e. the Thermal white point for the three highest illumination levels and the CRT white point for the 55 cd/m² level). The CAM97s2 surround conditions were set to ‘average’ for the three highest illumination levels and to ‘dim’ for the lowest. For a summary of CAM97s2 parameter values see Table 2.
5. EXPERIMENTAL RESULTS FOR OUTPUT GAMUTS

The measurements taken under the conditions described in Section 3 can yield a number of insights about the relationship of the colour gamuts of various media under a range of conditions. As the aim of this paper is primarily to look at gamut differences, it will first be the nature of the difference between the gamuts of the CRT and Thermal media under a range of illumination conditions that will be looked at here. This will then be followed by a look at how the gamuts of individual media change with changes of illumination level.

5.1. Comparison of CRT and Thermal gamuts

First of all, we will focus on the relationship between the CRT gamuts and the Thermal gamuts as it is this relationship between displays and prints that is most often of interest to users of colour management systems. The difference between members of these two sets can be considered from at least two points of view. First, what it would be if the two media were viewed simultaneously under different illumination levels. Second, what it would be if they were viewed separately under the same or different viewing conditions. The first of these scenarios would result in a single adopted white (i.e. the medium white–point with higher luminance) whereby in the second the adopted whites would be the white–points of the individual media. Note, that in all cases the medium white–points are measured telespectroradiometrically under the actual viewing conditions.

Before considering the range of possibilities that arise under the viewing conditions and points of view considered here, we will first look at what gamut differences are suggested when each of the two media (CRT and Thermal) are measured by conventional means (i.e. the way they would be measured if one would make just a single device profile for each of them). To do this, the CRT was measured in the way described in Section 3 but in a dark room which resulted in very little environmental flare and the setting of surround conditions to ‘dark’ in CAM97s2. The Thermal printer was measured using a GretagMacbeth Spectrolino spectrophotometer, XYZ values were calculated for standard illuminant D50, surround conditions were set to ‘average’ and the background (Yb) had a luminance which was 20% of the luminance of the adopted white. The luminance of the adapting field (L_A) was set to 1/5 of the CRT white’s luminance for both media as the measurements of the print did not result in luminance data. Clearly there are a number of ways for calculating single device profiles and the present one is only meant to be an example. What is more important is that it is single rather than what its details are. The gamut differences resulting from this data are shown in Figure 6 and their gamut volumes were 512,935 and 700,656 cubic CAM97s2 Jab units for the Thermal and CRT media respectively. Note that all ab plots in this paper are projections onto the ab plane while Ja plots are intersections of a gamut boundary and the Ja plane.

Figure 6. CRT and Thermal gamuts under ‘standard’ conditions.

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Figure 7. Gamut volumes for CRT and Thermal media viewed simultaneously under viewing conditions resulting in different perfect diffuser luminances.
We can now turn to considering the data collected under actual viewing conditions by first looking at the simultaneous scenario. The gamut differences for the CRT–Thermal pair are then shown in Figure 8 and the corresponding gamut volumes are shown in Figure 7.

As pointed out when discussing the ‘standard’ data, the key point to note is that the given pair of media can result in a number of gamut differences varying in magnitude and nature. What these figures show most clearly and what would be the case even if they did not exhibit some white point chromaticity differences (which here most affect the 55 cd/m² setup) is that the CRT and Thermal media change in opposite directions with changes in the level of illumination. While the Thermal gamut decreases with a decrease of illumination level, the CRT gamut increases.

For the levels looked at here this also means that a CRT to Thermal gamut mapping would at one end of the range involve little compression and could make use of expansion while at the other end there would be significant need for compression and virtually no room for expansion. Viewing these media under any of the actual illumination levels considered here would result in dramatic differences between what is seen to be the gamut difference and what gamut difference is suggested by the ‘standard’ gamuts. The point, however, is not a criticism of the ‘standard’ gamuts but that a single gamut representation cannot match the range of possible gamut differences between a set of media. The gamuts calculated under any of the actual illumination levels considered here would equally badly represent the other actual levels as would the ‘standard’ gamuts. So far the gamuts of the CRT and Thermal media were considered from the point of view of simultaneous viewing and this represents cases where images on these two media are compared side–by–side. For example, if an image on the CRT is to be reproduced on the Thermal medium and this reproduction is then held next to the CRT for comparison, then the two images could be from gamuts which have a range of gamut differences as illustrated in Figures 7 and 8.

Next, we will look at the possible gamut differences between these two media when viewed separately. This corresponds to gamut comparisons between the gamuts of sets of colours seen under different viewing conditions by a single observer at different times or by multiple observers at either a single or multiple times. Going back to the cross–media reproduction example from the simultaneous scenario, in this separate viewing scenario it would correspond to it being either only the CRT or only the Thermal medium that is present in an observers field of view. For example, if one person views the CRT image under one set of conditions (e.g. in a graphics studio) and another person views the Thermal image under another set (e.g. outdoors), then there are two gamuts corresponding to these two media being viewed under these two conditions and hence their difference can also be considered. Given the four levels of illumination used above, there are sixteen (4×4) gamut difference possibilities if the two media are viewed separately. The result of such a comparison of gamuts is shown in Figures 9 to 11.

From these figures we can again see the same trend as exhibited in the data obtained from their simultaneous viewing. The Thermal gamut decreases with perfect diffuser luminance while the CRT gamut exhibits an increase. It can also be seen that
gamut differences are smaller in general under these separate viewing conditions while still having a significant variation in the possible differences due to differences in illumination level. Viewing the CRT medium under 55 cd/m² conditions and the Thermal under 350 cd/m² conditions results in the two media having a very large overlap between their gamuts. Viewing both media under 240 cd/m² conditions gives very similar gamut volumes with a gamut volume difference of only 2,224 cubic CAM97s2 Jab units. The largest difference in this range of illumination levels results from having both media under the 55 cd/m² condition where the gamut volume difference is 429,954 cubic CAM97s2 Jab units. To put this figure into perspective we can see that it is two orders of magnitude larger than the smallest difference and almost twice the gamut volume of the Thermal medium under these conditions (i.e. 251,609). Hence the question of how large the difference is between the CRT and Thermal gamuts can both be that they are almost the same and that the CRT gamut is almost three times as large as the Thermal gamut. It all depends on viewing conditions and as can be seen from this data their influence is dramatic. Trying to describe colour imaging media using single gamuts cannot cover the wide range of perceived gamuts they can exhibit. This will further be illustrated by seeing how the gamuts of individual media seen in isolation change with changes in illumination levels.

![Figure 9. Gamut volumes for CRT and Thermal media viewed separately under viewing conditions resulting in different perfect diffuser luminances.](image)

**Figure 9.** Gamut volumes for CRT and Thermal media viewed separately under viewing conditions resulting in different perfect diffuser luminances.

<table>
<thead>
<tr>
<th>Luminance (cd/m²)</th>
<th>Perfect diffuser luminance for CRT viewing conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>55</td>
<td>Perfect diffuser luminance for CRT viewing conditions</td>
</tr>
<tr>
<td>130</td>
<td>Perfect diffuser luminance for CRT viewing conditions</td>
</tr>
<tr>
<td>100</td>
<td>Perfect diffuser luminance for CRT viewing conditions</td>
</tr>
<tr>
<td>55</td>
<td>Perfect diffuser luminance for CRT viewing conditions</td>
</tr>
</tbody>
</table>

**Figure 10.** CRT and Thermal gamuts viewed separately (under range of illumination levels; a axis ranges from –100 to 100 and J axis ranges from 0 to 100).
5.2. Other Medium Gamuts

To allow for easier inter-comparison between the other media considered here, gamut boundaries as well as gamut volumes are shown together in Figures 12 and 13. The *Thermal* and *CRT* boundaries, being based on the same data as used in the previous section, again show that these gamuts change in opposite directions with a change of illumination level and that the *Thermal* medium is subject to far less change than the *CRT* medium. This is due to the appearance of all colours from the *Thermal* medium being determined solely by the intensity of illumination whereas the appearance of the *CRT* medium is the result of a combination of its constant output and varying illumination levels. Due to the surface of the *CRT* being glossy, different levels of illumination result in changes in flare in the environment and hence different lightnesses for the medium’s black point. In other words changes in illumination levels primarily introduce a scaling to the *Thermal* medium’s colours in tristimulus terms, whereas they result primarily in an offset for the *CRT*, hence having a different impact on corresponding lightness ranges.
As the Laser medium is similar to the Thermal medium since both of them are prints, the same trend as seen for the Thermal gamuts can again be seen here for the Laser gamuts. Overall it can be seen that the gamut does not change significantly with change of illumination level. Moreover the lightness range stays virtually identical and changes in chromatic range are due primarily to changes in the redness–greenness direction.

The gamuts of the LCD medium can be seen to be far less dependent on viewing conditions than the gamuts of the other media considered so far. This is probably due to the LCD medium’s matte surface properties combined with it being a self–luminous medium and hence dependent primarily on its own output which is illumination independent. The LCD’s matte surface properties also account for there not being any flare effects for this medium between the two levels of illumination.

Finally, the gamut of the Projector medium can be seen to be very strongly illumination dependent, as it achieves colours by having the light it projects reflected from a surface. If there is other (achromatic) light reflected from that surface then we again have a similar situation as was the case with the CRT. The reason then for the effect here being stronger is that, at R=G=B=0% input, illumination of the CRT results in only a first–surface reflection from glass in front of a black background, while that same input to the Projector results in a reflection of the light source from the highly–reflecting (white) surface onto which the Projector projects.

Figure 12. Gamuts Laser, Thermal, LCD, CRT and Projector media seen in isolation under different levels of illumination.

Figure 13. Gamut volumes of Laser, Thermal, LCD, CRT and Projector media.
6. CONCLUSIONS

Colour imaging media are affected by changes in illumination as a result of different ways of reproducing colours, including self–luminance and reflection, and a variety of possible surface properties ranging from the gloss of glass to the matteness of uncoated paper. These differences necessarily and in most cases dramatically influence the corresponding colour gamuts and hence necessitate a description of medium gamuts in a viewing condition dependent way. Describing a colour reproduction medium using a single gamut boundary inevitably leads to mismatch between what that gamut boundary suggests and how the gamut of the medium is seen under different conditions. While one solution to the problem is to generate a number of gamut boundaries for each medium – viewing condition combination, this would result in an explosion of gamut boundary descriptors even if one were to do it only for standardised O–VCs and it would always result in some degree of inflexibility. Alternatively and preferably this relationship could be modelled and this would result in the possibility of having a single reference gamut per medium which could then be modified to suit particular viewing conditions. As can be seen from Fig. 17 medium gamuts can be affected to different degrees ranging from virtually no difference as for the LCD medium, to a sixfold change as for the Projector medium. The most important point to be taken from this paper is that instead of a medium having a single gamut, it has a multitude of them.

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REFERENCES