A psychophysical analysis of the discernible palette for colour names

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A laboratory-based experiment with a colour-calibrated display was used to collect examples of colours that participants associate with each of 9 colour names. The gamut volumes for each of the clusters of colours in CIELAB space were calculated and a computational method was used to estimate how any distinct colours could be placed within each of these volumes. In the case of one of the colour names (pink), an unconstrained web-based experiment was carried out and the gamut volume for pink was similar to the gamut volume derived from the laboratory experiment. It was assumed that colours separated by more than 1 CIELAB unit would be visually distinguishable. The study gave estimates for the number of discernible colours for each of the 9 colour names. The work suggests that although focal colours may exist for each of the colour names used in the study, these colour names are generally not precise communicators of colour and different people might have quite different ideas, for example, about what is being communicated when people use specific colour names.

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Introduction

Seminal research by Berlin and Kay in 1969 supported the concept of colour universality which states that despite our different languages and cultures our perception of colour is essentially universal [1]. This contrasts with linguistic relativity (sometimes expressed as the Sapir–Whorf hypothesis) which posits that that the language that we speak affects our worldview and, in the context of colour, our colour perception. Today, there is still some controversy about the universalist approach and a number of studies have somewhat contracted the work of Berlin and Kay [2]. Berlin and Kay originally proposed that there are 11 basic colour names (black, white, red, green, yellow, blue, pink, grey, brown, orange and purple) which elicit colour sensations that are shared across all cultures. Some studies (including the original Berlin and Kay study) have observed a hierarchy for these colour names in that the names seem to develop in different languages in the same order; thus, for languages that have limited words for describing colour some colour names always precede others. For example, a language that has a word for brown always has a word for red (see the seven stages of this hierarchal system in Figure 1). In the Bassa language (spoken in Cameroon) there are only Stage I terms. Bassa has a word (zizzi) for light, warm colours that includes white and other colours that we would call red, yellow and orange; and there is a word (hui) for dark, cool colours that includes black, violet, blue and green. Beyond Stage VII sophisticated languages will use additional terms such as dark red and introduce non-basic colour names such as scarlet.

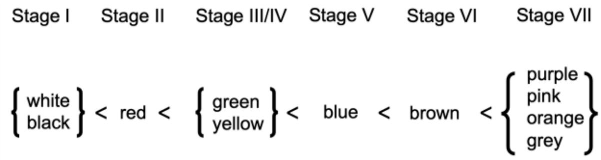


Figure 1: The seven stages of a hierarchal system of colour naming based on Berlin and Kay's work [2]. A culture that reaches one of these stages will always have words for the previous stages.

One recent study considered the relationship between this hierarchy of colour names and the way that we see the spectrum [3]. Our visual categorisation of the continuous variation in wavelength in the visible spectrum is not easy to explain. Loreto *et al.* asked participants to play a game and argued that the results of this were consistent with the Berlin and Kay colour name hierarchy [3]. Further, they suggested that universality of colour naming might be explained by visual saliency of, for example, the colour spectrum. Boynton and Olsen asked seven subjects to name 424 colours uniformly sampled from the OSA space; colours that were named according to one of the 11 basic colour terms were named faster than non-basic colour terms [4]. This finding was supported by later research with many more participants [5].

A separate problem is that of determining how many distinct colours there are in the world. To address this problem we need to define what is meant by 'colour'. If colour was to be defined as a physical phenomenon then one might argue that there are an infinite number of possible colours (though perhaps constrained by quantum effects). However, in this paper we define colour as a perception which we believe is consistent with the view of most researchers [6]. This definition leads to one possible route to determining how many different colours there are by rephrasing the question as how many discernible colours there are. An early estimate put the number of such discernible colours at about 10 million [7, p388]. However, a later study considered the visual uniformity of CIELAB colour space and yielded 2.28 million colours contained within the boundary of the MacAdam Limits [8]. Similar methods have since been used by other authors [9-10]. It has been estimated that there are about 2.3 million discernible colours in natural scenes [11]. Meanwhile, others have argued that estimating the number of discernible colors is very difficult to do because it depends upon many factors such as the colour temperature of the light source and the colour space used for any uniform-spacing calculations [12]. Morovic *et al.* also argued that it was difficult to arrive at a single reliable estimate for the number of discernible colours because of factors such as the effect of light source on the gamut volume; nevertheless, they concluded that at a lower limit there were at least 1.7 million colours [13].

This paper is concerned with the number of discernible colours of a given colour name: for example, how many different pinks are there? A number of studies have attempted to determine the colour gamuts of colour names or to segment colour space into regions that are represented by certain colour names. For example, Lin *et al.* developed a colour-naming model to categorise all colour coordinates in CIELAB colour space into the 11 basic colour names [14]. Recently, a number of researchers have carried out interesting online colour-naming experiments to enable studies to be completed with large numbers of participants [15-16]. Sivik and Taft undertook a study of colour names in Swedish and noted that the universality from the Berlin and Kay study refers to focal colours; that is, colours that best represent a particular colour name [17]. Nevertheless, they note (citing Lehrer [18]) that when observers are asked to specify, on a colour chart with continuous colour changes, the boundaries for the area covered by particular colour names, a range of colours are selected; however, the dispersion was not greater between languages than between observers within one language. Other findings contradict this and find differences between observers who speak different languages [19]. Lin *et al.* undertook a cross-cultural study (English vs. Chinese) where participants were asked to name 200

ISCC-NBS colour samples [20]. They found that the 11 basic colour names were the most frequently used names by both groups. A close agreement was found between the two cultural groups in terms of colour categories though differences were found with non-basic colour names. Bartleson stressed the importance of distinguishing between hue names and colour names; in this study, we are explicitly concerned with colour names [21]. However, the work is restricted to the 9 of the 11 basic colour names that have previously been mentioned.

Methods

Two studies are reported. The first was carried out in the laboratory using a single colour-calibrated display and the second was carried out online where participants viewed a variety of displays in various states.

In the laboratory study, 31 participants (all of whom had normal colour vision according to the Ishihara Colour Test plates) were asked to select colours on an emissive display using a colour-picker tool when prompted with colour names. Each participant was asked to select three colours for each of 9 colour names (red, green, yellow, blue, pink, grey, brown, orange and purple). Nine of the eleven basic colour names were included but white and black were not used. Participants tended to select the focal colour (the colour they most closely associate with the colour name) for their first selection. For the second selection they were asked to select a colour that was maximally different to the first colour that they selected but which was still described by the colour name; for the third selection they were asked to select a colour that was maximally different to the first two colours selected for that colour name. The reason for this was that we are interested in ascertaining the range of colours that correspond to each colour name rather than the focal colour for each name. However, the assumption is that all three colours selected by a participant for a colour name are colours that the participant would be happy to refer to by that name. The experiments were carried out in a darkened room with a display configured to the sRGB specification (white point CIE x = 0.3115, y = 0.3299, max luminance 118.6 cm/m^2, gamma ~2.4). Table 1 shows measurements of the display made using a Minolta CS2000 tele-spectroradiometer from a distance of 80cm.

Stimulus	**Luminance cd/m^2**	CIE x	CIE y
White [255 255 255]	118.62	0.3115 (0.3127)	0.3299 (0.3290)
Red [255 0 0]	24.70	0.6397 (0.6400)	0.3294 (0.3300)
Green [0 255 0]	85.36	0.2969 (0.3000)	0.6011 (0.6000)
Blue [0 0 255]	8.70	0.1528 (0.1500)	0.0606 (0.0600)

Table 1: Measurements of the display used in the laboratory experiment (the chromaticities in parentheses are those of the sRGB standard).

The compliance to sRGB (demonstrated by Table 1) allows the standard sRGB relationship to be used to convert the display RGB values (with range 0-1) for the colours selected by the participants to CIE XYZ values (D65/1931) using Equations 1 and 2.

If RGB > 0.04045

$$RGB\_linear = ((RGB+0.055)/1.055)^{2.4}$$

else (1)

$$RGB\_linear = RGB/12.92$$

$$\mathbf{T} = \mathbf{MD} \tag{2}$$

where **D** is a 3×N array of RGB_linear values for N colours, **T** is a 3×N array of CIE XYZ values, and **M** is a transfer matrix thus:

$$\mathbf{M} = \begin{matrix} 0.4124 & 0.3576 & 0.1805 \\ 0.2126 & 0.7152 & 0.0722 \\ 0.0193 & 0.1192 & 0.9305 \end{matrix}$$

Since 31 participants took part in the experiment and each selected 3 colours for each colour name, there were 93 colour selections per colour name. The convex hull of the cloud of 93 points for each colour name is considered to be the colour gamut for each colour name and defines that volume of colour space in which colours are described by the colour name. The participants were recruited from the University of Leeds campus and were confirmed to have normal colour vision before taking part. For the laboratory experiment, participants were required to sign a written consent form before taking part in the experiment. For the online experiment the participants were asked to agree to taking part in the experiment using a checkbox before data were collected. All data that were collected were anonymised in accordance with the protocol that was approved (LTDESN-161) by the Ethics Committee of the University of Leeds. No personal information, or information that could identify a participant, was recorded.

In the online experiment a different set of participants were invited to take part. These participants were recruited through social media (Facebook and LinkedIn). The online experiment only collected colours for the colour name ‘pink’. In the online experiment participants were invited to select as many colours as they liked to represent the colour pink. In total, 356 colours were selected for this colour name. Whereas the laboratory-based study was carried out using a GUI written in MATLAB, the online study was written using HTML and javascript. A third-party javascript colour picker called IRO [22] was used for the online study. For this reason, the colour-picker was different in the two experiments (see Figure 2).

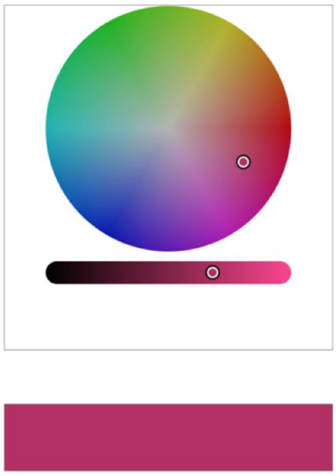
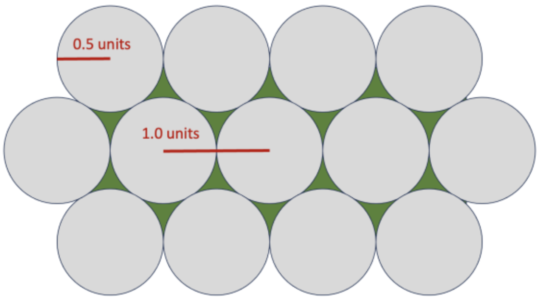


Figure 2: The colour-picker GUIs used in the laboratory (shown on the left) and the online (shown on the right) experiments. The laboratory colour picker was the standard one provided with MATLAB (ver R2021b) and the online colour picker was a javascript application called IRO [22].

Within each gamut the number of discernible colours was calculated using a method that was previously used to determine the number of discernible colours that can be generated by a display [10]. In this method the volume of the convex hull is calculated using the *convhulln* function in MATLAB that implements the Qhull algorithm [23]. If a set of spheres of radius 0.5 are densely packed in CIELAB space then the centres of adjacent spheres will be 1 CIELAB unit apart. If we assume that colours that are less than 1 CIELAB unit apart are visually indistinguishable then the number of distinguishable colours in a given volume of space is equal to the number of spheres that can be densely packed within that space (and this is simply found by dividing the volume of the space by the volume of a sphere with radius 0.5). However, the problem with this is that spheres do not pack in 3D space without leaving spaces between them. This is illustrated in Figure 3 for the case of hexagonal-packed circles in a 2D space.

The packing density of hexagonal-packed circles (as shown in Figure 3) in 2D space is 0.907 (in other words they cover only about 90% of the space). However, the packing density of spheres in 3D space is only about 0.74.



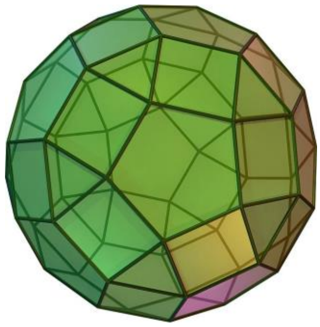


Figure 3 (left): A dense packing arrangement of circles of diameter 0.5 in 2D space. Each circle is 1.0 units from the centres of the six adjacent circles. All points within a circle represent colours that are indistinguishable; however, the green areas represent areas of the space that are not covered by the circles.

Figure 4 (right): The rhombicosidodecahedron *tiles perfectly in a 3-D space.*

A rhombicosidodecahedron is an Archimedian solid; a polyhedron with 20 triangular faces, 30 square spaces and 12 regular pentagonal spaces (Figure 4) that packs a 3-D space with density of 1. The radius R of a sphere circumscribed by the rhombicosidodecahedron is related to the edge length A of the rhombicosidodecahedron by Equation 3.

$$R = \frac{A}{2}\sqrt{\frac{3}{2}(\sqrt{5}+1)} \tag{3}$$

Based on Equation 3, for a radius R = 0.5, we can calculate the edge length A = 0.2523. The volume V of the rhombicosidodecahedron is related to A according to Equation 4,

$$V = \frac{60+29\sqrt{5}}{3}A^3 \tag{4}$$

and this means that for a rhombicosidodecahedron of radius 0.5, the volume V = 0.668 units^3. This means that approximately 1/0.668 rhombicosidodecahedra fit inside a space of volume 1 units^3. The number N of rhombicosidodecahedra (whose centres are spaced 1 CIELAB unit apart) in a gamut volume V is given by V/0.668. Since the centres of these rhombicosidodecahedra are spaced 1 CIELAB unit apart and using the value of 1 CIELAB ΔE as a just noticeable colour difference threshold, the number N of rhombicosidodecahedra is an estimate of the number of discernible colours in the gamut.

Results

Figure 5 shows sRGB representations of the colours selected for the colour names in the laboratory-based experiment. Each row of Figure 5 shows the colours selected by a single participant. Figure 6 shows the CIE chromaticities of the colours that were selected by the participants in the laboratory-based experiment for each of the colour names. The same information is shown in Figure 7 for the a*-b* plane of the CIELAB colour space. Given that CIELAB is an approximately uniform colour space it is interesting to note that the gamut volume of the colours that can be described as red seems to be smaller than for the other chromatic colours when viewed as a 2-D area.

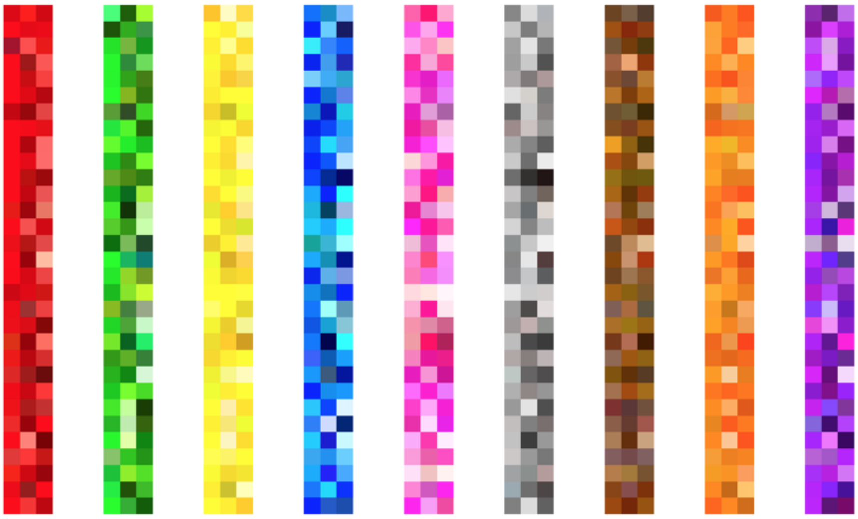
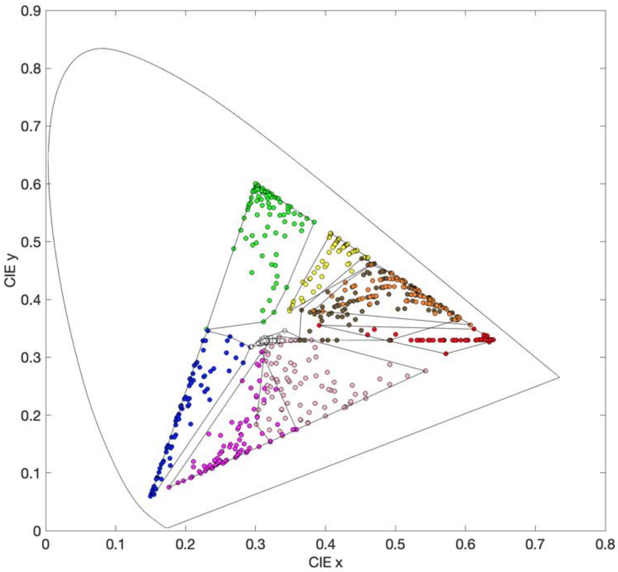


Figure 5: sRGB representations of the colours selected in the laboratory-based experiment for each of the colour names (from left to right): red, green, yellow, blue, pink, grey, brown, orange and purple. Each row represents the colours selected by a single participant.



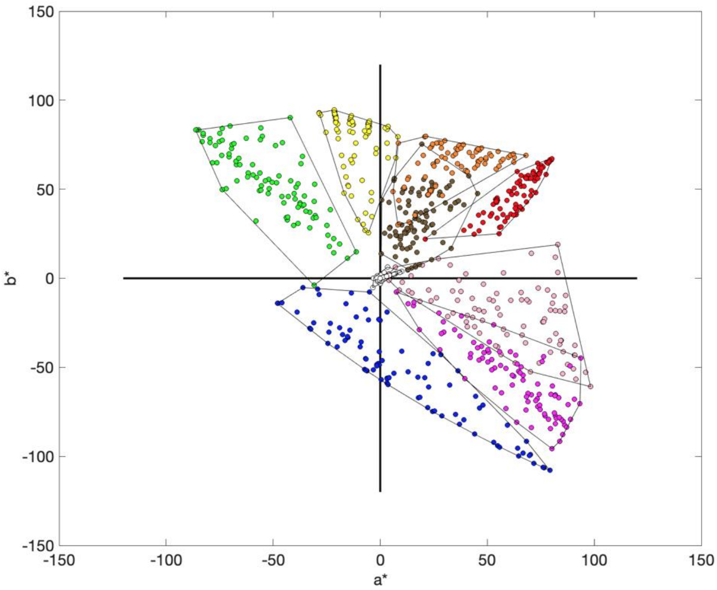


Figure 6 (left): Colour gamuts of the colours selected for each of the colour names in the CIE xy chromaticity space. The solid lines show the convex hulls.
Figure 7 (right): Colour gamuts of the colours selected for each of the colour names in the a-b* plane of CIELAB colour space. The solid lines show the convex hulls.*

Several interesting insights can be derived from Figures 6 and 7. Most hues, for example, can be described by one of the basic colour terms red, green, yellow, blue, pink, brown, orange or purple. However, there are a few gaps. Table 2 shows the range of hues (in CIELAB space) that correspond to the colour names used in this study. There is a distinct gap (hue angles 109° – 115°) between yellow and green which could probably be accounted for by the term lime green or the term chartreuse, the former being common in the UK and the latter being popular in USA.

Colour name	CIELAB hue range
Red	24 – 47°
Pink	323 – 42°
Purple	302 – 335°
Blue	188 – 307°
Green	115 – 187°
Yellow	84 – 109°
Orange	45 – 84°
Brown	21 – 89°

Table 2: The range of hues that correspond to each colour name in CIELAB colour space for illuminant D65.

There is also some evidence of a gap between blue and green that might be accounted for by the colour name cyan. It is also noticeable that pink (323° – 42°) corresponds to a much greater hue range than does red (24° – 47°). This is interesting because the Cambridge Dictionary, for example, defines pink as a 'pale red colour' [24] and a HunterLab blog post [25] describes pink as 'a lighter shade of red'. However, in our data, although red and pink share common hues, the term pink extends to much bluer hues than red, suggesting that pink is not simply a pale red.

Brown corresponds to a wide range of hues (21° – 89°) that includes those of orange (45° – 84°) and red (24° – 47°). Bartleson suggested that it was not uncommon to hear that 'brown is merely a dark orange' and suggested that 'there is a modicum of truth in such statements because brown lies between yellow and red along the hue continuum' [21]. Bartleson also noted that brown is a colour name rather than a hue name. Our data are consistent with these statements in that brown shares hue angles with red and orange and, to some extent, with yellow. Our data suggest, however, that brown is a wider colour name than merely being dark orange.

Although Figures 6 and 7 are interesting, they show the colour gamuts in 2-D colour planes whereas the true gamuts are 3-D in CIELAB colour space. Figure 8 attempts to reveal the 3D properties by plotting Lightness and Chroma values for the colours described as pink and red (on the left) and orange and brown (on the right). In these plots it is evident that in addition to the hue relationships that can be seen in Figure 6, colours described as pink are generally lighter than those that are described as red and span a wider range in Chroma. Brown colours are generally darker and less chromatic that orange colours.

Table 3 shows the gamut volumes (computed using the convhulln code) for the colours as calculated in CIELAB colour space for illuminant D65. From Table 3 it is evident, for example, that we estimate that there are nearly 100,000 different pinks and over 160,000 different greens.

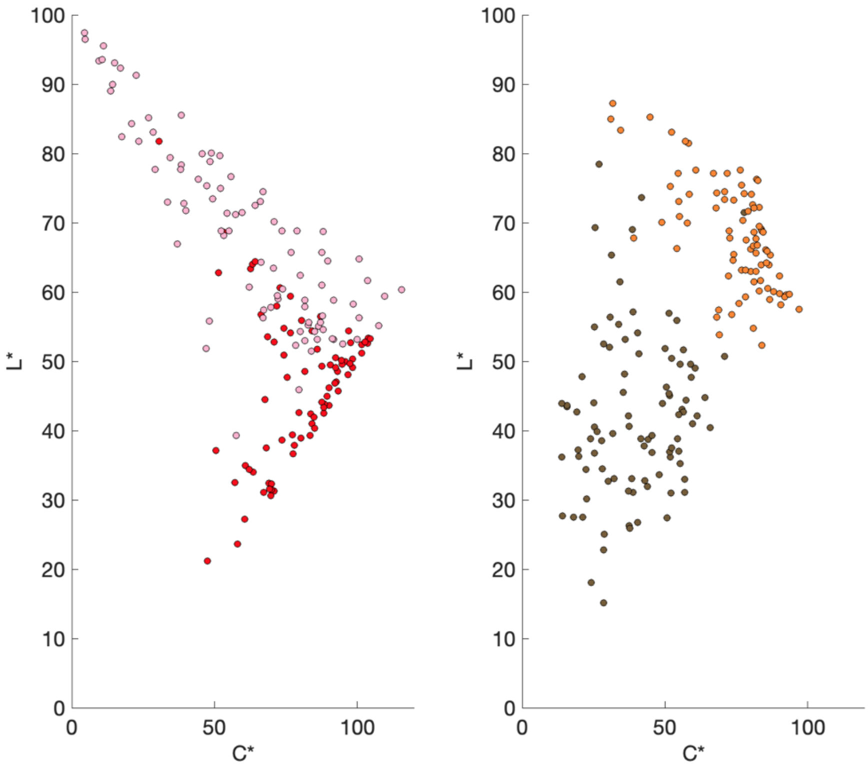


Figure 8: Comparison of CIELAB L-C* plots for colours described as pink and red (left) and orange and brown (right).*

Colour name	Gamut volume	Number of colours
Red	21185	31693
Green	107262	160465
Yellow	14082	21066
Blue	93679	140145
Pink	66546	99553
Grey	2521	3771
Brown	53124	79474
Orange	19016	28448
Purple	89436	133797

Table 3: The gamut volumes and the number of discernible colours for each colour name in CIELAB colour space for illuminant D65.

Figure 9 shows a comparison in CIELAB a*-b* space between the colours selected for pink in the laboratory experiment (red symbols) and in the online experiment (blue symbols). Note that in the controlled experiment the RGB data are assumed to be sRGB even though in many cases this will likely not be the case. Despite the online experiment being uncontrolled where the display, the settings on the display, the viewing environment and the motivation of the observer could vary, there is a striking similarity between the colorimetric data obtained from the two experiments.

Based on the methodology that has been employed we might expect these estimates of the number of colours to be lower limits; that is, we cannot rule out that if we recruited more participants we would obtain slightly larger gamuts for each colour name. Do the estimates in Table 3 seem reasonable? If we add up all the colours in Table 3 we arrive at a total of just under 700,000 colours that can be described

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by one of the 9 colour names used in this study. Given that recent estimates for the total number of discernible colours range from at least 1.7 million [13] to 2.83 million [8] and given how much of the chromaticity diagram, for example, is occupied by colours that could be described by one of the 9 colour names used in this study, our estimate of about 700,000 colours that could be described by one or more of the 9 colour names used in this study does not seem unreasonable.

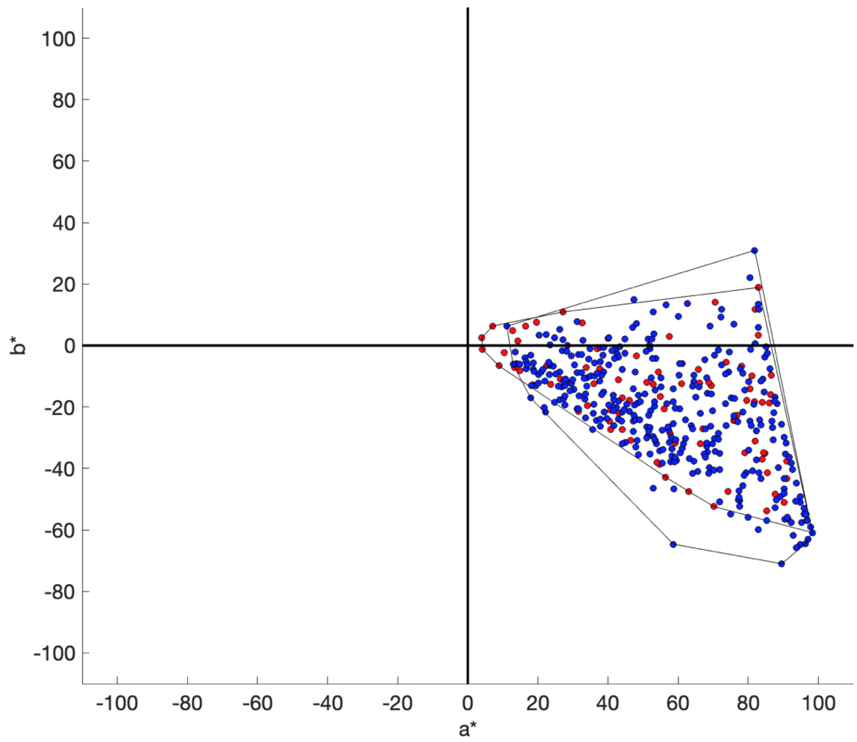

Figure 9: Comparison of CIELAB a-b* plots for pink colours obtained in the laboratory experiment (red symbols) and the online experiment (blue symbols).*

Nevertheless, the 2-D gamut (as illustrated in Figure 9) based on the online data is a little larger than for the laboratory data (though note that if one or two of the online data were removed the 2-D gamuts would be almost identical). The size of the 3-D gamut volume estimated from the online data is 94155 cubed CIELAB units which is 50% larger that the estimation from the laboratory data (66546); consequently, the online experiment yields an estimate of 140,897 pinks (compared with 99,553 from the laboratory experiment).

Discussion

There are several limitations to this study such as the relatively small number of participants that have been used and some inaccuracies that may result from the assumption that the display's colour output can be described the sRGB model. We should also consider whether the instructions to the participants which encouraged them to select colours that were as different as possible to each other might have biased the results.

A major concern is that we calculated our gamut volumes in CIELAB colour space which although approximately visually uniform is clearly not perfectly uniform. The assumption that a CIELAB ΔE of 1 is the threshold for colour discrimination might also be questioned. It would be interesting to carry out the computations in a more visually uniform colour space. The number of colours that corresponds to each of the colour names may seem large; however, if anything these estimates may be underestimates since we might expect slightly larger convex hulls if we had access to many more participants. Some additional insights were identified. For example, although colours associated with pink are generally lighter than those associated with red, the range of hues that are associated with pink is much wider than those associated with red (for example, some pinks are much bluer than any reds).

The experiment was effectively conducted for a D65 white point (the display in the laboratory experiment was set to D65). What would happen if the experiment was repeated using a different white point, say, illuminant A? Despite the phenomenon of colour constancy we might expect some shift in colour appearance if we moved from D65 to A. This undoubtedly could affect the gamut volumes that were derived in this study for the various colour names. However, it is not clear whether the number of colours that correspond to each colour name would increase if multiple illuminants were considered; but, it would be more likely to increase the number than decrease it. Therefore, the possibility of including more viewing conditions implies that the numbers of colours reported in this study may be underestimates.

One of the potential uses of understanding that, for example, there are just over 31,000 perceptually different reds is that this can counter the simplification that there is only one red. The widespread adoption of colour wheels in design teaching, for example, can lead to the misunderstanding that there is only one red (or, at least that the name red refers to a small range of colours). Colour wheels also often embody the idea that in subtractive colour mixing, red + yellow = orange. The reality is that before we even start to think about what a mixture of red and yellow colorants would make we need to consider which red and which orange. Although our language is somewhat categorical in nature, and this clearly reflects the fact that our colour vision may also be categorical to some extent (for example, we tend to see bands of colour in the rainbow) it is also helpful to remember that the attributes of colour perception are also continuous. The relative similarity between the data for pink obtained in a controlled laboratory experiment and in an unconstrained online experiment suggests that the results obtained are somewhat robust. This study also provides some support for the validity of online experiments in this field despite the variables that exist in that paradigm.

Conclusion

Despite the relatively small number of participants and the choice of colour space, this study has provided estimates for the number of colours that correspond to particular colour names and we argue that these estimates may be lower limits of the true values. The work highlights the limitations of using language as a way to describe colour experience. Future directions for this work might explore the gamut volume estimations in a more uniform space associated with a modern colour appearance model. It would also be interesting to compare the colour-name gamut volumes for non-basic colour names (e.g. cyan and magenta) with the volumes for the basic colour names used in this study.

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