# Towards the design of a blending system for pre-coloured fibres

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**Abstract**

In order to create a commercial system for blending pre-coloured fibres, that will appear visually solid once combined, it is necessary to understand the maximum colour difference required between the blend components. Based on this understanding the lowest number of primaries required to populate a given colour gamut can be determined.

A series of psychophysical experiments were carried out to explore the relationship between the colour difference between fibre-blend components and whether the resulting blended samples are perceived as being visually solid. Experiments were carried out with loose stock fibre, yarn and knitted samples. Generally, it was found that the likelihood that a blend appeared as visually solid increased as the average colour difference between the blend components, or primaries, decreased. The value of the mean colour difference, for which 50% of participants viewed the blend as being visually solid, was found to be 20.8, 20.5 and 18.0 for fibre, yarn and knitted samples respectively. Consequently, it was found that it is more difficult to obtain a solid shade with the knitted form than with the loose-stock fibre form.

## Introduction

Blending of pre-coloured fibres, in which fibres of different colour are intimately mixed together, offers a way to achieve a wide colour gamut from a relatively small number of 'primaries'. The advantages of this approach can be both environmental and economic. For example, some coloration methods may be more environmentally sustainable than traditional dyeing, but the method may only be economic if relatively large quantities of fibre are coloured at one time; an example of this is spun-dyed fibre. Fibre blending potentially allows a relatively small number of colour primaries to be produced in large quantities that can later be blended together to produce a wide range of colours. A further potential advantage of this approach is that the decision on the colour of the blend is made later in the textile process which could enable more rapid responses to changing consumer demand. Fibre blending can also be used as part of a recycling effort whereby waste textile materials are mechanically reduced to fibres before being carded and re-used [1].

The blending of coloured fibre can take place at various stages of the fibre-production cycle including, for example, before opening, during drawing, at the roving frame, or during spinning itself [2]. However, to develop a commercially viable system it is necessary to have models that can predict the colour of blends, given the colour of the primaries used in the blend and their proportional amounts. Fortunately, a number of methods have been shown to be able to predict the colour of fibre blends including the Stearns-Noechel model [3-4], the Friele model [5-6], the Kubelka-Munk model [7-9] and artificial neural networks [10-13] with varying degrees of success.

However, in addition to the problem of colour prediction is the question of how many primaries are required to essentially cover the normal gamut of coloured textiles and how should these be distributed in colour space? The fewer the number of primaries the more economical the system can be; on the other hand, if the primaries are too few then the mixtures are likely to appear mottled (mélange) rather than solid. There may be, of course, market opportunities for mélange fibres. However, in this work the goal is to produce fibres that look visually solid, as if they are made from a single colour, and therefore the question is, how close in colour space do the primaries need to be so that their mixtures are visually solid? It is likely that at some viewing distance (or level of magnification) the individual colours of the pre-coloured fibres in the blend will always be visible. Therefore, the question can finally be recast as: how many primaries are required so that their mixtures cover the gamut of coloured textiles and appear to be visually solid at some specified viewing distance? This is the key question that the work in this paper was designed to address. The viewing distance studied was between 45 and 50 cm as people tend to consider this distance as comfortable when they stand together [14]. However, it will be shown that the methods that are developed in this work could be easily applied to any viewing distance and any sub-volume of the full colour gamut. The work will also consider whether the physical form of the samples (that is, fibre, yarn or knitted samples) affects the visual assessments.

## Experimental

### Determination of ΔE threshold between primaries

*Theoretical Considerations*

For conventional dyeing processes three-dye recipes are typical, although for various reasons sometimes more than, or even less than, three dyes are used in a commercial recipe. The use of three dyes creates a colour gamut that is three dimensional. If a single-dye recipe is used the gamut is essentially a line in colour space (albeit usually a curved one) as the dye concentration is varied. If a two-dye recipe is used the colour gamut is a plane in colour space; three-dye recipes extend this to a 3-D colour gamut. However, for fibre blending four primaries are required to create a three-dimensional gamut. If a single primary is considered then the colour gamut is a single point in colour space; if two or three primaries are considered then the colour gamut is a line or a plane respectively; if four primaries are used then the colour gamut is a volume. This is illustrated in Figure 1 (left pane).

Previous work by one of the authors has suggested that the mean colour difference between the components of a blend can be used as an indicator of whether the blend would likely be perceived as being visually solid [15]. For a blend containing four components there are six colour differences between the primaries (see Figure 1) and the mean of these can be used as an indication of how sparsely distributed the components are in colour space. In this study, we will construct blends where the mean ΔE between the blend components varies and assess the extent to which each blend appears visually solid.

*Figure 1 about here*

*Preparation of Samples*

Pre-coloured spun-dyed viscose staple fibre (1.7 dtex with fibre length of 50 mm) was provided by Lenzing AG [16] in 16 different primary colours. Further details about these samples are provided in a previous publication that used the same samples [12]. A total of 10 blends were prepared, each made from four of the primary colours. In making the blends, careful preparation and handling was essential for accurate colour measurement. The fibre was first conditioned (room temperature of 20°C and relative humidity of 65 ± 5 %) for 48 hours and was then weighed to 2 decimal places. The fibre was then opened by hand, taking care to distribute the different colours of the blend evenly, in a sample area of 210 mm x 148 mm before being passed three times through a bespoke, 0.5 m wide small-sample Tathams carding machine. The machine consisted of an automatic feed belt, interconnecting feed rollers, licker-in, single main cylinder with three pairs of workers and strippers, single doffer and a fly comb. At the end of the fly comb, a second conveyor belt transported the web to a lapper, laying the web in a parallel batt formation. The machine dimensions and direction of rollers can be seen in Figure 2.

*Figure 2 about here*

After the first and second pass through, the parallel batt was rotated 90°. The carding machine was cleaned of loose fibre between every sample in order to minimise fibre cross-contamination between samples.

After carding, the spectral reflectance of each blended sample was measured using a Spectraflash® 600 PLUS spectrophotometer (100% UV, specular component excluded, large aperture view, optical geometry of d/8°). Reflectance factors at 35 wavelengths (10-nm intervals between 360 nm and 700 nm) were then exported into MATLAB for data analysis, comparison and conversion to CIELAB (D65 illuminant, 1964 CIE standard observer) coordinates. Table 1 lists the CIELAB colour coordinates of the 16 primaries that were used in the study and Table 2 lists the recipe components of each of the 10 blends.

*Table 1 about here*

*Table 2 about here*

The 10 blends were prepared as five pairs. Each pair (B1-B5) of blends were constructed from four primary colours where the mean colour difference (CIELAB ΔE) between the components was 25 (blends B1.A and B1.B), 22 (blends B2.A and B2.B), 19 (blends B3.A and B3.B), 18 (blends B4.A and B4.B) and 15 (blends B5.A and B5.B). These levels of colour difference were selected because a previous study had suggested that the threshold for a blend being visually solid was a mean colour difference between the components of approximately 20 CIELAB ΔE units [15].

Figure 3 shows two examples of the blends that were produced as carded samples. Each of the ten blends was then spun into single-ply yarn at 28 tex (508 turns per metre twist) by Lenzing AG (Austria). The direction and the amount of twist were measured using a James Heal manual twist testing instrument. The direction of twist was Z.

The set of individual yarns can be seen in Figure 4.

*Figure 3 about here*

*Figure 4 about here*

Each yarn was wound around a piece of 7.5 × 7.5 cm neutral grey card with sufficient thickness so that the grey card was not visible. There was insufficient yarn to create larger samples. However, previous studies have used these dimensions [17] and one particular source has recommended 5 × 5 cm as the minimum size for visual observations about colour [18].

A plain knit fabric, also known as single jersey, was also produced from each of the 10 blends on a 12 gauge Dubied V-bed flat knitting machine. Plain knit was chosen because it is a uniform fabric structure which is simple to produce and uses a minimum amount of yarn. Also, plain knit is the most popular in the fashion industry and is said to account for approximately 90% of all knitted fabrics produced [19]. Steam from a domestic iron was used to induce fabric relaxation before mounting the knitted fabric, using double sided adhesive tape, onto neutral grey card of 7.5 x 7.5 cm with the technical face of the fabric facing outward. Another piece of 7.5 x 7.5 cm grey card was adhered to the back of each sample and marked with the respective colour blend number. Each sample had an average of 18 courses and 29 wales per 3 cm, giving an average stitch density of 522 stitches per 3 $cm^2$. Four of the 10 mounted knitted fabrics can be seen in Figure 5.

*Figure 5 about here*

*Psychophysical Experiments*

A VeriVide light viewing booth with a source of simulated D65 light was used to illuminate the textile samples. The samples were placed one at a time on the floor of the viewing booth and viewed from an angle of approximately 45$^o$ and a distance of approximately 45 cm, a comfortable viewing distance [14], and a common distance used in psychophysical experiments [17]. A total of 22 participants were recruited for the experiment through social media and flyers that were distributed around the university campus. Before visually assessing the textile samples, all 22 participants were screened for colour deficiencies using the Ishihara colour vision test. One participant was identified as having a colour vision deficiency and was therefore not eligible to take part in the remainder of the experiment. Therefore, 21 participants (9 male, 12 female) with normal colour vision took part in the assessment of textile samples. Prior to taking part in the assessments, participants were shown examples of single colour fibre, yarns and knitted samples and also mélange reference samples. Participants were then shown each of the 30 samples (10 blends × 3 material forms), one at a time presented in random order, and asked to state whether they thought the sample was composed of a single colour or contained more than one colour. The experiment was therefore a 2-alternative forced-choice paradigm. On average, participants completed the visual observations in about 20 minutes.

**Results and Discussion**

Table 3 shows the results of the visual assessments of the loose stock carded fibre samples. The results show that the likelihood that participants will view the samples as being visually solid increases as the mean colour difference between the constituent primaries decreases. The rightmost column of Table 3 shows, for comparison, the results from a previous study by one of the authors [15]. This previous study used the same samples but employed slightly different wording during the psychophysical experiment (in that study participants were asked whether the samples were visually solid, almost solid or not solid, whereas in this study they were asked whether the samples are composed of a single colour or not). However, there is strong agreement between the experimental results from the two studies. Whereas the previous study only considered fibre and knit samples, this study has extended the work to include fibres, yarns and knitted samples. Table 4 shows the results obtained in this study with fibre, yarn and knitted samples. The results generally indicate that the probability that a blend is perceived as being visually solid does increase, as the mean colour difference between the blend components decreases, thus confirming the previous hypothesis [15].

*Table 3 about here*

*Table 4 about here*

In Figure 6 the data from Table 4 are plotted and linear regression has been applied. The coefficient of determination ($r^2$) was found to be 0.69, 0.55 and 0.42 for the carded, yarn and knitted samples respectively. However, there is clear evidence of an inverse relationship between the mean colour difference between the blend components and the likelihood that participants will view the samples as being visually solid in all three cases. The linear model can be used to estimate the threshold $\Delta E$; that is, the value of $\Delta E$ above which a certain proportion of the population agree that the sample is visually solid. In this study two threshold have been used, $\Delta E_{50}$ and $\Delta E_{75}$, corresponding to 50% and 75% of the participants respectively. The value of $\Delta E_{50}$ was found to be 20.8, 20.5 and 18.0 for fibre, yarn and knitted samples respectively. The value of the more stringent threshold of $\Delta E_{75}$ was found to be 17.5, 16.5 and 12.75 for fibre, yarn and knitted samples respectively.

*Figure 6 about here*

## Implications for Commercial Fibre Blending Systems

In principle, a large colour gamut for blended fibre can be achieved using just four primary samples that would be mixed together in various proportions. However, it is evident that in order to achieve this gamut the primaries would need to have large colour differences between them. Of course, four primaries could be used to enable a small colour gamut, but for a large colour gamut many more than four primaries are likely required. A commercial system with a large colour gamut would consist of $N$ primaries in colour space connected by Delaunay triangulation (as illustrated in Figure 7). In this system, any point in colour space within the gamut would be covered by a tetrahedron, the vertices of which would be four colour primaries that could be used to form a blend corresponding to the target colour.

*Figure 7 about here*

The threshold mean colour difference between the primaries (determined as ΔE = 18 for knitted samples in this study) for visually solid blends would dictate the size of the tetraheda in Figure 7 and hence the number of samples $N$ required to cover the majority of colour space. Related work [15] has explored the relationship between the mean value of ΔE between the vertices of the tetrahedra and the number of samples $N$ required (see Figure 8). Given the threshold ΔE of 18, this leads to an estimate of $N$ = 150. In other words, the commercial implications of this work are that a system that attempts to create visually solid blends, from a limited number of primaries, would need about 150 primaries.

Whether this is practical or not would depend upon specific operational and other commercial considerations. However, note that this system could be used to develop fixed-primary coloration systems that cover a limited colour gamut (for example, blacks or navy colours) and the value of $N$ for such systems would obviously be a great deal smaller than 150.

*Figure 8 about here*

**Conclusions**

This research tested the hypothesis that the smaller the colour difference between the components of a fibre blend, the greater the likelihood that observers would view the blend as being visually solid. Moreover, the aim was to determine the threshold value of $\Delta E$; that is, to answer the question of how close together in colour space a set of blend components need to be in order for the blend to appear visually solid. Of course, the answer to this question is to an extent dependent upon the observer viewing distance. In this study, a viewing distance of 45cm was used because this is a distance people typically stand comfortably when engaged in conversation with each other, it could also be considered to be a typical distance at which consumers may view garments that they are considering to purchase. The threshold $\Delta E$ would no doubt vary with viewing distance but at the distance used in this study the threshold value (at which 50% or more of observers stated that the blend was visually solid) was 20.8, 20.5 and 18.0 CIELAB units for fibre, yarn and knitted samples respectively. The commercial applications of this work were considered and it was concluded that based on the threshold $\Delta E$ of 18 (which was found for knitted samples) a coloration system that produces solid colours could be obtained using 150 fixed primaries. Sub-systems could obviously be generated that would cover smaller parts of colour space and would require fewer primaries.

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Table 1: CIELAB colour coordinates of primary samples used in the blends.

| **Primary ID** | **L*** | **a*** | **b*** |
|---|---|---|---|
| P2.1 | 36.9 | 0.6 | -4.3 |
| P2.2 | 39.2 | 6.6 | 25.6 |
| P2.3 | 61.3 | 4.0 | 31.4 |
| P2.4 | 68.1 | -31.2 | -17.5 |
| P2.5 | 74.4 | -9.1 | -24.1 |
| P2.6 | 20.2 | 3.3 | -18.2 |
| P2.7 | 71.8 | -23.5 | -26.1 |
| P2.8 | 74.5 | -11.3 | -19.7 |
| P2.9 | 39.1 | 1.9 | -36.4 |
| P2.10 | 40.9 | -3.7 | -22.3 |
| P2.11 | 32.0 | -1.0 | -15.0 |
| P2.12 | 36.2 | 28.3 | -31.6 |
| P2.13 | 19.4 | 3.1 | -14.6 |
| P2.14 | 50.6 | 7.1 | 45.9 |
| P2.15 | 35.4 | 4.4 | - 47.1 |
| P2.16 | 50.8 | 11.2 | 44.7 |

Table 2: Specification of the components of each of the 10 blends.

| **Blend ID** | **Recipe for the Blend** | | | |
|---|---|---|---|---|
| B1.A | 20% P2.1 | 30% P2.10 | 20% P2.11 | 30% P2.12 |
| B1.B | 50% P2.1 | 25% P2.10 | 15% P2.11 | 10% P2.12 |
| B2.A | 15% P2.6 | 15% P2.9 | 15% P2.10 | 55% P2.15 |
| B2.B | 30% P2.6 | 20% P2.9 | 30% P2.10 | 20% P2.15 |
| B3.A | 20% P2.9 | 30% P2.10 | 20% P2.11 | 30% P2.13 |
| B3.B | 30% P2.9 | 20% P2.10 | 30% P2.11 | 20% P2.13 |
| B4.A | 50% P2.2 | 25% P2.3 | 15% P2.14 | 10% P2.16 |
| B4.B | 30% P2.2 | 20% P2.3 | 30% P2.14 | 20% P2.16 |
| B5.A | 25% P2.4 | 25% P2.5 | 25% P2.7 | 25% P2.8 |
| B5.B | 30% P2.4 | 20% P2.5 | 30% P2.7 | 20% P2.8 |

Table 3: Per cent of observers that rated the samples as being single colour (visually solid). For comparison, the rightmost column shows the results from a previous study whereby the same samples were assessed.

| **Blend ID** | **Mean DE between primaries** | **Participant Score % Solid** | **Participant Score % Solid [13]** |
|---|---|---|---|
| B1.A | 15 | 90 | 100 |
| B1.B | 15 | 81 | 100 |
| B2.A | 18 | 95 | 80 |
| B2.B | 18 | 90 | 85 |
| B3.A | 19 | 43 | 55 |
| B3.B | 19 | 48 | 45 |
| B4.A | 22 | 52 | 45 |
| B4.B | 22 | 71 | 40 |
| B5.A | 25 | 5 | 5 |
| B5.B | 25 | 0 | 5 |

Table 4: Per cent of observers that rated the samples as being single colour (visually solid) for the fibre, yarn and knitted samples.

| **Blend ID** | **Mean DE between primaries** | **Participant Score (Fibres)** | **Participant Score (Yarns)** | **Participant Score (Knit)** |
|---|---|---|---|---|
| B1.A | 15 | 90 | 76 | 76 |
| B1.B | 15 | 81 | 57 | 62 |
| B2.A | 18 | 95 | 81 | 33 |
| B2.B | 18 | 90 | 81 | 43 |
| B3.A | 19 | 43 | 57 | 43 |
| B3.B | 19 | 48 | 62 | 38 |
| B4.A | 22 | 52 | 57 | 38 |
| B4.B | 22 | 71 | 76 | 81 |
| B5.A | 25 | 5 | 0 | 14 |
| B5.B | 25 | 0 | 0 | 0 |

Figure 1: Arrangement of four primary constituents of a blend that can generate a 3-D colour gamut (left); demonstration of the six colour differences (straight lines) that can be calculated between the four components (right).

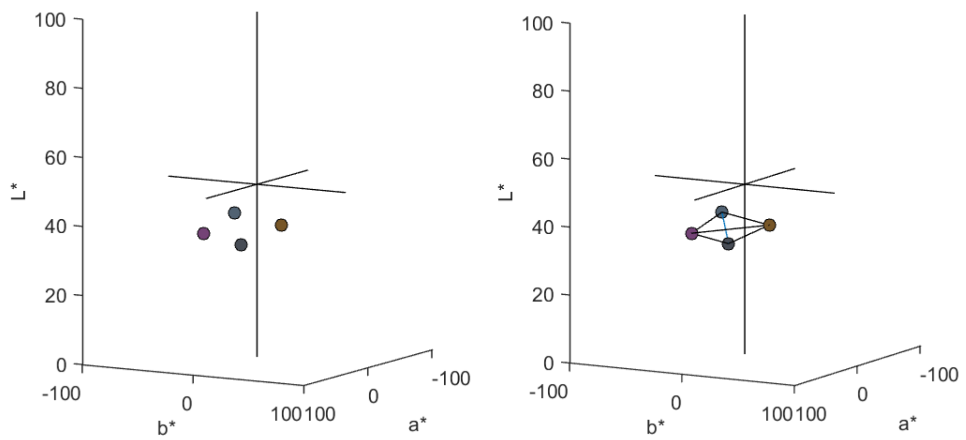

Figure 2: Layout of bespoke small sample Tathams carding machine (reproduced from Hemingray, 2014 [15]).

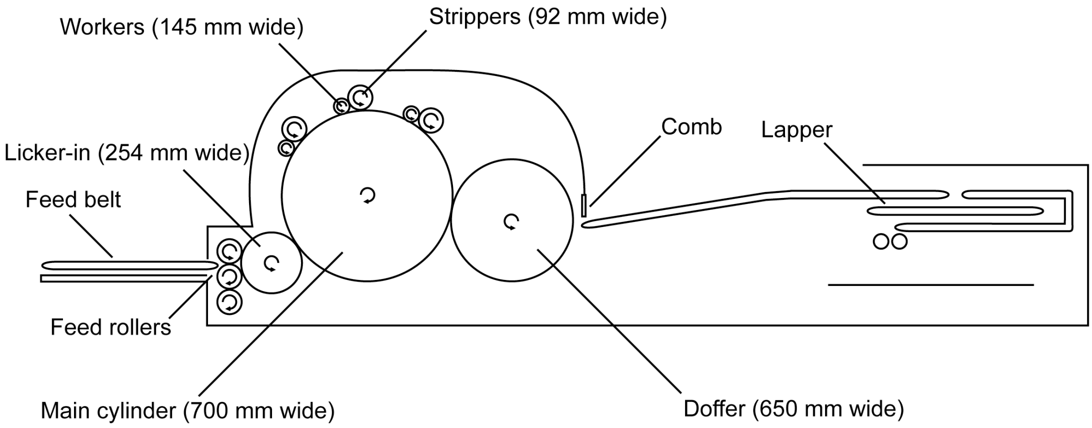

Figure 3: Images of the two blends prepared with a mean colour difference between the components of 25 CIELAB units showing B1.A (left) and B1.B (right).

Figure 4: The 10 blend colours as spun yarn.

Figure 5: Knitted samples for four of the blends.

Figure 6: Determination of the threshold ΔE for solid blends.

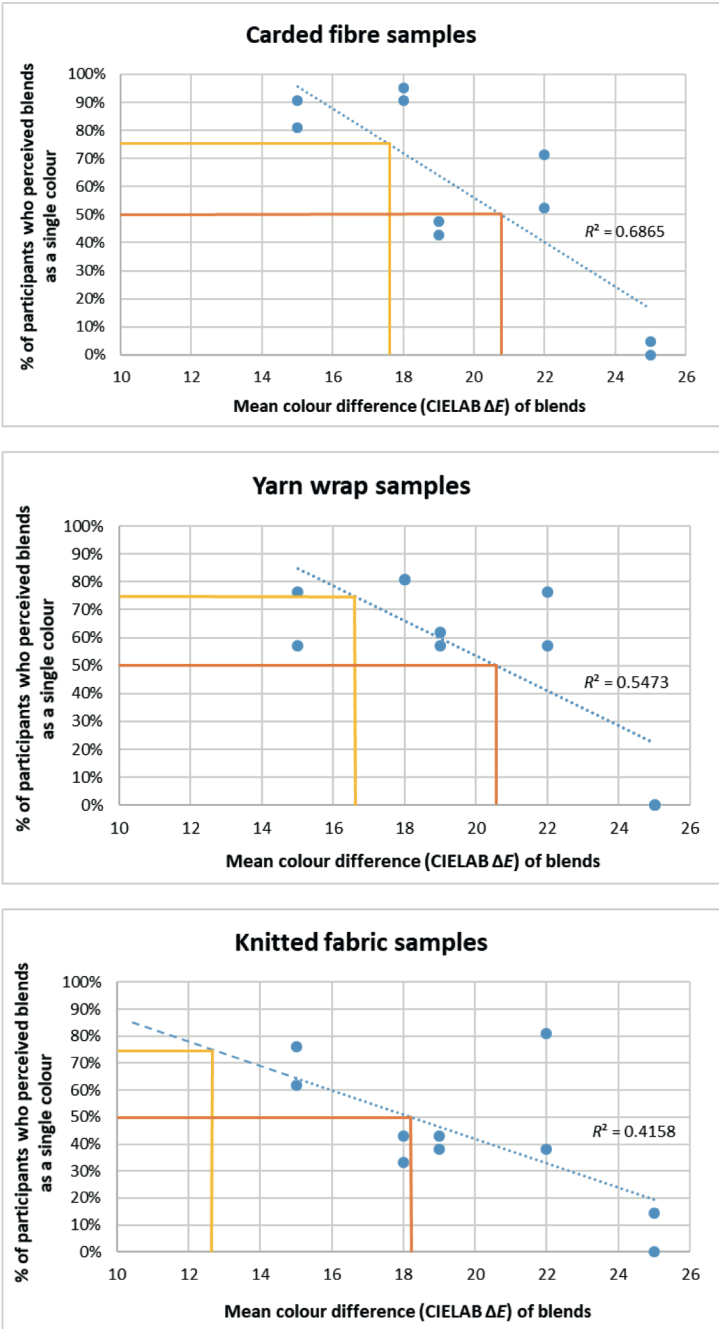

Figure 7: An example of 50 primaries in CIELAB colour space connected using Delaunay triangulation (reproduced from Hemingray, 2014 [15]).

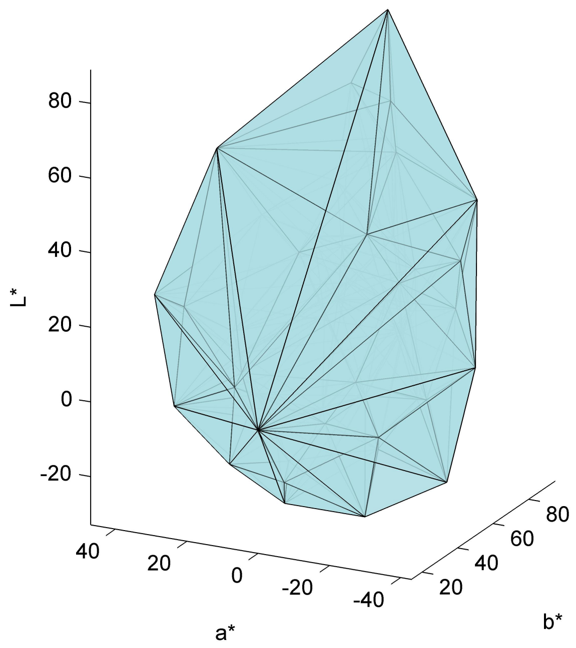

Figure 8: Relationship between the number N of primaries in a system and the mean colour difference between the vertices of the tetrahedral that can be formed (reproduced from Hemingray, 2014).