How well can people predict subtractive mixing?

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ABSTRACT

This study is a preliminary investigation towards the design of effective colour spaces and colour tools to allow users to quickly and accurately select a given colour in a digital-display environment. It has been shown that many non-expert users find the RGB colour space to be non-intuitive. The choice of colour space on various visual tasks has also been shown to be an important factor and that experts show greater precision in colour-matching experiments than non-expert observers. We propose that non-experts find manipulation and selection in an RGB colour space to be difficult because they do not possess an appropriate internal model for additive colour mixing. On the other hand, observers from a young age may develop a useful internal model of subtractive colour mixing processes as they experiment with inks and paints. The purpose of this work is to determine whether it is indeed the case that observers possess more useful internal models for subtractive colour mixing than for additive colour mixing. The work reported in this study describes only an assessment of subtractive colour mixing. Three experiments are described whereby expert and naïve observers select matches from a library of colours for individual samples or for imagined subtractive mixtures of paint samples. Qualitative and quantitative analyses are presented to measure the ability of observers to make predictions of subtractive mixing processes. When mixing the subtractive primaries (e.g. cyan with magenta) the performance of expert and naïve observers are the same but in general the expert performance far exceeds that of the naïve observer for other colours.

1. INTRODUCTION

This study is a preliminary investigation towards the design of effective colour spaces and colour tools to allow users to quickly and accurately select a given colour in a digital-display environment. We have found that some non-expert users find the RGB colour space to be non-intuitive and this has been confirmed formally elsewhere. The choice of colour space on various visual tasks has been shown to be an important factor. It has also been shown that experts show greater precision in colour-matching experiments than non-expert observers. It is possible that non-experts in particular find manipulation and selection in an RGB colour space to be difficult because they do not possess an appropriate internal model for additive colour mixing. On the other hand, observers from a young age may develop a useful internal model of subtractive colour mixing processes as they experiment with inks and paints. The non-expert, for example, would not be surprised to be informed that yellow and blue inks mixed together make green may find it hard to believe that red and green lights can be added together to make yellow. The purpose of this work is to determine whether it is indeed the case that observers possess more useful internal models for subtractive colour mixing than for additive colour mixing. The work reported in this study describes only an assessment of subtractive colour mixing (if accepted, it is expected that the final paper would also include a comparison with additive colour mixing).

The ability of observers to make predictions about subtractive colour mixing has been evaluated in this study. Although accuracy has been measured, greater emphasis has been placed upon the consistency of predictions by experts or naïve observers. The experimental paradigm chosen to investigate observers’ ability makes use of colour matching. No attempt has been made to distinguish between the performance of males and females since earlier work has indicated that differences between these two groups exist.

2. METHOD
In this study, a total of 12 observers (6 designated as expert and 6 designated as naïve) were asked to predict the colour that would result from a mixture of physical paint specimens. The expert observers were either academics or students in the fields of textile, fashion or graphic design in the School of Design at Leeds University. The naïve observers had no professional interest in colour. The observers were presented with pairs of painted samples (made from acrylic paint) and asked to select the colour that most closely matched their expectation of an equal (by weight) mixture of the two paints from a library of coloured samples. The library of colour samples was created using a HP8550 laser jet printer and were specified according to the samples of the Ned Graphics Printer Atlas.

In Part 1 of the study the observers were given a single paint sample and asked to locate the sample in the library that most closely matched that sample. Both sample and library were available to view at the same time. The purpose of this part of the study was to define the inherent error in the paradigm and was necessary given that the library and paint samples were not made from the same media and there was not always a perfect match in the library to each paint sample. Six samples were used in this part of the study.

In Part 2 of the study observers were given pairs of paint samples that represented two of the subtractive primaries (cyan, magenta, and yellow) and asked to record the closest sample in the library that would match the imagined mixture of the two samples. This part of the study was analysed separately from the third part of the study because it was thought that observers may have particular knowledge of the way in which the subtractive primaries mix together. There were three paired combinations of the three primaries.

In Part 3 of the study observers were given pairs of paint samples that represented non-primary colours (e.g. green, orange, etc). As in part 2, observers were asked to record the closest sample in the library that would match the imagined mixture of the two samples.

The CIE XYZ values (D65 illuminant; 1964 CIE standard observer) were measured for the selected colours using a Minolta CM2600 reflectance spectrophotometer. The variability between observers was quantified in terms of CIELAB colour-difference values from the average of each observer-set’s measurements. For each trail, the selections from each observer were plotted in a CIELAB a*-b* diagram and ellipses were fitted to the data so that the major and minor axes of the ellipse was equal to the standard deviations along the major and minor directions. The directions of the major and minor directions were determined using singular-value decomposition.

3. RESULTS

A crude representation of the results is shown in Figures 1-3. In Figure 1, the six samples that were matched in Part 1 are shown in the left-most column. The matches made by the observers are shown in columns 2-7.

![Figure 1: Representation of matches in Part 1. Each column shows the match made by an observer (experts in top half; naïves in bottom half) to the left-most colour.](image)

![Figure 2: Representation of matches in Part 2. Each column shows the match made by an observer (experts in top half; naïves in bottom half) to the imagined mixture of the colours in the two left-most columns. For comparison, the physical mixture of the two colours is shown in the third column.](image)
In Figure 2, a similar scheme is used to represent the results of Part 2. The two samples that were shown to the observers and imagined to be mixed are shown in columns 1 and 2. Column 3 shows the actual physical mixture of the two paints (this, of course, was not shown to the observers during the experiment). It can be seen that, although there is variation, it is clear the observers were able to do the task and from this we can infer that they have knowledge of how the subtractive primaries used in Part 2 behave in mixture. Indeed, some variation between observers would be expected since the observers were given a task for which there was no unique solution (two different yellow paints may look visually identical when applied as an opaque layer but then produce quite different results when mixed with the same blue paint). The accuracy of the observers is therefore not as relevant as the variation between their responses.

![Figure 2](image.png)

**Figure 2**: A similar scheme is used to represent the results of Part 2. The two samples that were shown to the observers and imagined to be mixed are shown in columns 1 and 2. Column 3 shows the actual physical mixture of the two paints (this, of course, was not shown to the observers during the experiment).

The variation of the observers’ responses is illustrated in Figure 2 for Part 1 of the study. There seems little evidence of any difference in performance of the expert and naïve observers in terms of the simple matching task. In Figure 3 the variation in responses for the three primary mixtures are illustrated.

In Figure 4 the variation of observer responses is far greater as would be expected. There is generally little difference in performance between the expert and naïve groups though it is noted that the consistency of the naïve group was slightly better for the mixture of cyan and magenta. The average colours produced by the two groups (indicated by the centre of the ellipses) are very similar.

Figures 5 and 6 show the performance of the observers in Part 3 of the study where mixtures of non-primary colours were considered. In Figure 5 the two colours that were presented to the observers are not shown but the physical mixture (which was not shown to the observers) is shown in the left-most column. There is markedly more variation between the observers’ responses in Figure 5 when compared with Figure 2. This informal observation is also evident in Figure 6 where the ellipses are much larger than in Figure 4 for the naïve observers. The major finding from Part 3 of the study is that the variation in responses for the naïve group is much greater than for the expert group when mixtures of non-primary colours were considered.

![Figure 3](image.png)

**Figure 3**: Ellipses show the variation in observer matches for the six samples in Part 1 of the study. The major and minor axes of the ellipses indicate the standard deviations in responses for expert (red lines) and naïve (blue lines) observers.
Table 1 shows a quantitative analysis of the study. For each individual sample (Part 1) and each pair of samples (Parts 2 and 3) the CIELAB colour difference was computed between each observer’s response and the average of either the expert or naïve observers’ responses. The average colour difference was then computed for each sample or pair of samples for expert and naïve observers separately.

**Figure 4:** Ellipses show the variation in observer matches for the three paired samples in Part 2 of the study. The major and minor axes of the ellipses indicate the standard deviations in responses for expert (red lines) and naïve (blue lines) observers.

Table 1 shows a quantitative analysis of the study. For each individual sample (Part 1) and each pair of samples (Parts 2 and 3) the CIELAB colour difference was computed between each observer’s response and the average of either the expert or naïve observers’ responses. The average colour difference was then computed for each sample or pair of samples for expert and naïve observers separately.

**Figure 5:** Representation of matches in Part 3. Each column shows the match made by an observer (experts in top half; naives in bottom half) to the left-most colour.

**Figure 6:** Ellipses show the variation in observer matches for the three paired samples in Part 3 of the study. The major and minor axes of the ellipses indicate the standard deviations in responses for expert (red lines) and naïve (blue lines) observers.
A summary of the results is shown in Table 1. They confirm that the performances of expert and naïve observers were very similar for both Part 1 and Part 2 of the study but that experts outperformed naïve observers for Part 3 (see also Figure 6).

Table 1: Mean CIELAB colour differences for Parts 1, 2 and 3 for both expert and naïve observers.

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<tr>
<td>Mean DE</td>
<td>5.11</td>
<td>17.91</td>
<td>13.30</td>
<td>4.51</td>
<td>17.85</td>
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<td>Min DE</td>
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<td>16.99</td>
<td>8.37</td>
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<td>13.34</td>
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<tr>
<td>Max DE</td>
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<td>18.64</td>
<td>15.84</td>
<td>6.40</td>
<td>20.46</td>
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4. CONCLUSIONS

Three experiments are described whereby expert and naïve observers select matches from a library of colours for individual samples or for imagined subtractive mixtures of paint samples. Qualitative and quantitative analyses demonstrate the ability of observers to make predictions of subtractive mixing processes. When mixing the subtractive primaries (e.g. cyan with magenta) the performance of expert and naïve observers were found to be the same but in general, for the other colours, the expert performance far exceeds that of the naïve observer.

References