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Vividness as a Colour Appearance Attribute

Helene B. Midtfjord, Phil Green, Peter Nussbaum; Norwegian University of Science and Technology; Gjovik, Norway

Abstract

It is desirable to communicate colour with intuitive terms which are understood not only by experts. Studies have showed that chroma, saturation and colourfulness are more difficult to understand for "ordinary people" than other colour terms. Vividness has recently it been proposed as a formal colour scale, and it is believed to be more intuitive than other colour science terms. In this work we investigate how people interpret vividness of colour samples and test current models by collecting visual data in a psychophysical experiment. 31 people were asked to judge the vividness of 53 NCS patches and 53 colour matches on display on a scale from 0 to 100. The majority of the variations in the vividness data is predicted by chroma, while the results indicate that lightness does not contribute in prediction of the observers' interpretation of vividness. Current models did not outperform chroma as a single predictor for the vividness data obtained in this experiment.

Introduction

Vivid is a term that has long been used, both in everyday language and also in the colour community. Recently it has been proposed as a formal colour scale attribute that adds a new dimension to the usual cartesian and polar coordinates. Berns proposed vividness together with depth as triangular coordinates with white, black and full colour as apices in the CIELAB colour space [1]. These dimensions correspond in a general way to the experience of mixing black and white with a primary colorant, where the chroma and lightness of the colour change simultaneously. Berns confirmed the existence of these simultaneous colour change in shadow series and pigment mixing. Vividness is assumed to be the colour scale from black to full colour, and is defined as an attribute of colour used to indicate the degree of departure of the colour from a neutral back colour. Berns model for vividness is given by the following equation:

$$\mathrm{V_B} = \sqrt{(L^*)^2+(a^*)^2+(b^*)^2} = \sqrt{(L^*)^2+(C^*_{ab})^2}, \qquad (1)$$

where L^*, a^*, and b^* are the CIELAB correlates for lightness, redness-greenness and yellowness-blueness, respectively, and C^*_{ab} is the CIELAB chroma.

Studies have showed that chroma, saturation and colourfulness are more difficult to understand for naive observers and have poorer consistency in visual assessments than the other two colour dimensions, lightness and hue [2][3]. In their work, Cho et al.[4] present a comprehensive study where 132 observers rated 120 NCS chips in terms of 15 different categorical scales. The aim of the study was to test whether any of the 15 terms would better reflect naive observer's view of the third dimension, and thus, can replace the conventional chroma, saturation and colourfulness. The four scales that showed the best correlation with the third dimension were *saturated*, *vividness-dull*, *distinct-indistinct* and *intense-weak*. Two vividness models have been based on the experimental data obtained by Cho et al. [4]. The following vividness model is proposed by Li et al. [5] as an extension to CAM16:

$$\mathrm{V_L} = 4.9+\sqrt{(\mathrm{J}-58)^2+(\mathrm{a_M})^2+(\mathrm{b_M})^2}, \qquad (2)$$

where J is the CAM16 colour coordinate for lightness, and $\mathrm{a_M}$ and $\mathrm{b_M}$ are the Cartesian representation of CAM16 colourfulness, given by $a_M = M\cos(h)$ and $b_M = M\sin(h)$, where M is the CAM16 correlate for colourfulness, and h is CAM16 hue angle. The other model which is based on the data in [4] is proposed by Cho et al. [6]:

$$\mathrm{V_C} = k_M + k_L\sqrt{(L^*-L^*_0)^2+k_A(a^*-a^*_0)^2+k_B(b^*-b^*_0)^2}, \quad (3)$$

where k_M, k_L, k_A, k_B, L^*_0, a^*_0 and b^*_0 were obtained by fitting their experimental data. The coefficients take on the following values for vividness: $k_M = -1.81$, $k_L = 0.07$, $k_A = 0.76$, $k_B = 0.38$, $L^*_0 = 61$, $a^*_0 = 2$ and $b^*_0 = 16$.

Method

A psychophysical experiment was conducted in which 31 observers evaluated the vividness of 106 colour samples. Our experiment was performed under the same conditions as in Cho et al. [4]. 53 Hard copy and 53 display samples were used to compare vividness across media. The observers were asked to perform a numerical scaling, from 0 to 100, where 0 denotes minimum vividness and 100 denotes maximum vividness, when vividness is defined by the four synonyms 'intensely coloured', 'bright', 'striking' and 'distinct'. It was alternated which sample set the observers evaluated first. In both cases, the colour samples were presented to the observer in a randomised order, and the observers were self-calibrated with three test colours in the beginning of the experiments.

Choice of Vividness Descriptors

The purpose of this type of colour appearance research is to investigate whether the common meaning of an adjective can be intuitively transferred from everyday use to a colour domain. Thus, the experiment assumes that the adjective in question is familiar and meaningful to the observer. Since this was not the case when Norwegian observers assessed vividness in our initial pilot study, we do not assume universal understanding of the vividness term for the current experiment, and decided to provide the ob-

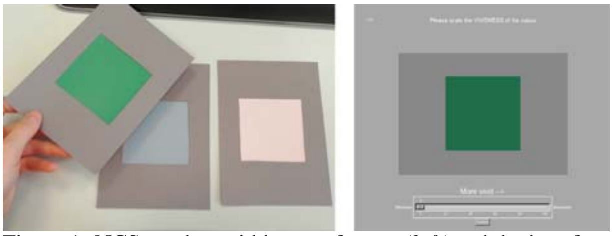


Figure 1: NCS patches within gray frames *(left)* and the interface for the display colours *(right)*.

servers with descriptors of vividness to ensure their understanding of the term.

Vividness descriptors were collected from English dictionaries. The vividness terms is used in three different contexts: the first is people, animals and objects; the second is physical or mental images, memories, imagination, written or oral accounts; the third is colour. Descriptors for vividness in a colour context are bright[7][8][9][10], strong [7][10], brilliant [11][9][12], intensely bright [11], intensely deep [7], glaring [11], strong [13], high in chroma [13], and pure [12]. Descriptors for vividness in other contexts are clear [11][7][8][9][10][13], lively [7][12][13], detailed [8][9][10], intense [9][13], vigorous [7][13], fresh [12][13], striking [12], distinct [12], powerful [8], sharp [13], vigorous [7] and animated [12].

It is desirable to chose descriptors that are transferable to a colour context and that are independent of each other. It is also desirable to avoid colour science terminology, such as chroma. Four descriptors were chosen: *intensely coloured*, *bright*, *striking* and *distinct*.

Samples

Cho et al. used 3×3 inch Natural Colour System (NCS) patches framed by a gray coloured board as colour samples. NCS patches of the same size was used in our experiment. A total of 53 standard colours from the NCS was used in our experiment. The sample set includes red, yellow, blue and green colours, with hues of R, Y, R90B, and G, respectively. The colours have chromaticness between 4 and 65 and blackness between 5 and 80. These colours were different from the experiment in [4]. A grey coloured board was attached as frames to the NCS patches. The viewing conditions in our experiment resemble the original experiment[4] as closely as possible. The hard copy samples were viewed in a JUST Normlicht Color Communicator viewing cabinet with D50 simulating illumination at 60 cm distance.

Colour matches for the NCS patches in the viewing cabinet was produced on display, and formed a second sample set. The size of these patches was also 3×3 inches, and had similar surround and background as the first sample set. Three hard copy samples and the interface for the display colour samples are showed in Figure 1.

The colour samples, their frame (background) and surround in the viewing cabinet and on the display were measured with a Minolta CS-2000 telespectroradiometer, under the viewing condition for the experiment. Tristimulus XYZ values for each colour sample were calculated using the CIE 1964 (10 degree observer) and D50 illuminant according to [14]. The luminance of the white

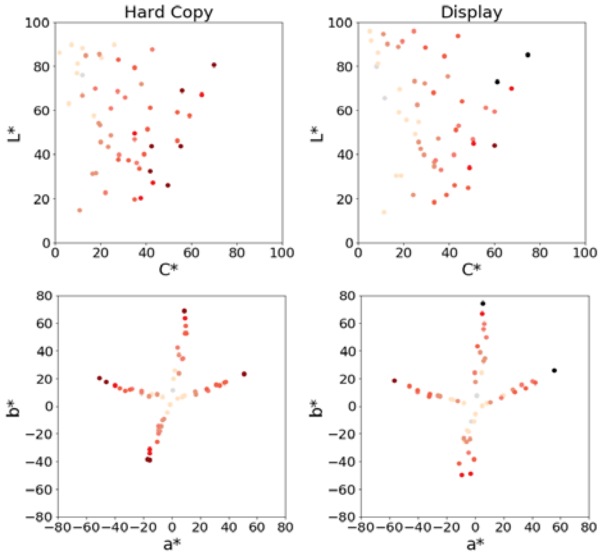


Figure 2: Colour measurements for hard copy and display colours in CIELAB colour space. The plots are colour coded according to averaged vividness scores from the experiment; higher chroma and darker colour indicate higher visual vividness. The colour coding are based on 10 bins of vividness scores.

point of a perfect diffuser in the viewing cabinet and the white point on the display were 315 cd/m^2 and 271 cd/m^2, respectively. Figure 2 show plots of the sample measurements, which are quite similar for the NCS samples and the display samples.

Observers

There were 31 participants in the experiment. Their ages were between 23 and 58, with an average age of 32 years. 42 % of the observers were female. There were 16 different nationalities, distributed as follows: 9 Norwegians, 4 Pakistani, 2 Italians, 2 Germans, 2 Iranians, 2 Ethiopians, and one from Switzerland, England, Romania, Macedonia, Kosovo, Greece, Georgia, Vietnam, China and Algeria. The observers are considered naive.

Experimental Results

Figure 3 shows box plots for the vividness scores obtained in the experiment for hard copy and display colour samples. The whiskers show that almost the entire scale was used for some samples, indicating disagreement among the observers. The line inside the box mark the median scores. Often, the median score is different from mean score (the middle of the box), which means that the distribution of scores is skewed rather than normally distributed. Despite the variations, it can be concluded that there are samples which have significantly different vividness scores.

The vividness scores from the 31 observers were averaged for each sample, and the results is regarded as the visual vividness of the samples. The colour encoding in Figure 2 illustrate the visual vividness according to the colour measurements. The figure gives some indication of relationships between our experimental data and the colour dimensions. Table 1 show the correlation between the vividness data and colour appearance attributes. The

Table 1: Correlation coefficients calculated between vividness data and colour appearance attributes in terms of CIELAB and CAM16

r	Hard copy samples	Display samples
CIELAB C^*_{ab}	0.85	0.83
CIELAB $L*$	-0.42	-0.04
CAM16 C	0.95	0.85
CAM16 M	0.95	0.85
CAM16 s	0.89	0.64
CAM16 J	-0.45	-0.06
CAM16 Q	-0.43	-0.05

Table 2: Inter- and intra-observer variability computed by standard deviation

SD	Hard copy samples	Display samples
Inter-observer	18	20
Intra-observer	8	7

relationship between the experimental data and the colour dimensions will be discussed further in the sections to come.

Table 1 show that colour appearance attributes has greater correlation with the vividness data for hard copy samples than for display samples. This might be explained by the observer variability.

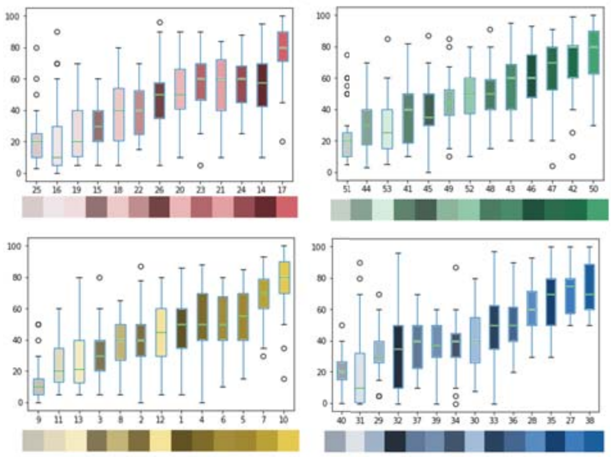
Observer Variability

Variability was computed as standard deviation (SD). Three random colour samples were repeated during the experiment, for the sake of computing the intra-observer SD which indicate the repeatability of the assessments. Table 2 show that there are quite some disagreement between the observers. It seems that our observers were slightly more in agreement in their assessment of the NCS patches compared to the display colours. There are some factors that could have affected the assessments for the two samples sets: firsly, the observers placed the NCS patches in the viewing cabinet themselves, so that these samples might have been viewed more freely than the display samples. Also, the observers would have their hand as a reference point when assessing the NCS patches, which was not the case for the colours on display. The intra-observer SD indicate that observers gave more consistent answers for display samples than for hard copy samples.

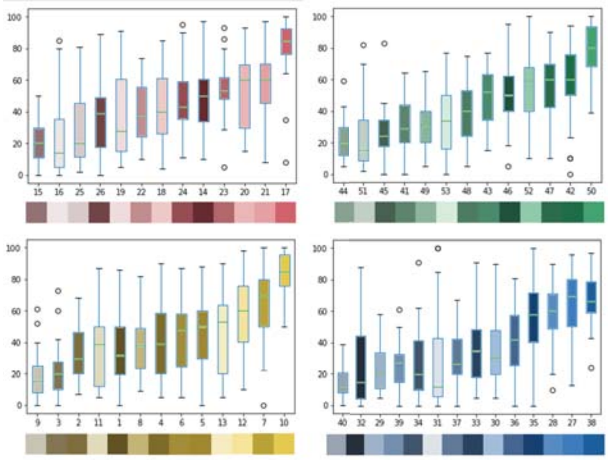
An interesting observation is that the inter-observer SD of the visual assessments (which is independent of chroma and hue angle) show a parabolic dependency of lightness. Figure 4 show the intra-observer SD plotted against lightness. The variability is higher at the ends of the lightness scale, which indicate less consensus when the colour samples have either very high or very low lightness.

Lightness Dependency

The visual data was compared with lightness of the colour samples, which revealed poor or no correlation between the two. According to the coefficient of determination, R^2, CIE L^* can explain 18 % of the variations in the visual data for hard copy sam-



(a) Hard copy colour samples.



(b) Display colour samples.

Figure 3: Visual vividness of each colour sample for red hue (top left), green (top right), yellow (bottom left) and blue (bottom right). The y-axis is vividness scores. On the x-axis underneath each box is the sample number and illustration of the corresponding colour. The boxes mark 50 % of the given vividness scores. The whiskers mark the whole range of vividness scores given. The line inside the box mark the median vividness score.

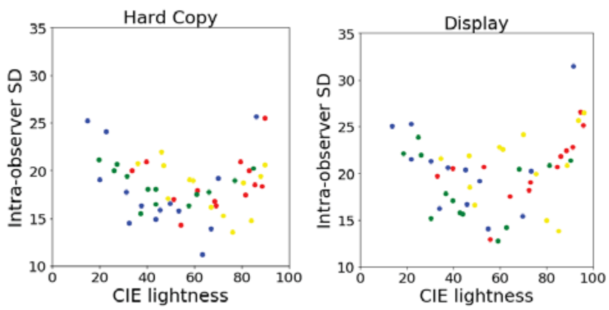


Figure 4: Inter-observer standard deviation (SD) plotted against CIE lightness.

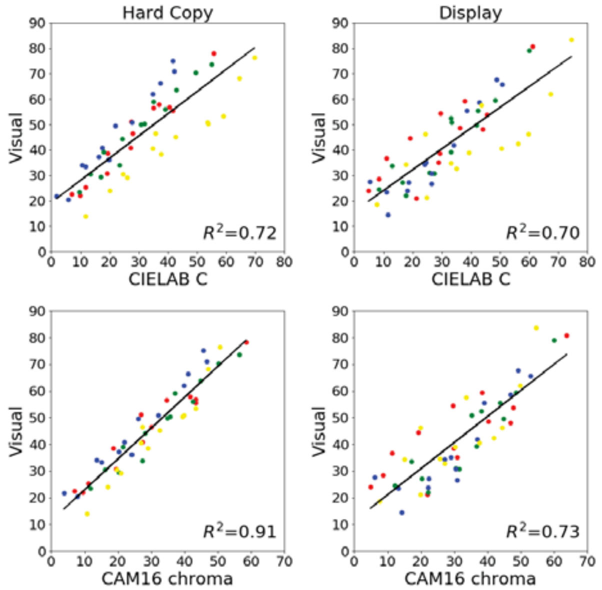


Figure 5: Averaged vividness scores from the experiment plotted against chroma.

ples, and nothing of the variations for display samples (R^2 is similar for CAM16 J). The correlation between lightness and visual data for hard copy samples is negative, which indicate that darker colours are perceived as being more vivid than lighter colours. This is a peculiar finding, since the observers were instructed that brightness is a criteria for vividness. When looking into the linear relationship between lightness and visual data for the colours separately, we find that $R^2 = 0.17$, $R^2 = 0.02$, $R^2 = 0.47$, $R^2 = 0.26$ for red, yellow, green and blue hard copy colours, respectively, and $R^2 = 0.0$, $R^2 = 0.15$, $R^2 = 0.19$, $R^2 = 0.09$ for red, yellow, green and blue display samples, respectively. Lightness predicts most of the variations in the visual data for green samples. When we look at the relationship between lightness and chroma for the green hard copy samples we see that there is a relationship with $R^2 = 0.42$ between the two. It is possible that lightness is not a causal factor for the visual data, but is a confounding predictor. When we look at a linear regression model that include both lightness and chroma for the green hard copy sample, the effect from lightness is not significant according to ANOVA, since its effect on vividness is already predicted by chroma.

Chroma Dependency

The visual data show high correlation with the chroma and colourfulness dimension. Figure 5 show the relationship between the visual results and CIELAB C^*_{ab} and CAM16 C, along with regression lines and coefficient of determination. We see that chroma predict the vividness data very well, and we see that CAM16 C has drastically improved the prediction of the vividness data for NCS samples compared to CIE C^*_{ab}, but not for the colours on display. The colour coding indicates a hue dependency for hard copy samples when vividness is predicted by CIELAB C^*_{ab}.

Hue Dependency

Hue angle predicts none of the variation in the vividness data on its own. However, Figure 5 show that predictions of the vividness data from C^*_{ab} is affected by hue angle. Since the gamut cusp resides in different lightness and chroma coordinates for the different hue angles, and the perception of vividness might be explained by one (or both) of them, it is reasonable to question if this point where chroma is perceived as its maximum can influence the prediction of vividness. An example can be seen in the visual data for the yellow and blue subset of the NCS samples. Both has a maximum vividness score of about 70. For yellow lightness and chroma are $L^* = 67$ and $C^* = 65$, while for the blue the same vividness is perceived at $L^* = 44$ and $C^* = 42$. I.e. the blue samples were much darker and less chromatic than the yellow samples and were still judged to be equally vivid.

Linear regression models for C^*_{ab} and combinations of lightness and chroma of the maximum chromatic colours in the NCS are tested. The best results is achieved when the lightness and chroma of the NCS cusp is multiplied, so that the fitted model becomes:

$$V = C^*_{ab} - \frac{2 \cdot C^*_{ab,cusp} L^*_{cusp}}{1000} + 23, \tag{4}$$

where where C^*_{cusp} and L^*_{cusp} are C^*_{ab} and L^* for the most chromatic NCS patch in the respective hue. The model predicts the visual data with $R^2 = 0.91$ and $R^2 = 0.73$, respectively. A model of the same form fitted to CAM16 coordinates does not improve the prediction of the visual results in comparison. In this model the cusp values does not have a significant contribution to the visual data for display samples.

A linear regression model where hue is included as a categorical factor together with chroma demonstrate better performance with $R^2 = 0.92$ and $R^2 = 0.76$ for hard copy and display colours, respectively (and all predictors are significant). The fitted model is:

$$V = \alpha \cdot C^*_{ab} + 14 \begin{cases} \alpha = 1.06 & \text{if} \quad h^*_{ab} \approx 20 \quad \text{(red)}, \\ \alpha = 0.73 & \text{if} \quad h^*_{ab} \approx 84 \quad \text{(yellow)}, \\ \alpha = 1.04 & \text{if} \quad h^*_{ab} \approx 164 \quad \text{(green)}, \\ \alpha = 1.13 & \text{if} \quad h^*_{ab} \approx 260 \quad \text{(blue)}, \end{cases} \tag{5}$$

where h^*_{ab} is the hue angle four the respective subsets. The coefficients that are produced by fitting out data to the model are very similar to the eccentricity factor, e_t, in CAM16[15], which is a function of hue that is included in colour appearance models to correct for the fact that perceived achromatic colours are not at the center of colours for low saturation [16][17]. The eccentricity factor is close to 0.8 for reds, 0.7 for yellows, 1 for greens and 1.2 for blues. So, it is showed that CAM16 embeds some of the hue dependency that is seen in our visual data, and explains why CAM16 C outperforms CIE C^*_{ab} in predicting our visual data.

Media Dependency

According to ANOVA, it can be concluded that the visual vividness scores are significantly different for hard copy colours and display colours for 30% of the samples. A hypothesis test is performed with a linear regression model for CAM16 chroma and media as a factor when all 106 samples are considered together. When fitted to the experimental data the equation becomes:

$$\mathrm{V} = C + 5.5 \cdot \beta + 9, \tag{6}$$

where C is CAM16 chroma and $\beta = 1$ for hard copy samples and $\beta = 0$ for display samples. The null hypothesis is that media of the colour samples does not effect the visual vividness, i.e. $H_0 : \beta = 0$. As we see in Equation 6, the visual data gives $\beta = 5.5$ with a p-value less than the 0.05 significance level (p=$1.7 \cdot 10^{-4}$). Thus, it can be concluded that the media is significant in this model, and that if vividness is predicted by CAM16 C, the vividness is 5.5 scores higher for NCS samples than for display samples. The model in Equation 6 accounts for 81 % of the variability of the combined data, while CAM16 C alone predicts 79 % of the variability in the combined data.

A similar test is performed based on a model with the same form as 4, and the fitted model is given by:

$$\mathrm{V} = \alpha \cdot C^*_{ab} + 5.7 \cdot \beta + 10 \begin{cases} \alpha = 1.08 & \text{if} \quad h^*_{ab} \approx 20, \\ \alpha = 0.74 & \text{if} \quad h^*_{ab} \approx 84, \\ \alpha = 1.06 & \text{if} \quad h^*_{ab} \approx 164, \\ \alpha = 1.15 & \text{if} \quad h^*_{ab} \approx 260, \end{cases} \tag{7}$$

where h^*_{ab} is the hue angle for the respective subset. In this model β has a p-value of $4.8 \cdot 10^{-5}$, and we can conclude that media has a significant effect when the visual data is predicted by hue dependent CIE chroma. When all 106 samples are considered together, the models in Equations 7 accounts for 83 % of the variability in the combined visual data, while the model in Equation 7 accounts for 81 % of the variability in the combined data.

Performance of Vividness Models

Figure 6 show the relationship between vividness models discussed in this paper. Table 3 summarised the models' performance. The coefficient of variation (CV) in the table express the percentage of disagreement between the experimental vividness and the predictions. The vividness model proposed by Li et al. and Cho et al. both predicts some of the variability of our vividness data. Because lightness is not a significant predictor for the vividness data obtained in this experiment, lightness will only produce noise in the predictions when included as a predictor in a model. This is why the model in Equation 2 and 3 are outperformed by chroma as single predictor for this particular data set. Berns' vividness model does not predict any of the variations in the data, which might be explained by the fact that the model in Equation 1 is not rooted in visual data, but as a new dimension in colour space, which seems coinciding with examples from everyday experiences.

The last two plots in Figure 6 show the relationship between the visual data and the fitted model in Equation 7. This model illustrate that the data set obtained in this experiment is explained well by the chroma dimension which is adjusted for hue. If we

Table 3: Performance of vividness models and CAM16 C by coefficient of determination and the coefficient of variation.

	Hard copy		Display	
	R^2	CV	R^2	CV
Li (Eq. 2)	0.63	22	0.47	27
Cho (Eq. 3)	0.52	105	0.45	106
Berns (Eq. 1)	0.01	74	0.09	85
Hue dependent C^*_{ab} (Eq. 7)	0.92	11	0.76	20
CAM16 C	0.91	37	0.73	32

compare with the relationship between CAM16 C in Figure 5, we see that most of the hue contribution is embedded in CAM16.

Conclusion

In this work we have asked 31 people to judge vividness of colour samples; 53 NCS patches and 53 colour matches on display. The observers were given four descriptors for vividness, *intensely coloured*, *bright*, *striking* and *distinct*, which were selected among definitions in English dictionaries. The study aimed to capture the observers' individual interpretation of what vividness means in a colour context, and the results may vary from other experiments. The observers represented 16 different nationalities and cultural backgrounds. They did not receive any colour science training prior to the experiment, and are considered to be naive.

The experiment shows higher agreement between the observers in their assessment of hard copy colours compared to assessment of display colours. Samples were judged to be about 5 vividness scores higher, on a scale from 0 to 100, for hard copy samples than for display samples. Lightness does not predict the visual data, but there is a strong correlation between the visual data and the chroma and colourfulness dimension. Vividness models from the literature were tested, but they did not outperform chroma as a single predictor for the vividness data obtained in this experiment. In this experiment, it seems that vividness is interpreted to describe the chroma and colourfulness dimension.

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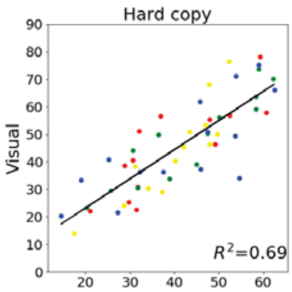
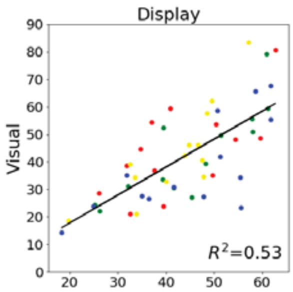
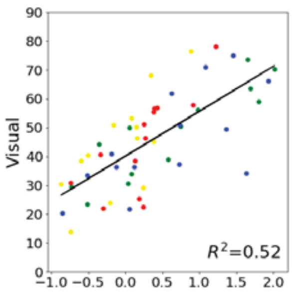


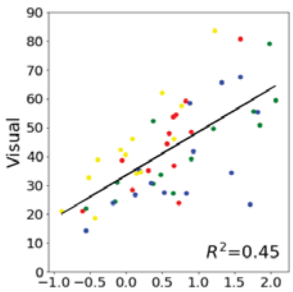
(a) Li vividness from Eq.2.



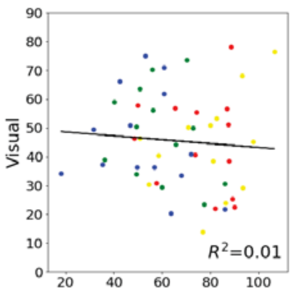
(e) Li vividness from Eq. 2.



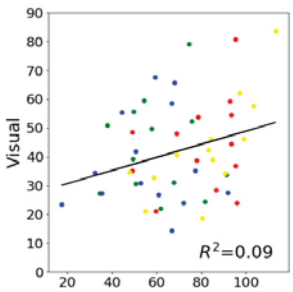
(b) Cho vividness from Eq. 3.



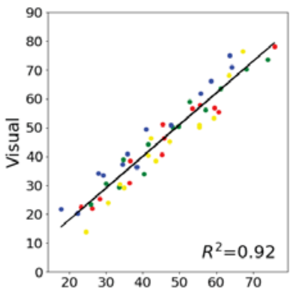
(f) Cho vividness from Eq. 3.



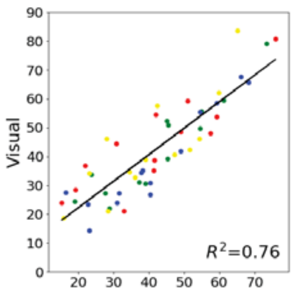
(c) Berns vividness from Eq. 1.



(g) Berns vividness from Eq. 1.



(d) Hue relative C^*_{ab} from Eq. 7.



(h) Hue relative C^*_{ab} from Eq. 7.

Figure 6: Relationship between visual data and vividness models for hard copy and display samples.

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