A Cross-Cultural Colour-Naming Study. Part III — A Colour-Naming Model

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Received 7 April 2000; accepted 25 August 2000

Abstract: A colour-naming model was developed to categorize volumes for each of the 11 basic names in CIELAB colour space. This was tested with three different sets of data for two languages (English and Mandarin), derived from extensive colour categorization experiments. The performance of the model in predicting colour names was satisfactory, with an average prediction error of 8.3%. © 2001 John Wiley & Sons, Inc. Col Res Appl, 26, 270–277, 2001

Key words: colour-naming model; basic colour names; CIELAB colour space

DEFINING THE REGIONS

Part I of this study gathered a large number of colour names from subjects speaking the English and Mandarin languages, and analyzed them to determine the culture and gender differences. It was confirmed that the 11 basic colour names found by Berlin and Kay[1] were the most widely used for both languages. Codability analysis was applied to determine their relative consistency of usage. In Part II of the study, colours were mapped to coordinates in the NCS colour space, and the centroid and spread of the volume occupied by each colour were determined from analysis of observer data.

This article develops a colour-naming model, based on the data gathered in Experiments I and II. Its validity is demonstrated with a third independent dataset, but it must be emphasized that it has been based on data derived from British and Chinese observers viewing surface colours under specified conditions of illumination, geometry, and surround. Its applicability to other viewing environments and observers having different cultural or linguistic backgrounds should, therefore, be treated with caution. Many languages name basic colour categories — including primary basic colour categories, such as red — more broadly than does Mandarin (cf. MacLaury:[2] Fig. 2.25, Colorado language).

The objective of the colour-naming model described below is to name a colour unambiguously whenever a colour specification is given in CIELAB values. The categorization of basic colours in CIELAB colour space was carried out using an optimizing method. Boundaries for each of the 11 basic names were determined to minimize prediction errors from the experimental data. Finally, all 11 colour volumes were further refined to leave no gap in CIELAB space. The naming model was thus established in four stages.

Stage 1: Boundaries for White, Gray, and Black

The colour volumes of achromatic colours, i.e., black, white and gray, are defined by a cylindrical shape, which is constrained by the lightness and chroma boundaries. This is illustrated in Fig. 1. Achromatic colours used here include those with no hue or very little hue attribute (hence, low chroma). The model assumes that these colours are hue-independent. In the real world, many chromatic colours having low C^* values are also considered as achromatic colours, i.e., near white, near gray, and near black colours as confirmed in the experiment of Part II. The level of lightness (L^*) decides whether the colour is designated black, gray, or white. Hence, both chroma and lightness are used to define the boundaries for three achromatic colours: white, gray, and black.

Stage 2: Boundaries for Pink and Brown

The regions corresponding to pink and brown have a 3-dimensional fan shape, because these colours exist only within certain ranges defined by lightness, chroma, and hue angle. An increase of chroma beyond some threshold turns pink to red, and brown to orange. Hence, these two colours

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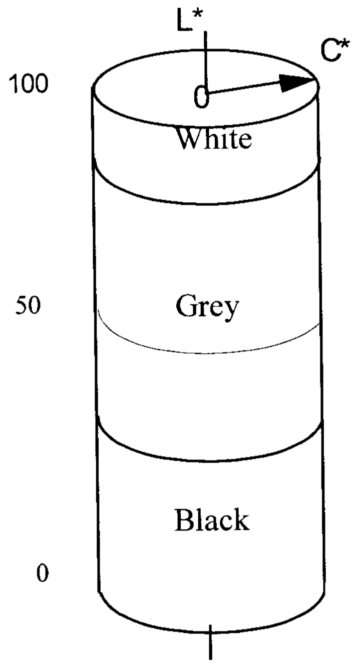

FIG. 1. Lightness boundaries for three achromatic basic names: White, Gray, and Black.

require the specification of all three boundaries in CIELAB space, viz. lightness, chroma, and hue angle as shown in Fig. 2.

Stage 3: Boundary for Yellow

Yellow colours occupy a region with a high level of lightness within certain hue limits, and they are not restricted by chroma. When lightness decreases, however, colours having the same chroma and hue angle change from yellow to green as shown in Fig. 3. This was an important finding of Experiments I and II.

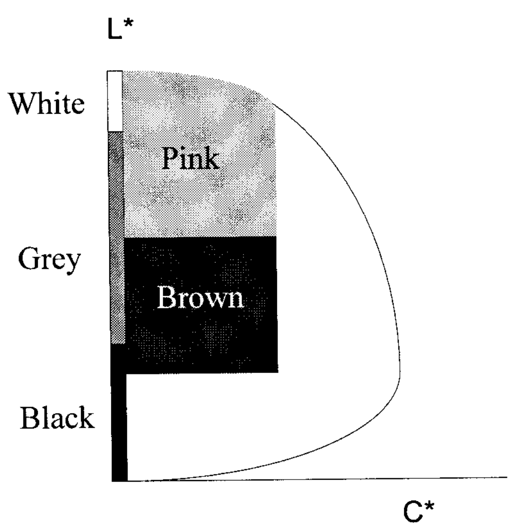

FIG. 2. Lightness and chroma boundaries for Brown and Pink basic names.

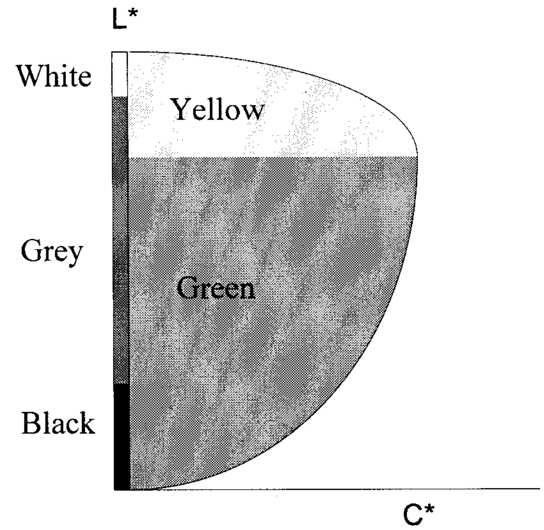

FIG. 3. Lightness and chroma boundaries for Yellow and Green basic names.

Stage 4: Boundaries for Red, Orange, Green, Blue, and Purple

After the specification of the achromatic, brown, pink, and yellow colour volumes, the remainder of colour space can be divided into five regions using hue angle, as shown in Fig. 4. These correspond to the five basic colours: red, orange, green, blue, and purple.

EXPERIMENTAL DATABASE

The 200 ISCC-NBS colours used as samples in Experiment I[3] are plotted on the CIELAB $C^*h°$ diagram as shown in Fig. 5. The colours were divided into five lightness ranges: $L^* \leq 30$, $30 < L^* \leq 40$, $40 < L^* \leq 60$, $60 < L^* \leq 80$, and $80 \leq L^*$. Although the number of ISCC-NBS colours used in Experiment I was much smaller than the number of NCS samples used in Experiment II,[4] they were quite evenly spaced in the CIELAB colour space. Figure 6 shows the 1526 NCS colours used in Experiment II plotted on the CIELAB $C^*h°$ diagram, with different lightness in five ranges: $L^* \leq 30$, $30 \leq L^* \leq 40$, $40 \leq L^* \leq 60$, $60 \leq L^* \leq 80$, and $80 \leq L^*$. This provided a comprehensive coverage of the CIELAB colour space.

In Fig. 7, the 1012 NCS colours chosen by the British

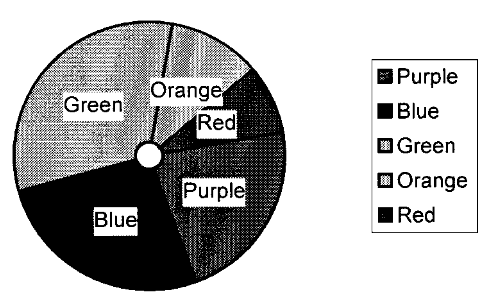

FIG. 4. Hue boundaries for Red, Orange, Green, Blue, and Purple basic names.

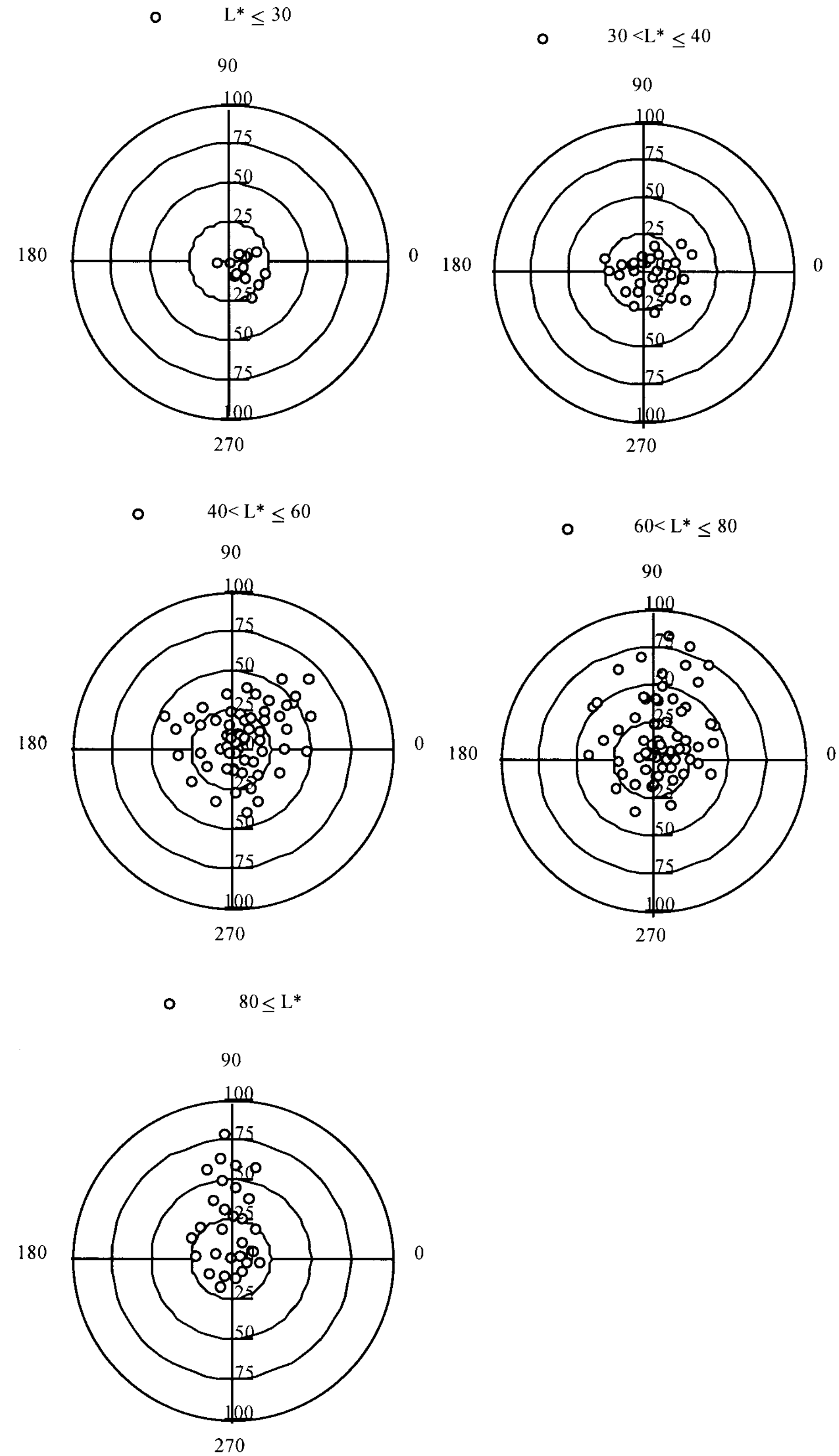

FIG. 5. 200 ISCC-NBS colours plotted on CIELAB $C^*h°$ diagram.

subjects are plotted on the CIELAB $C^*h°$ diagram. These colours are divided into one achromatic and eight chromatic basic colour categories and are drawn in nine diagrams. Figure 7 shows that the colours are scattered around the hue angle. However, it appears that there is some overlap between neighboring colour regions. Similar plots were also produced for the 200 colours used in Experiment I. It was found that although there were large differences between

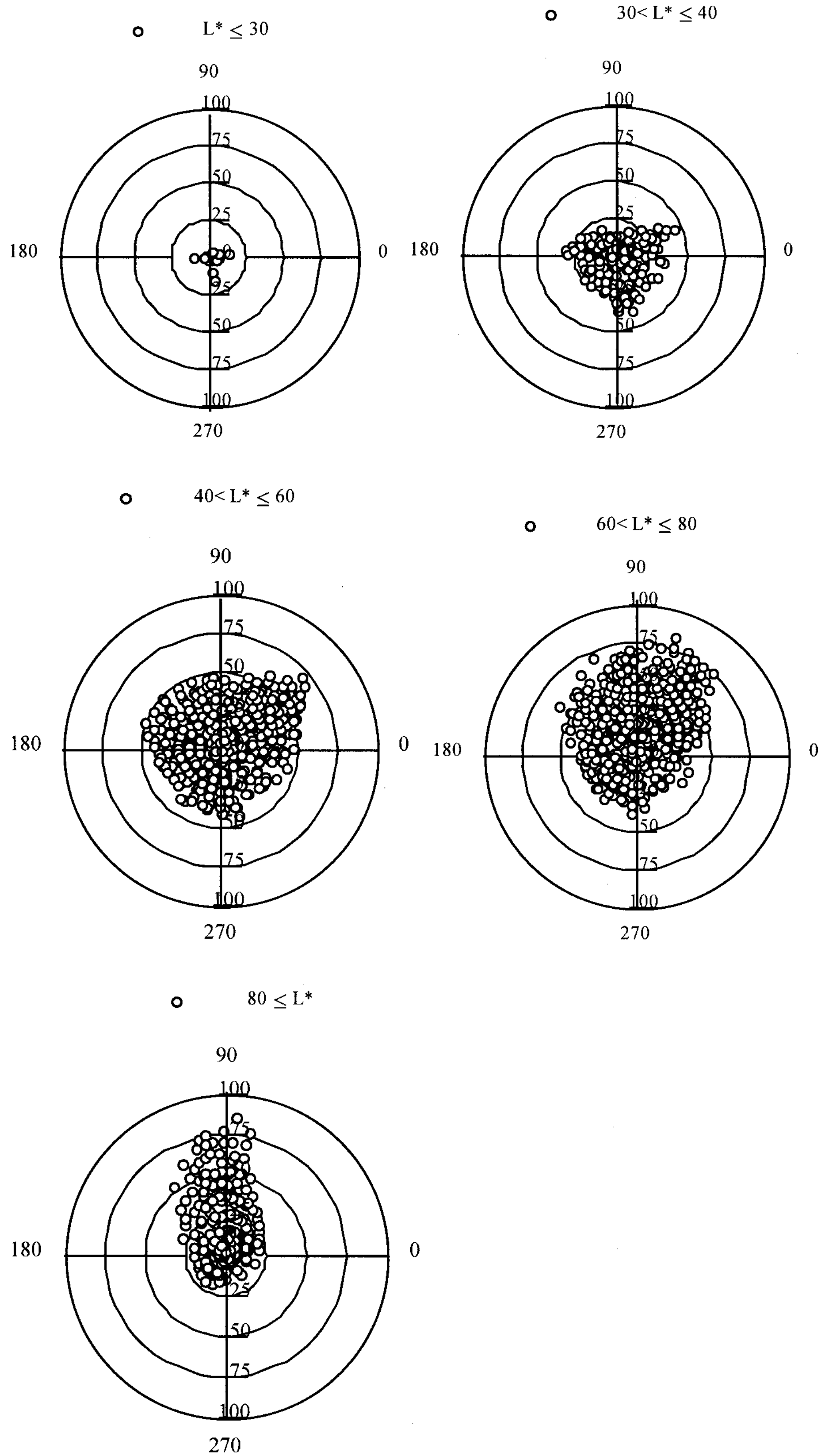

FIG. 6. 1526 NCS colours plotted on CIELAB *C**h° diagram.

the two sets of viewing conditions, the two ethnic groups and the differing methods of assessment, the scattering pattern of the colour areas for each basic name was very similar. Hence, it was decided to combine the results of Experiments I and II, including both English and Chinese colour names.

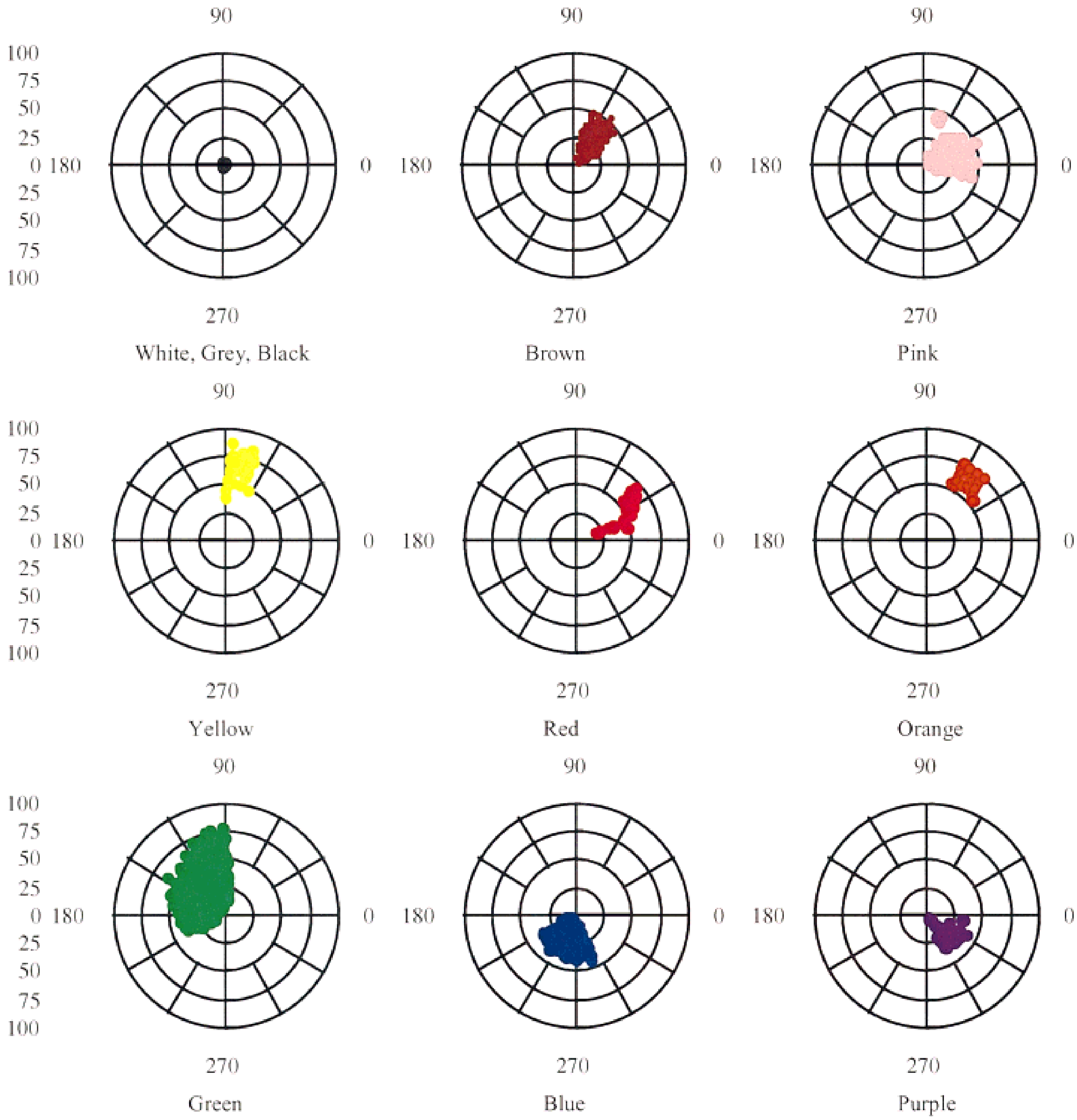

FIG. 7. 1012 NCS colours distributed in CIELAB $C^*h°$ space.

COMPUTING THE BOUNDARIES

The results from both Experiment I and Experiment II were used to derive the colour-naming model. Each colour that was named a basic colour by more than 50% of subjects in Experiment I was taken as a test colour. There were 133 and 101 ISCC-NBS colours for the Chinese and British groups, respectively. From the results of Experiment II, the colours selected in each of the 11 basic colour volumes were used (797 and 1012 NCS colours for the Chinese and British groups, respectively).

Test software was developed, with the boundaries of each basic colour defined in CIELAB colour space, i.e., by L^*, C^*, and h° values. The boundary values were iteratively adjusted to minimize the value of a measure, "wrong frequency" (WF), calculated as follows:

$$WF = K(WI_1 + WE_1) + \sum_{i=1}^{M} WIF_i + \sum_{j=1}^{N} WEF_j, \quad (1)$$

where WI_1 and WE_1 are the numbers of wrongly included and wrongly excluded samples, respectively, in Experiment I; WIF_i and WEF_j represent the frequencies of the wrongly included and wrongly excluded samples i and j, respectively, in Experiment II; M and N are the total numbers of wrongly included and wrongly excluded samples in Experiment II; and K is a constant used to give equal weighting to the samples in Experiments I and II.

The model was developed in four independent stages as described earlier:

Stage 1: Define the boundaries ($\pm L^*$ and $\pm C^*$) for the three achromatic basic colour names, i.e., white, gray, and black.

TABLE I. Computed boundaries for each basic colour.

Stage	Basic colours	L^*_{ab} +(≤)	L^*_{ab} −(>)	C^*_{ab} +(≤)	C^*_{ab} −(>)	h^0 (anti-clockwise) +(≤)	h^0 (anti-clockwise) −(>)
1	White	100.00	88.85	5.22	0.00		
	Gray	88.56	42.16	7.46	0.00		
	Black	36.31	0.00	1.74	0.00		
2	Brown	70.22	33.47	52.33	7.37	29.82	72.53
	Pink	92.11	49.42	49.86	4.74	−17.42	74.79
3	Yellow	90.78	71.72	—	—	65.13	99.42
4	Red	—	—	—	—	15.14	40.92
	Orange	—	—	—	—	40.21	65.98
	Green	—	—	—	—	88.49	201.99
	Blue	—	—	—	—	198.58	287.71
	Purple	—	—	—	—	295.50	353.85

Note: Symbol '—' indicates no specific constraint on the boundaries.

Stage 2: Define the boundaries (± *L**, ± *C** and ± h°) for pink and brown.

Stage 3: Define the boundaries (± *L** and ± h°) for yellow.

Stage 4: Define the boundaries (± h°) for red, orange, green, blue, and purple. Note that, although no explicit *L**, *C** limits are defined for red and orange, there is no ambiguity, because pink and brown have already been removed in Stage 2.

Table I shows the result of the computational procedure to determine the boundaries of the 11 basic colours, expressed in CIELAB coordinates. White has the smallest volume, whereas green occupies the largest volume (h° ranges from 88–202°). The colour volumes for brown and pink are intertwined in lightness, chroma, and hue angle.

REFINING THE BOUNDARIES

A detailed inspection of the optimized boundaries in Table I shows both overlaps and gaps in colour space, such as the gap between black and gray colours and the large overlap between brown and pink colours. For achromatic colours, the chroma values of gray are less than 7.46, and the lightness values are constrained between 42.16–88.56, whereas the lightness values of black are below 36.31. Thus, there appears to be a lightness gap between gray and black colours.

The physical colours within the gap and the colours predicted by the model were visually checked. From this assessment, a modified model was established with new boundaries as shown in Table II. In this model there is a one-to-one correspondence between colour names and colour coordinates, i.e., each colour name can be located in one well-defined region of colour space and each location in colour space is associated with a unique colour name.

In this simple model, no modifiers are defined. Further refinement would permit different subregions of the basic colours to be differentiated. For example, all dark desaturated (low chroma) colours with a lightness value less than 30 (except black), could have the modifier "DARK" added to the name.

MODEL PERFORMANCE

Three sets of experimental data were used to test the model. In general, the model accurately predicted these colours.

British Dataset

Out of the total of 1113 colour samples used in Experiments I and II, 138 were named as one of the 11 basic names

TABLE II. Refined boundaries for each basic colour.

Stage	Basic colours	L^*_{ab} +(≤)	L^*_{ab} −(>)	C^*_{ab} +(≤)	C^*_{ab} −(>)	h^0 (anti-clockwise) +(≤)	h^0 (anti-clockwise) −(>)
1	White	100	90	5	0	—	—
	Gray	90	40	5	0	—	—
	Black	40	0	5	0	—	—
2	Brown	60	29	44	5	25	80
	Pink	100	60	50	5	340	65
3	Yellow	100	71	—	—	65	100
4	Red	—	—	—	—	10	40
	Orange	—	—	—	—	40	66
	Green	—	—	—	—	66	196
	Blue	—	—	—	—	196	290
	Purple	—	—	—	—	290	10

Notes: 1. All colours except 'black' should have a modifier 'dark' added when $L^* < 30$.
2. Symbol '—' indicates no specific constraint on the boundaries.

TABLE III. Result of using the model for British group.

	WI (No.)	WE (No.)	WD (No.)	No. of basic colours
WHITE	0	1	1	2
BLACK	0	0	0	5
GRAY	0	2	2	10
RED	0	0	0	6
YELLOW	1	0	1	15
GREEN	0	0	0	34
BLUE	0	0	0	22
ORANGE	0	0	0	11
PURPLE	2	0	2	11
BROWN	1	0	1	7
PINK	1	2	3	15
Total	5	5	10	138

Note: WI (No.) indicates the number of colours wrongly included. WE (No.) indicates the number of colours wrongly excluded. WD (No.) indicated the number of 'wrong decision' colours. No. of Basic Colours is the total number of basic colours named by over 50% of subjects.

by more than 50% of the British subjects. In other words, these 138 colours had a high naming consensus for British subjects.

A colour was counted as "wrong decision" when the colour name predicted by the model disagreed with the experimental results. (Note that the term "wrong decision" is used here only to represent a measure of fit. It does not mean that names for samples beyond the colour limits are actually wrong, because basic colour names across different languages could have large areas of overlap.) Table III lists the number of wrong decisions produced by the model for each basic colour category, with a total of 10 errors over the 11 basic names. The model's performance was considered to be good, with both in-class and out-of-class prediction errors of 5/138 = 3.6%. There were no wrong decisions for black, red, green, blue, and orange colours, meaning that the model could successfully predict these colours and provide colour names accurately in all cases.

One white was predicted as PINK and wrongly included in the PINK category, because its C^* value (5.22) was slightly higher than the threshold (5.00). Two grays were predicted as YELLOW or BROWN because of their higher chroma values. Two pinks were predicted by the model as PURPLE because of their lower L^* values (53.45 and 49.42, both less than 60). These wrongly predicted examples are not considered serious, because in each case they are located close to the boundary between two basic colour volumes in CIELAB space, and both names were used in the colour name database.

Chinese Dataset

Table IV lists the results of predictions by the model for 170 colours (out of 133 ISCC-NBS colours and 797 NCS colours) named by the majority of Chinese subjects (>50%) from Experiments I and II. The model's performance for the Chinese subjects was not as good as for the British subjects, with both in-class and out-of-class prediction errors of 20/170 = 11.8%.

Some of the reasons for prediction errors were similar to those for the British dataset. The colour named WHITE (C^* value of 5.22) by subjects was again predicted as PINK. It was also wrongly included by some subjects in the PINK category. Two colours named GRAY by the subjects were predicted as YELLOW and BROWN due to slightly higher chroma values. One colour named PINK by subjects was predicted as PURPLE due to slightly lower lightness values. Only black was predicted correctly in all cases.

There were also other "wrong decision" colours for Chinese subjects for different reasons. Four yellows were predicted as GREEN due to the slightly lower L^* values (61.43, 62.33, 62.56, 69.17 — all of which are lower than the threshold 71.00). These were also included wrongly by some subjects in the GREEN category. Browns were difficult colours for Chinese subjects, and none of the colours was named BROWN consistently by the majority of Chinese subjects.

Lü's Chinese Dataset

The objective of this study was to devise a model that would provide an accurate name for any colour with a given CIELAB specification. Lü's[5] model used the Berlin and Kay set, for which the colour coordinates (expressed as CIE x,y,Y) were determined from the Munsell renotation table[6] under C/2° conditions. These data were transformed to CIELAB values.

Among 297 colours chosen and named by Lü's subjects, 65 colours were consistently named by more than half the group. Predictions for these colours were made using the model, with the results given in Table V. Overall the model performance was good, with both in-class and out-of-class prediction errors of 6/65 = 9.2%. There was no wrong decision for white, red, blue, purple, and pink. Two oranges

TABLE IV. Result of using the model for Chinese group.

	WI (No.)	WE (No.)	WD (No.)	No. of basic colours
WHITE	0	1	1	4
BLACK	0	0	0	8
GRAY	0	4	4	19
RED	0	3	3	12
YELLOW	2	4	6	20
GREEN	6	0	6	42
BLUE	1	1	2	24
ORANGE	0	5	5	20
PURPLE	4	1	5	13
BROWN	3	0	3	0
PINK	4	1	5	8
Total	20	20	40	170

Note: WI (No.) indicates the number of colours wrongly included. WE (No.) indicates the number of colours wrongly excluded. WD (No.) indicated the number of 'wrong decision' colours. No. of Basic Colours is the total number of basic colours named by over 50% of subjects.

were predicted as YELLOW due to slightly higher lightness (71.45 compared with threshold 71.00). Three browns were predicted as two GREEN and one ORANGE due to their slightly higher chroma, which was outside the BROWN boundary. A check against the data presented in Lü's article[5] showed that these wrongly predicted colours had also been included in other categories by subjects, although with lower frequency.

TABLE VI. Experimental viewing conditions.

Parameter	Experiment I	Experiment II
Paper surface	Glossy	Semi-matt
Background	Gray	White
Viewing field	10°	2°
Daylight	Natural[a]	Artificial
Surround	White	Gray[a]

[a] British subjects only.

SUMMARY

A colour-naming model was derived to categorize all colour coordinates in CIELAB colour space into 11 basic colour names. The model gave good predictions of results for the group of British subjects, and reasonable predictions of results for the Chinese subjects and an additional dataset from Lü.[5] In general, the results were considered to be satisfactory, with the average error over all three datasets being 31/373 = 8.3%.

The model was derived from colour names collected in two sets of experiments, which were conducted under a wide range of viewing conditions as shown in the Table VI.

It can be seen from Table VI that although the viewing conditions, observers, and experimental techniques in Experiments I and II were largely different, results from the two sets of data were highly consistent. The model based upon these datasets, therefore, should also be quite robust.

Three further areas should be studied. First, an experiment should be conducted with subjects of other races and other languages to refine the boundaries of the colour-naming model. Second, the boundaries of modifiers in each basic colour volume should be derived, to make the model more complete and more precise. Finally, new results should be produced for naming CRT colours, which are frequently seen against dim or dark surrounds, unlike the surface colours seen against lighter surrounds.

TABLE V. Result of using the model for Lü data.

	WI (No.)	WE (No.)	WD (No.)	No. of basic colours
WHITE	0	0	0	1
BLACK	1	0	1	2
GRAY	0	1	1	5
RED	0	0	0	5
YELLOW	2	0	2	3
GREEN	2	0	2	11
BLUE	0	0	0	9
ORANGE	1	2	3	4
PURPLE	0	0	0	13
BROWN	0	3	3	5
PINK	0	0	0	7
Total	6	6	12	65

Note: WI (No.) indicates the number of colours wrongly included. WE (No.) indicates the number of colours wrongly excluded. WD (No.) indicates the number of 'wrong decision' colours. No. of Basic Colours is the total number of basic colours named by over 50% of subjects.

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