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Psychophysical Measurements to Model Intercolor Regions of Color-Naming Space

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Abstract. *In this paper, we present a fuzzy-set of parametric functions, which segment the CEILAB space into 11 regions, which correspond to the group of common universal categories present in all evolved languages as identified by anthropologists and linguists. The set of functions is intended to model a color-name assignment task by humans and differs from other models in its emphasis on the intercolor boundary regions, which were explicitly measured by means of a psychophysics experiment. In our particular implementation, the CIELAB space was segmented into 11 color categories using a triple-sigmoid function as the fuzzy-sets basis, whose parameters are included in this paper. The model's parameters were adjusted according to the psychophysical results of a yes/no discrimination paradigm where observers had to choose (English) names for isoluminant colors belonging to regions in between neighboring categories. These colors were presented on a calibrated CRT monitor (14-bit × 3 precision). The experimental results show that intercolor boundary regions are much less defined than expected, and color samples other than those near the most representatives are needed to define the position and shape of boundaries between categories.*
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INTRODUCTION

One of the goals of image recognition and labeling algorithms is to provide a lexical description of the contents of an image. To do this, the algorithm should be able to identify objects and objects' properties in the same way humans do. In this context, it is important to remind ourselves that the (much smaller) problem of assigning a given name to each particular color in an image has not yet been solved. Far from it, there is still a lack of understanding of the link between low-level color features and the high-level semantics that humans use to name these colors (the so-called semantic gap).

Much of what we understand today about perceived color categories and language comes from Berlin and Kay's[1] large survey of languages. Their main findings pointed to the existence of 11 basic terms (categories) common to the most evolved languages. Since then, many workers have explored the relationships between perceived colors and language.[2–7] Most of these works have confirmed the existence of the 11 basic terms and have located the best representatives (also called *focal colors*) and in some cases estimated the boundaries of each basic color on different color spaces.

There have been some recent computational models,[8–11] which automate the color-naming task, incorporating results from previous psychophysical experiments. However, in most cases, the experimental data collected are near the so-called focal colors or colors that are the most representative of a given color name. One arguable weakness of this approach is that it relies on subjective membership values given to color samples by observers using an arbitrary rating scale. Moreover, these ratings are likely to be more accurate near the focal colors and less accurate near the color boundaries, i.e., the positions of the boundary lines may not be accurately defined, and the same is true for the slopes of the membership functions. This leaves a large amount of uncertainty when modeling the regions of color space that are near the color-name boundaries, which are usually just interpolated, assuming that the boundaries are equidistant from the corresponding focal colors. A separate issue concerns the sharpness of the transition between a color name and the next, which varies for the different color boundaries and is usually estimated from insufficient data.

Our particular solution to these problems is to redefine the boundary regions by means of a parametric model, which adjusts its frontiers (both position and transition steepnesses) according to psychophysical data collected in conflictive regions of the color space. One very convenient model for this purpose was proposed by Benavente et al.,[10] and our psychophysical data were collected with this model in mind by means of an experiment designed so that subjects have a very limited choice of responses (see below).

A PARAMETRIC MODEL TO REPRESENT COLOR BOUNDARY TRANSITIONS

The computational model proposed in 2008 by Benavente et al.[10] is a good candidate for adapting the color-name boundaries to a new set of psychophysical results. It considers Berlin and Kay's 11 basic colors and uses parametric fuzzy membership functions (three-dimensional regions, which define the certainty of a certain value—color—to be named with its corresponding color name) based on a combination of sigmoids with an elliptical center. The main advantage of

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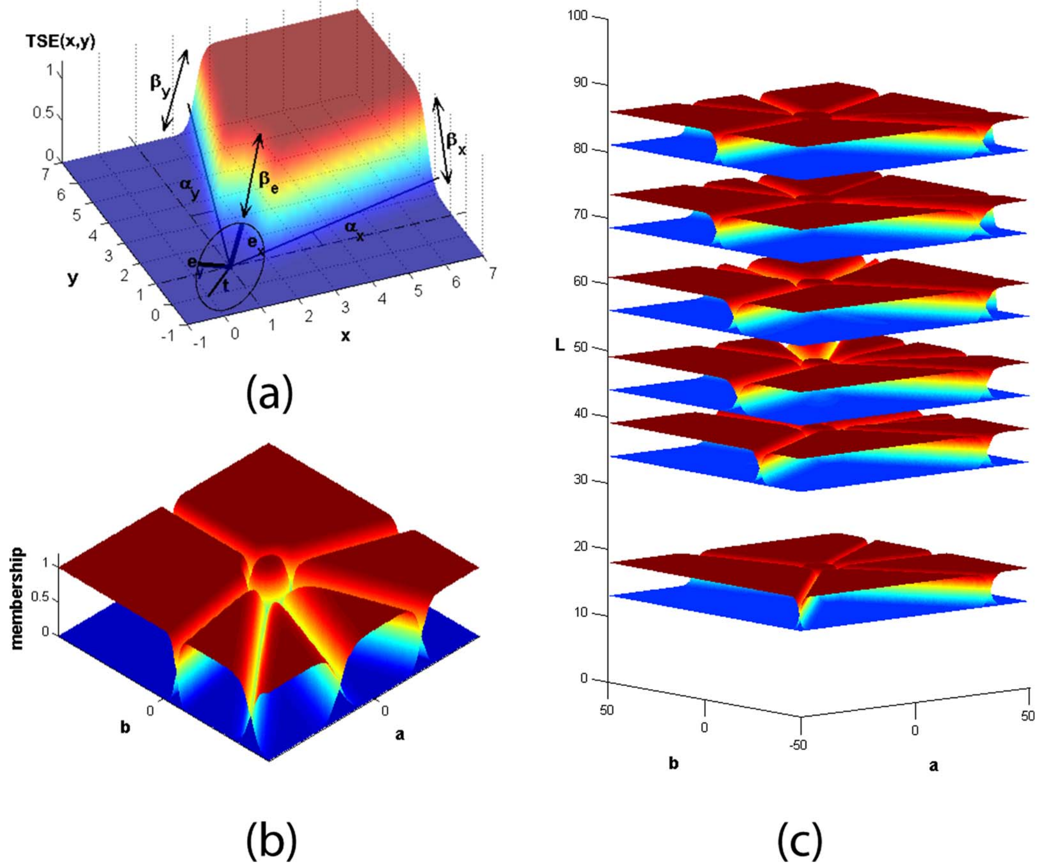

Figure 1. Fuzzy membership regions proposed by Benavente *et al.* to segment the color space, based on a product of sigmoids and an elliptical center. Panel (a) shows an individual TSE function, panel (b) shows the combination of different TSEs to obtain the color space segmentation for a given value of *L*, and panel (c) shows the six different levels of *L* as defined by the model.

this model is that it contains parameters, which can be adjusted to modify the shape of its regions and does a reasonable job of fitting to previous psychophysical data.[1–4] Panel (a) of Figure 1 shows the characteristic sigmoids used as membership functions for this model.

The shape of the membership functions is determined by the following relationship:

$$\mathrm{TSE}(\mathbf{p};\theta) = \mathrm{DS}(\mathbf{p};\mathbf{t},\theta_{\mathrm{DS}}) \cdot \mathrm{ES}(\mathbf{p};\mathbf{t},\theta_{\mathrm{ES}}), \tag{1}$$

where TSE is the acronym for *triple-sigmoid* with *elliptical* center (the product of all functions), ES represents the *elliptical-sigmoid* function (which models the central achromatic region)

$$\mathrm{ES}(\mathbf{p};\mathbf{t},\theta_{\mathrm{ES}}) = \frac{1}{1+\exp\left[-\beta_e\left(\left(\dfrac{\mathbf{u}_1 R_\phi T_t \mathbf{p}}{e_x}\right)^2 + \left(\dfrac{\mathbf{u}_2 R_\phi T_t \mathbf{p}}{e_y}\right)^2 - 1\right)\right]} \tag{2}$$

and DS (*double-sigmoidal* function) is the product of the functions S_1 and S_2 (sigmoidal functions oriented with respect to x and y, respectively)

$$\mathrm{DS}(\mathbf{p};\mathbf{t},\theta_{\mathrm{DS}}) = S_1(\mathbf{p};\mathbf{t},\alpha_y,\beta_y) \cdot S_2(\mathbf{p};\mathbf{t},\alpha_x,\beta_x), \tag{3}$$

$$S_i(\mathbf{p};\mathbf{t},\alpha,\beta) = \frac{1}{1+e^{-\beta \mathbf{u}_i R_\alpha T_t \mathbf{p}}}, \quad i = 1,2. \tag{4}$$

This model divides the CIELAB color space in six levels along the *L*-axis, and all the colors inside each level are modeled by a set of TSE functions. An example of how different membership functions combine to divide one level of the CIELAB color space is shown in panel (b) of Fig. 1. In panel (c) the six planes with the TSE functions are shown in the center of each level.

Table I shows a list of the parameters that best fitted the model defined above to fuzzy data provided by Seaborn et al.,[8] which were obtained from Sturges and Whitfield consensus areas (regions of no confusion). For more details see Benavente et al.[10]

PSYCHOPHYSICAL METHODS TO EVALUATE COLOR BOUNDARY TRANSITIONS

With the aim of providing the model with data to better adjust its color transitions, we designed a psychophysical experiment where subjects had to name color patches located

Table I. List of parameters that define the fuzzy membership regions proposed by Benavente *et al.*[10] for all six luminance planes.

Achromatic axis

Black-gray boundary $t_b = 28,28$, $\beta_b = -0,71$

Gray-white boundary $t_w = 79,65$, $\beta_w = -0,31$

Luminance plane 1

$t_a = 0,42$, $e_a = 5,89$, $\beta_e = 9,84$

$t_b = 0,25$, $e_b = 7,47$, $\phi = 2,32$

	α_a	α_b	β_a	β_b
Red	−2.24	−56.55	0.90	1.72
Brown	33.45	14.56	1.72	0.84
Green	104.56	134.59	0.84	1.95
Blue	224.59	−147.15	1.95	1.01
Purple	−57.15	−92.24	1.01	0.90

Luminance plane 2

$t_a = 0,23$, $e_a = 6,46$, $\beta_e = 6,03$

$t_b = 0,66$, $e_b = 7,87$, $\phi = 17,59$

	α_a	α_b	β_a	β_b
Red	2.21	−48.81	0.52	5.00
Brown	41.19	6.87	5.00	0.69
Green	96.87	120.46	0.69	0.96
Blue	210.46	−148.48	0.96	0.92
Purple	−58.48	−105.72	0.92	1.10
Pink	−15.72	−87.79	1.10	0.52

Luminance plane 3

$t_a = -0,12$, $e_a = 5,38$, $\beta_e = 6,81$

$t_b = 0,52$, $e_b = 6,98$, $\phi = 19,58$

	α_a	α_b	β_a	β_b
Red	13.57	−45.55	1.00	0.57
Orange	44.45	−28.76	0.57	0.52
Brown	61.24	6.65	0.52	0.84
Green	96.65	109.38	0.84	0.60
Blue	199.38	−148.24	0.60	0.80
Purple	−58.24	−112.63	0.80	0.62
Pink	−22.63	−76.43	0.62	1.00

Luminance plane 4

$t_a = -0,47$, $e_a = 5,99$, $\beta_e = 7,76$

$t_b = 1,02$, $e_b = 7,51$, $\phi = 23,92$

	α_a	α_b	β_a	β_b
Red	26.7	−56.88	0.91	0.76
Orange	33.12	−9.90	0.76	0.48
Yellow	80.10	5.63	0.48	0.73
Green	95.63	108.14	0.73	0.64
Blue	198.14	−148.59	0.64	0.76
Purple	−58.59	−123.68	0.76	5.00
Pink	−33.68	−63.30	5.00	0.91

Luminance plane 5

$t_a = -0,57$, $e_a = 5,37$, $\beta_e = 100,00$

$t_b = 1,16$, $e_b = 6,90$, $\phi = 24,75$

	α_a	α_b	β_a	β_b
Orange	25.75	−15.85	2.00	0.84
Yellow	74.15	12.27	0.84	0.86
Green	102.27	98.57	0.86	0.74
Blue	188.57	−150.83	0.74	0.47
Purple	−60.83	−122.55	0.47	1.74
Pink	−32.55	−64.25	1.74	2.00

Luminance plane 6

$t_a = -1,26$, $e_a = 6,04$, $\beta_e = 100,00$

$t_b = -1,81$, $e_b = 7,39$, $\phi = -1,19$

	α_a	α_b	β_a	β_b
Orange	25.74	−17.56	1.03	0.79
Yellow	72.44	16.24	0.79	0.96
Green	106.24	100.05	0.96	0.90
Blue	190.05	−149.43	0.90	0.60
Purple	−59.43	−122.37	0.60	1.93
Pink	−32.37	−64.26	1.93	1.03

in regions far away from the most representative colors (focal colors). These experimental colors were chosen to lie along a line (in CIELAB space) crossing the border between two color names according to the original Benavente et al.[10] model. The two initial colors (or reference colors) had the same luminance ("L" value) and were chosen to be sufficiently apart so that their names were not confused. There were 37 color pairs in three L planes in total ($L=36$, $L=58$, and $L=81$). Achromatic boundaries (those around the "achromatic center") were not explored here. Given the particular characteristics of these frontiers (e.g., background color and adaptation states influence on the results, the appearance of contact points among three color regions, etc.) they will be explored in a future experiment. Figure 2 shows the arrangements of these initial colors in CIELAB space. The solid lines represent the transitions going from one color name to its neighbor along which experimental colors were chosen.

In a given experimental trial, subjects were presented with the calibrated square color patches at the center of a CRT monitor (Viewsonic pf227f) using Cambridge Research Systems Bits++ video processor capable of displaying colors

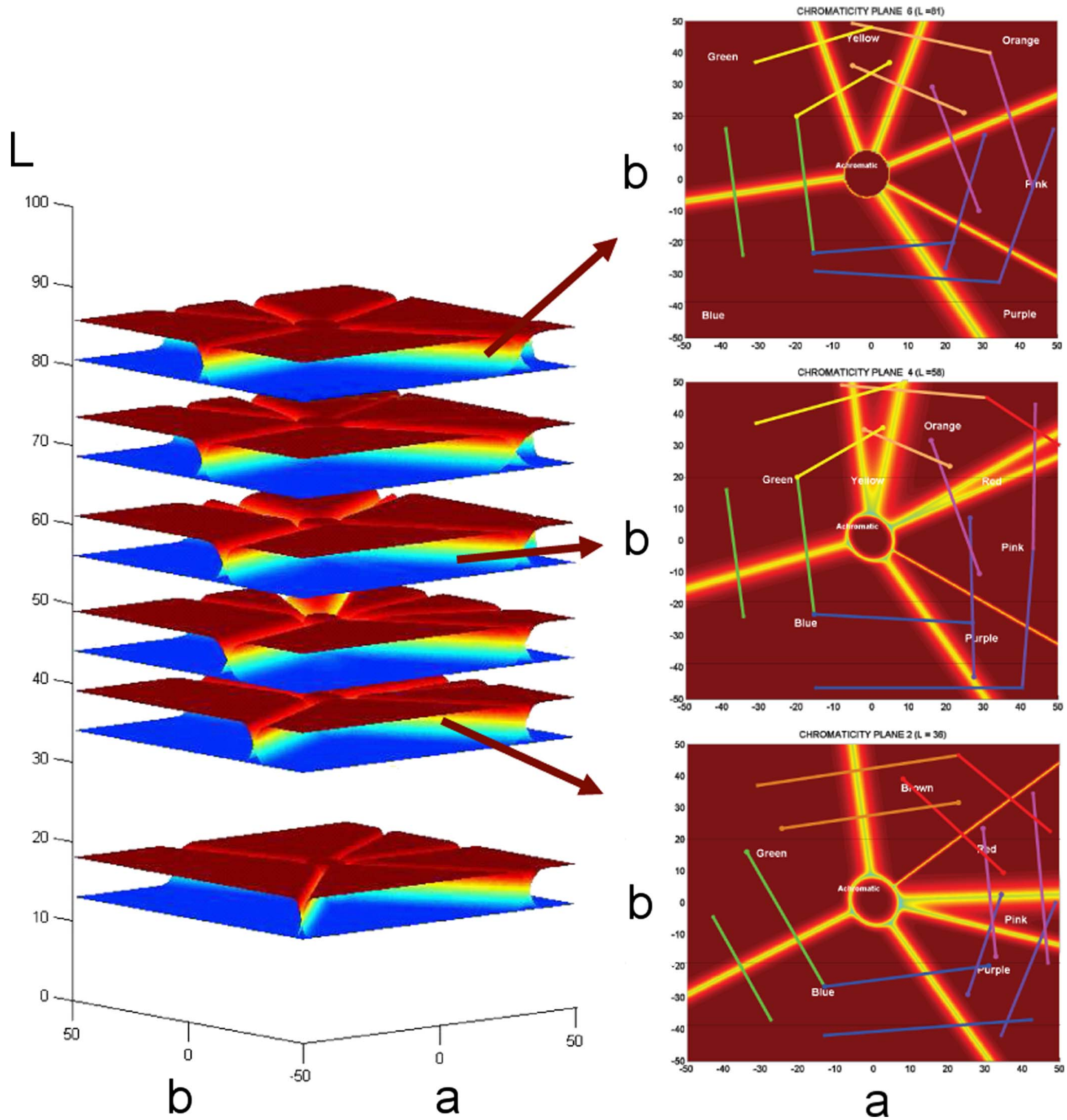

Figure 2. Disposition of the initial colors in CIELAB space. They were selected to lie across the boundaries of the color-name regions of Benavente *et al.*[10]

with 14-bit precision. The patches subtended 5.2° to the observers, the viewing distance was 166 cm, and the presentation time was 500 ms. The background to the color sample was black, but to give observers a luminance reference, there was a white frame 23 mm wide at the borders of the screen (D65, Lum=124.83 cd/m^2). After each presentation there was a gray mask for at least 1 s. The short presentation times were chosen to minimize possible color afterimages (caused by fatigued cells in the retina) or any other adaptation effects.

There were ten naive observers (all native English speakers) and two experienced observers (native Spanish speakers with a good level of spoken English). All of them were tested with the Farnsworth D-15 test to guarantee normal color vision. After each presentation, observers were asked to select the name that best described the color that they had just seen among two words appearing on-screen after the presentation (yes/no paradigm). The algorithm selected the (intermediate) colors to be presented next following a QUEST (Ref. 12) protocol (number of trials=40). Each color pair

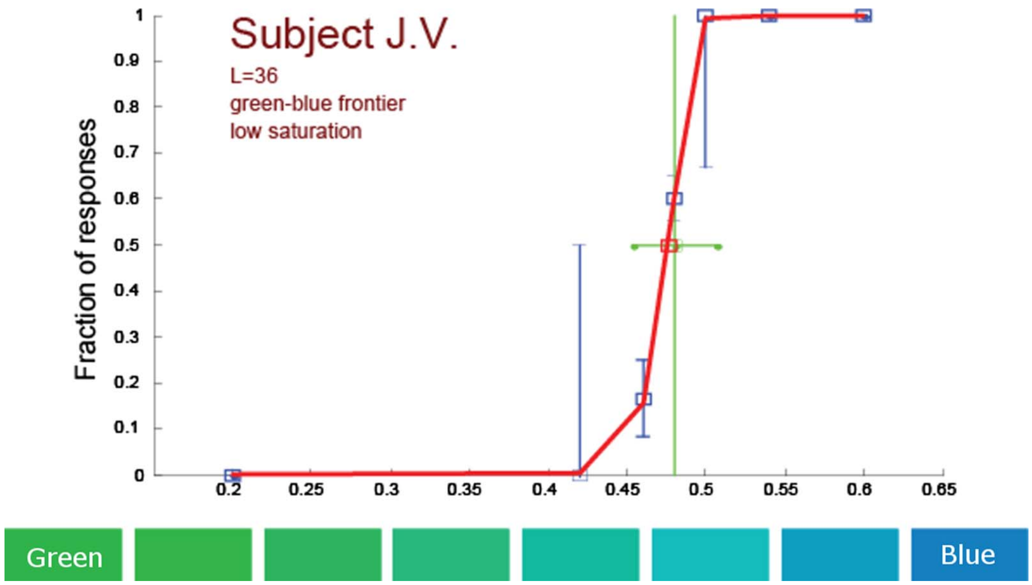

Figure 3. Exemplary result from a single experiment (for subject J.V.) involving the green-blue color boundary ($L=36$, low saturation color pair). The solid line shows the psychometric function, and the cross represents QUEST's mean threshold estimate.

was repeated three times, and 50% thresholds were determined using the QUEST's mean threshold estimate.[13,14]

RESULTS

Figure 3 shows an exemplary set of results, where the x-axis represents the color transition along the line crossing the low saturation blue-green color-name boundary. Each empty box represents the average of several presentations (color patches) in a given section of the continuous line. In this example, an x value of 0 equals "green" (one of the extremes of the low saturation green-blue line in the previous figure) and 1 equals "blue" (the other extreme). A higher value of the y-axis means that colors were labeled as blue in most presentations, and a low value means that the color was labeled as green in most presentations. The threshold lies where colors were equally labeled green or blue by subjects (50% of responses).

Figure 4 shows a summary of the results for all 12 subjects corresponding to the intermediate ($L=58$) plane. The radial pseudocolored lines of the central figure represent the color-name boundaries determined by Benavente et al.[10] Notice that the size of the "red" region is relatively small. This is because the Benavente et al. model was based on fitting psychophysical data produced with physical samples, which have a restricted color range because of the limitations in reproducing some colors with pigments (as noticed by Boynton[15]). Thresholds across color boundaries were measured (three times for each subject), and the regions where these thresholds fall are highlighted as bars. Gray bars represent the regions where the majority of the thresholds occurred for all subjects (the length of the bar is equal to the standard deviation of the distribution of thresholds). Black bars represent the position of secondary peaks in bimodal distributions, signaling the presence of another possible threshold. We did not find any significant difference between the majority of speakers of English as a first language and the two speakers of English as a second language (as reported elsewhere[16]). Fig. 4 also shows the histogram distribution of six exemplary boundary zones. In these histograms, the distance between each pair of colors was divided in ten "bins." The appearance of secondary peaks seems to indicate that in some cases perhaps extra color categories (apart from the initial 11) may be needed to account for the large variability of the data. For example, in all cases the boundary between green and blue presents a secondary peak, which may indicate the presence of an intermediate "turquoise" color area. Other frontiers seem to be more or less unchanged.

The results of the experiment were used to readjust the parameters of the color-naming model. On the three levels ($L=36$, $L=58$, $L=81$) used in the experiment, α parameters (which control the location of the boundaries) were modified to place the boundary between each pair of neighboring colors at the angle corresponding to the highest peak of the distribution of thresholds from the experiment. On the other hand, β parameters (which control the slope of the membership transition), were readjusted according to the standard deviation of the calculated thresholds. Parameters of the intermediate levels, for which there are no experimental data, were interpolated from the measured values. In Table II we present the new set of parameters for the color-naming model obtained after the readjustment process.

Figure 5 shows the new set of color-name boundaries, accounting for the new data (intercolor regions have been redrawn). The enlarged "uncertainty regions" around the color boundaries account for the fact that there were large variations in the position of the threshold across subjects and in some cases for the same subject. The black dashed lines on the last panel of Fig. 5(b) were added to draw attention to the emergence of intermediate areas between

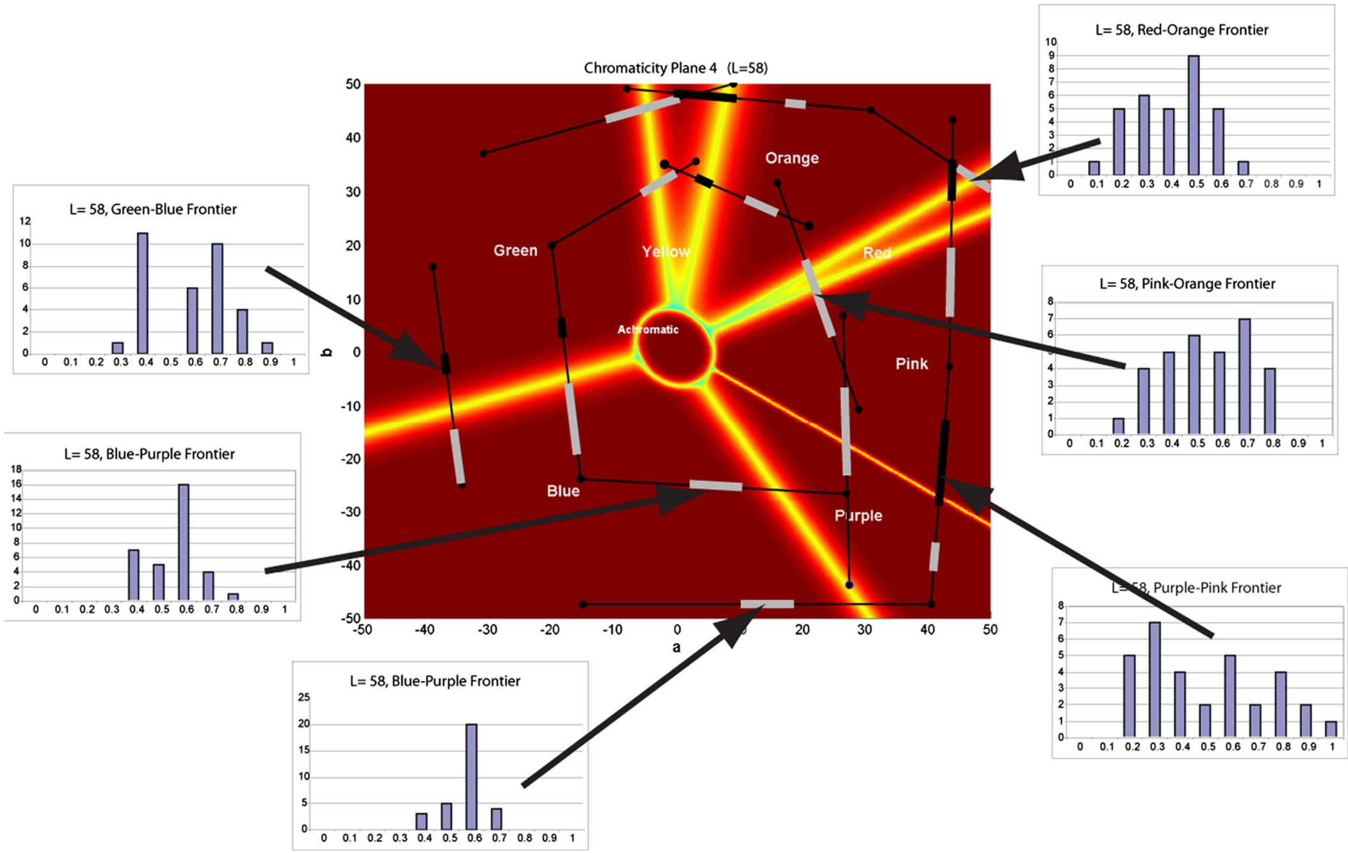

Figure 4. Experimental results for plane $L=58$. The hot spots (pseudocolored radial lines in the central plot) represent the color-name boundaries of the Benavente *et al.* model.[10] Thresholds were measured for all observers along the solid lines on the chromaticity plane (central plot). The gray and black bars show the regions where the majority of the thresholds was measured. Some of the histograms showing the distribution of thresholds along the lines are shown as side-figures. The length of the bar is equal to the standard deviation of the measured thresholds.

color regions (such as that appearing between blue and green, which correspond to turquoise, a color considered nonbasic). Such areas are determined by the appearance of secondary peaks in the histogram distribution of thresholds, and they happen mostly because some observers, when forced to choose, cluster together the intermediate color with blue and some others cluster it with green. A similar effect appears consistently between the purple and pink regions.

CONCLUSIONS AND FUTURE WORK

In this paper we have refined our previous parametric model of color naming. This model (originally introduced by Benavente et al.) consists of a fuzzy mathematical formulation with a set of functions providing memberships for 11 basic color categories. The improvement consists of determining the shape and position of the color categories' boundaries by measuring them psychophysically (as opposed to just interpolating from focal colors data). The psychophysical experiment is based on a yes/no paradigm using only the 11 basic terms, and the model was readjusted to account for its results. The new set of parameters for the color-naming model was obtained. Although we have not compared our results to color-naming data from previous research, we are currently compiling such evaluation.

Our results also show that to adjust the model we need both, the samples near the focal colors and psychophysical measures on the boundary regions. The latter not only can help further define the position of the intercolor regions, but also provide a measure of the uncertainty between colors. Our results may be interpreted as some evidence for the need of other nonbasic color categories to explain specific uncertainties. This is suggested by bimodal threshold distributions on certain intercolor regions, which may be due to the emergence of nonbasic categories that shift the boundary depending on the observer. Hence, one way to improve the color-naming model could be to consider new color terms for these intercolor regions. For example, looking at the results outlined in Fig. 5 one could speculate that:

(a) As mentioned before there might be an "emerging" color-name region between blue and green (turquoise) and between purple and pink (mauve).
(b) In the blue/purple interface there might be another emergent color (that has been called violet[5] and could also be called indigo).
(c) In the area bordering the orange/pink/brown/yellow/regions several bimodal threshold distributions have emerged. Some possible names have been

Table II. New set of parameters adjusted to account for the results of the psychophysical experiment.

Achromatic axis

Black-gray boundary	$t_b = 28,28$, $\beta_b = -0,71$
Gray-white boundary	$t_w = 79,65$, $\beta_w = -0,31$

Luminance plane 1

$t_a = 0,42$, $e_a = 5,89$, $\beta_e = 9,84$

$t_b = 0,25$, $e_b = 7,47$, $\phi = 2,32$

	α_a	α_b	β_a	β_b
Red	−2.24	−56.55	0.40	0.50
Brown	33.45	−5.00	0.50	0.45
Green	85.00	115.00	0.45	0.25
Blue	205.00	−155.00	0.25	0.60
Purple	−65.00	−92.24	0.60	0.40

Luminance plane 2

$t_a = 0,23$, $e_a = 6,46$, $\beta_e = 6,03$

$t_b = 0,66$, $e_b = 7,87$, $\phi = 17,59$

	α_a	α_b	β_a	β_b
Red	10.00	−45.00	0.20	0.25
Brown	45.00	−5.00	0.25	0.45
Green	85.00	115.00	0.45	0.25
Blue	205.00	−159.00	0.25	0.60
Purple	−69.00	−115.00	0.60	0.45
Pink	−25.00	−80.00	0.45	0.20

Luminance plane 3

$t_a = -0,12$, $e_a = 5,38$, $\beta_e = 6,81$

$t_b = 0,52$, $e_b = 6,98$, $\phi = 19,58$

	α_a	α_b	β_a	β_b
Red	13.57	−55.00	0.25	0.57
Orange	35.00	−28.76	0.57	0.52
Brown	61.24	0.00	0.52	0.45
Green	90.00	112.00	0.45	0.20
Blue	202.00	−160.00	0.20	0.50
Purple	−70.00	−112.63	0.50	0.42
Pink	−22.63	−76.43	0.42	0.25

Luminance plane 4

$t_a = -0,47$, $e_a = 5,99$, $\beta_e = 7,76$

$t_b = 1,02$, $e_b = 7,51$, $\phi = 23,92$

	α_a	α_b	β_a	β_b
Red	15.00	−57.00	0.40	0.70
Orange	33.00	−20.00	0.70	0.48
Yellow	70.00	5.67	0.48	0.30
Green	95.67	110.00	0.30	0.20
Blue	200.00	−163.00	0.20	0.40
Purple	−73.00	−115.00	0.40	0.25
Pink	−25.00	−75.00	0.25	0.40

Luminance plane 5

$t_a = -0,57$, $e_a = 5,37$, $\beta_e = 100,00$

$t_b = 1,16$, $e_b = 6,90$, $\phi = 24,75$

	α_a	α_b	β_a	β_b
Orange	29.00	−15.85	0.60	0.54
Yellow	74.15	7.00	0.54	0.47
Green	97.00	110.00	0.47	0.20
Blue	200.00	−160.00	0.20	0.37
Purple	−70.00	−116.00	0.37	0.45
Pink	−26.00	−61.00	0.45	0.60

Luminance plane 6

$t_a = -1,26$, $e_a = 6,04$, $\beta_e = 100,00$

$t_b = 1,81$, $e_b = 7,39$, $\phi = -1,19$

	α_a	α_b	β_a	β_b
Orange	29.00	−13.00	0.40	0.60
Yellow	77.00	10.50	0.60	0.65
Green	100.50	110.00	0.65	0.25
Blue	200.00	−155.00	0.25	0.35
Purple	−65.00	−127.50	0.35	0.65
Pink	−37.50	−61.00	0.65	0.40

proposed for this area, such as beige,[4,17] cream,[4,17] peach,[3,5] tan,[3] and flesh.[5]

Considering the above, it might be desirable to extend the parametric model by adding new fuzzy-sets. The current model assumes the Berlin and Kay hypothesis of 11 basic terms by constraining all the sets to a unity-sum at any point in the space. New color terms could be inserted on this frame as special sets with membership functions overlapping the current ones without the unity constraint. These nonbasic color categories emerging from intercolor uncertain regions would require a deeper study to be assigned with an agreed color term. In this paper we have hypothesized with some terms for the uncertainty regions. Further research is required to extend the model of basic terms, to better locate the exact regions, and to set agreed terms for them.

Finally, it has been suggested that our choice of color space (CIELAB) is obsolete and that a more perceptually equidistant space (such as CIECAM02) should have been selected. Although the variability of results (some subjects produced large threshold variations even when presented with the same initial color pair for the second time a few

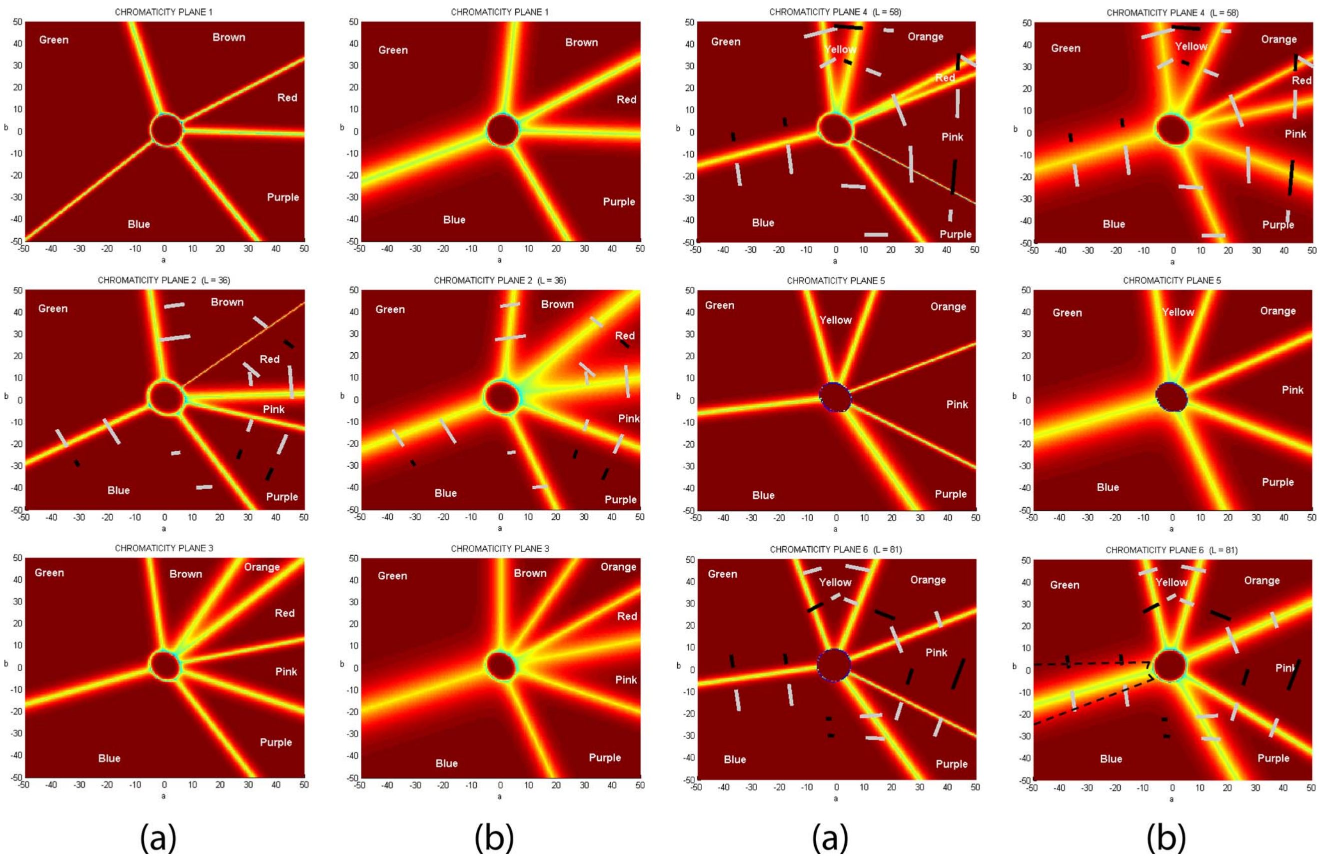

Figure 5. A new set of color-name boundaries, adapted to fit our experimental results. (a) The initial boundaries for the model presented in Benavente *et al.*[10] (b) The readjusted model. The results of the experiment are superimposed on their corresponding plots.

minutes later) is bound to mask any further refinements coming from the selection of color space, this might be an option to explore in the future.

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