A computational model for colour categorization

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Abstract

In 1969, Berlin and Kay suggested that there exist certain universal patterns in colour naming across various cultures speaking different languages. The World Colour Survey (WCS) strengthened their hypothesis by identifying some universal properties in colour categorization across 110 unwritten languages. Baronchelli et al. employed elementary language games between agents of the same population in their computational simulation of the WCS and produced similar results. We also employ a similar numerical model to observe some universal relations between categorization systems of different agents.

1. **Motivation**

Berlin and Kay's result was contrary to the linguistic relativity principle. According to this principle, people's thinking and their cognitive categories are influenced by the language they speak and thus, the colour perception categories will also be different. In our model, we use a simple biological constraint, the human Just Noticeable Difference (JND) to prove the emergence of certain conserved features across different populations.

In 2003, Kay and Regier randomized the original data of the WCS for 110 languages and created new randomized data sets. A dispersion measure was introduced by transforming the Munsell chip which represents the focal colour point of some category in a language to a point in the CIEL*a*b^* space. It is a three dimensional colour scale in which L^* represents the coordinate for lightness, a^* for red/green, and b^* for yellow/blue components.

After transforming all the focal colour chips (of all categories of each language in WCS) into points in the CIEL*a*b^* space, the dispersion value is calculated as follows:

$$D_{human} = D_{wcs} = \sum_{l,l^* \in wcs} \sum_{c \in l} \min_{c^* \in l^*} \; distance(c, c^*)$$

where l and l^* are two different languages from the survey, c and c^* are the corresponding basic colour terms, and the distance refers to that in CIEL*a*b^* space.

It was found that the dispersion measure $D_{neutral}$ for random data sets is 1.14 times the dispersion obtained for human languages D_{human}. From this analysis, we can easily conclude that the human language categories are more clustered (since their dispersion value is lower) than their neutral/randomized counterparts.

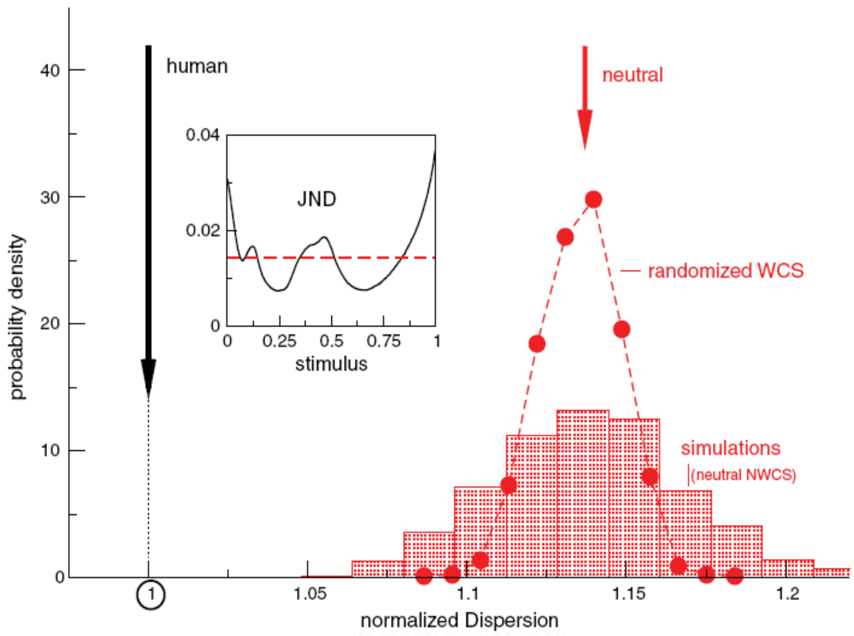
Baronchelli et al.'s simulation of the numerical WCS involving a number of interacting agents in a population has produced results which are remarkably close to the graph obtained below.

(a) In the first round of simulations, the human JND function $d_{min}(x)$ is used and D_{human} is calculated.

(b) In the next round, a uniform JND function = 0.0143 = average of the human JND over [0,1) is used to get $D_{neutral}$.

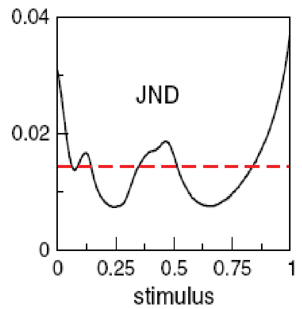
When the ratio $D_{neutral}/D_{human}$ is calculated, it is close to 1.14, the same value obtained by Kay and Regier by randomizing the actual data sets of the WCS. Thus, this computational model is in good confirmity with the actual human colour categorical perception.

In this project, we try to simulate a numerical model (similar to Baronchelli et al.'s) and correlate the results.



$D_{human} < D_{neutral}$ (Image source: Fig. 2 in [a])

2. **Human JND function**
Our perception of colours is nonuniform. The precision with which we perceive a colour depends on its wavelength. The JND is defined as a function of the wavelength of various colours in the visible spectrum. In order to distinguish two stimuli from the same scene, they must be separated by atleast the distance given by the JND function. The wavelengths in visible spectrum are mapped to the interval [0, 1). In the following figure, the JND for x=0.5, $d_{min}(0.5) = 0.0143$ which means that if the normalized wavelength of a colour in the visible spectrum is 0.5, the other colour stimuli in the scene should have a wavelength difference of atleast 0.0143 from our current colour's wavelength of 0.5.



Human JND Function (Image source: Fig. 3 in [a])

3. **Pseudocode of the category game model**
The game has a population of N=50 agents. Initially, each agent has only one colour category [0,1) and has no word assigned to it. As words are added, categories increase but remain contiguous and non-overlapping. At each individual time step, two agents (speaker and hearer) are chosen randomly. The scene contains M stimuli, where M is equal to 2. This pair is shown a set of stimuli whose wavelengths differ by at least the Just Noticeable Difference.
Every word in a category has an associated score. When the word is added, its score is

$s = 0.5$. If there is a successful communication using this word, its score increases according to the formula $s = s^{*}0.9 + 0.1$. New words are added to a category only if it is empty or if the maximum score of any word in this category is equal to 0.5. And, successful communication to hearer increases the scores of corresponding word in both the agents.

The speaker discriminates the scene and produces an utterance (if a new word is added, it is communicated else the word with maximum score is used). Here, a discriminated stimulus is the one which is the only stimulus from the given scene grouped under a particular category C (spanning across $[a, b)$ where a and b are the normalized wavelengths in $[0, 1)$) of the speaker. But, if a topic (say h) is not already discriminated, it means that there is another stimulus 'o' from the scene which is mapped to the same category 'C' as h. In this case, the speaker discriminates the topic h by creating two new categories from C. The point $p = (o + h)/2$ is calculated. Now, C is split into new categories by this boundary (The new categories extend from $[a, p)$ and $[p, b)$). If required, the newly formed categories are given a new word in addition to the already existing inventory of words from C. Each word belonging to a category has an associated score which increases with the number of successes.

Now, the hearer looks up the word associations of his categories and if he points to the correct category containing the speaker's topic, it is a success and the corresponding word's score increases. If he cannot choose a unique category, he randomly picks a category from the list of all those categories which contain the speaker's utterance. If the word is not understood, the speaker unveils the topic and hearer simply adds the word to the category containing the topic. In case of a failure, the hearer adds the word to his category with an initial score $s = 0.5$ (after discriminating the scene). This is how categories are formed on every interaction between speaker and listener.

At the end of all iterations, 10^4 games are played per agent. Each agent will have developed his perceptual categories on the basis of the games played during the simulation.

4. **Results**

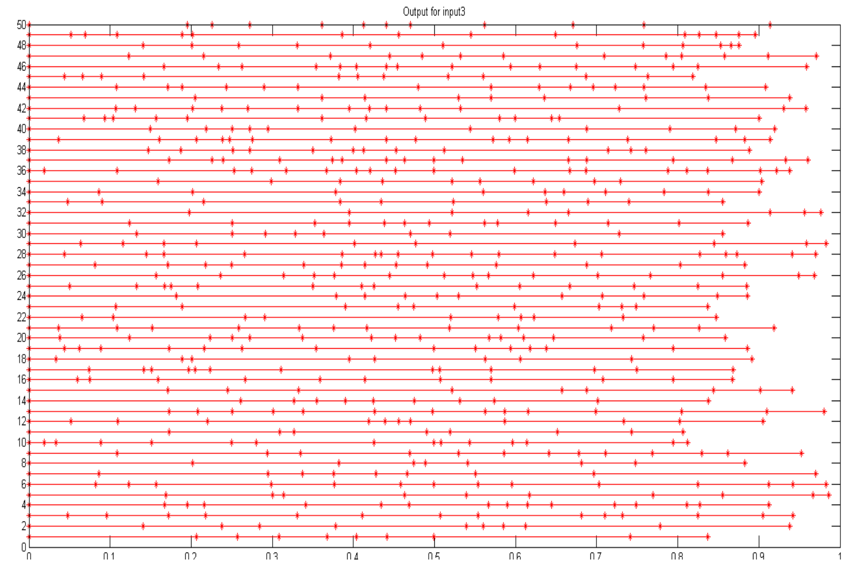
   (a) **Simulation 1:**

   The population consisted of $N = 50$ agents. 2,70,000 games were played. Each language game consisted of $M = 2$ stimuli which had to be communicated by the speaker to the hearer. The uniform JND function $d_{min}(x) = 0.0143$ was used.

The visible spectrum (Image source: Wikipedia [e])

   The actual wavelength range is 380nm to 750nm. It is normalized to the interval [0, 1). According to the wavelengths from the visible spectrum, the normalized boundaries for various colours are as follows:

   0–violet–0.189–blue–0.257–cyan–0.311–green–0.513–yellow–0.568–orange–0.65–red–1



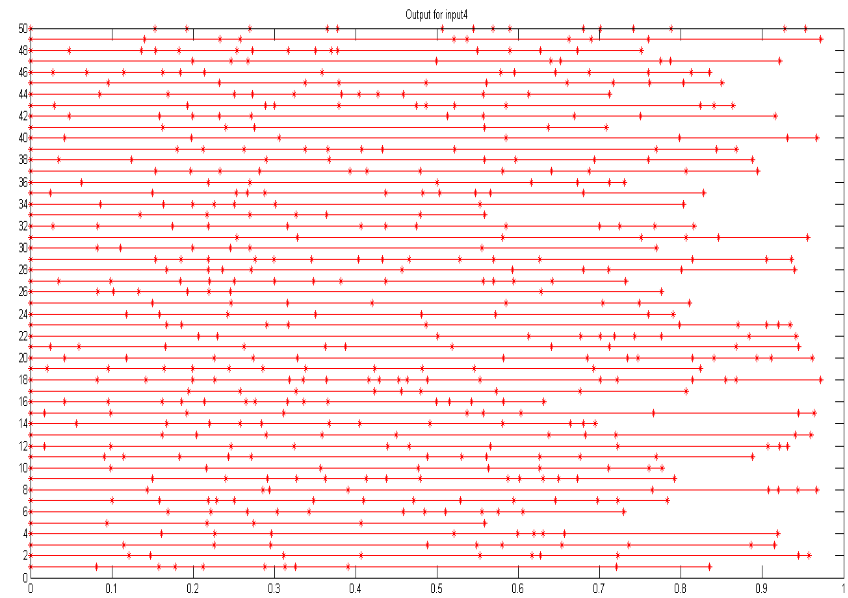
Uniform JND function (10^4 games per agent)

Though the agents' categories are non-overlapping, in the region $[0, 0.1)$, very few agents have developed category boundaries which is in confirmation with the visible spectrum. Many agents have developed categories around 0.2, 0.4, 0.5, and 0.6. In the region [0.8, 1) there are few boundaries and this is reflected across the entire population.

i. Average no. of words in the lexicon of each agent = 17.5
ii. Total no. of words in the emergent lexicon = 172
iii. Average no. of categories formed per agent = 11.4

(b) **Simulation 2:**

$N = 50$ and $M = 2$ are unchanged. 5,10,000 games were played. The uniform JND function $d_{min}(x) = 0.0143$ was used.



Uniform JND function ($2 * 10^4$ games per agent)

Clearly, in this case, many categories of different agents are clustered around in the region between 0.2 and 0.3. This clearly indicates that this result is more convergent than the previous case. The categories are longer in length, similar to those in the visible spectrum.

i. Average no. of words in the lexicon of each agent = 21

ii. Total no. of words in the emergent lexicon = 141

iii. Average no. of categories formed per agent = 11.9

(c) **Simulation 3:**

$N = 50$ and $M = 2$ are unchanged. 2,70,000 games were played. The discrete JND function was used.

The discrete (approximate) JND function we used is as follows:

$d_{min}(x) = 0.0225$ in [0, 0.125)

0.01 in [0.125, 0.25)

0.01 in [0.25, 0.375)

0.0175 in [0.375, 0.5)

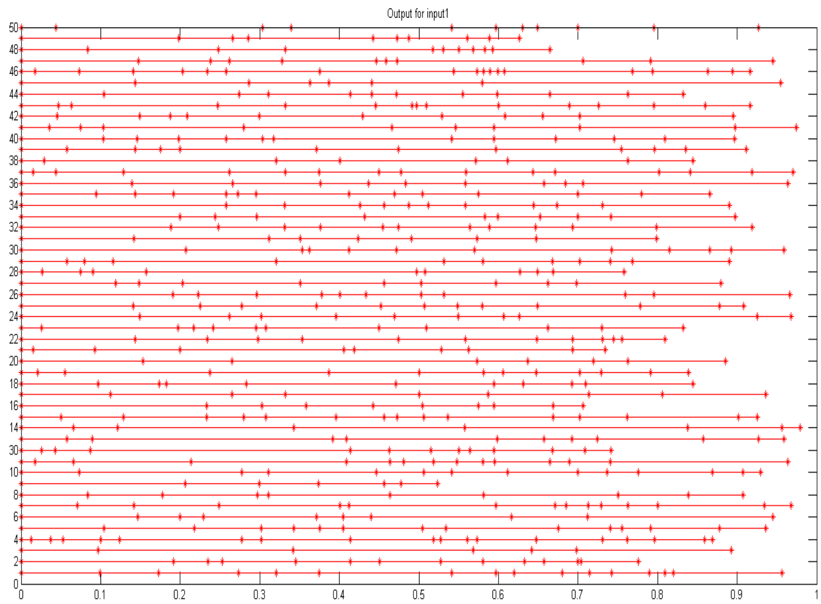
0.01 in [0.5, 0.625)

0.008 in [0.625, 0.75)

0.015 [0.75, 0.875) and

0.03 in [0.875, 1).

The above regions were obtained from the JND distribution curve.



Discretized JND function (10^4 games per agent)

Very few perceptual categories are formed in the region [0.75, 1) because of the high value of JND in this region.

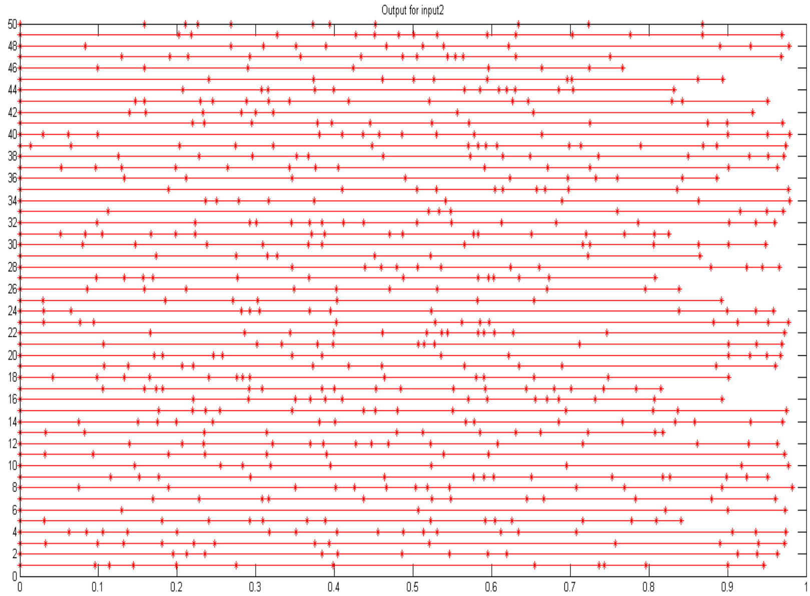
i. Average no. of words in the lexicon of each agent = 16.2

ii. Total no. of words in the emergent lexicon = 136

iii. Average no. of categories formed per agent = 12.4

(d) **Simulation 4:**

$N = 50$ and $M = 2$ are unchanged. 5,10,000 games were played. The discrete JND function was used.



Discretized JND function ($2 * 10^4$ games per agent)

i. Average no. of words in the lexicon of each agent = 22.4
ii. Total no. of words in the emergent lexicon = 152
iii. Average no. of categories formed per agent = 13.5

5. Conclusion

Though all colour categories of every agent are well formed with winning words whose score is $s >= 0.9$, the emergent lexicon has too many words corresponding to a same region of the visible spectrum. For example, in case (a) presented above, the region [0, 0.2) has three different associated words. Hence, a single stimulus has many winning interpretations from various agents. Due to this reason, all agents could not come up with a common lexicon. Thus, their partitions of the colour spectrum are also different.

6. Acknowledgement

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7. References

(a) The research paper "Modeling the emergence of universality in colour naming patterns," authored by Andrea Baronchelli, Tao Gong, Andrea Puglisi, and Vittorio Loreto; Proceedings of the National Academy of Sciences USA 2010 vol. 107 no. 6 pg. 2403

(b) The research paper "Cultural route to the emergence of linguistic categories," authored by Andrea Puglisi, Andrea Baronchelli, Vittorio Loreto; Proceedings of the National Academy of Sciences USA 2008 105:7936-7940

(c) The World Color Survey website: http://www.icsi.berkeley.edu/wcs

(d) WCS Data Archive: http://www.icsi.berkeley.edu/wcs/data.html

(e) Wikipedia's page on Visible spectrum: http://en.wikipedia.org/wiki/Visible_spectrum