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Color naming universals: Too many exceptions to the rule(s)?

Vivian M. De La Cruz[1]
Dept. of Cognitive Science
University of Messina
vdelacruz@unime.it

Alessio Plebe
Dept. of Cognitive Science
University of Messina
aplebe@unime.it

Abstract The domain of color terms has been a privileged terrain for the debate on linguistic relativism. In this long-standing issue significant new evidence has recently emerged from fields such as anthropology, neurocognitive studies, and neurcomputational modeling, here reviewed. The new picture that has emerged, shows the color naming universals hypothesis currently beset with a rising number of important counter examples, which we also review. This growing list of exceptions, leads us to reflect on whether color naming universals are really so "universal" after all. The conclusion we lean towards, is that human color perception is fundamentally guided by a common neurophysiological endowment that is possibly marginally modified by the environment, but mainly modulated by the way particular spoken languages partition the color continuum through the use of color words.

Keywords: Color naming universals, Color terms, Linguistic relativity, Categorical perception, Neurocomputational models

0. Introduction

The domain of color terms and color cognition has traditionally been a privileged terrain of debate in the universalism/relativism issue. In the physics of light, there is nothing that suggests that boundaries between colors should be drawn in one place as opposed to another, and so in this sense, the way we segment the color spectrum in different places is arbitrary. This has led some to think, that the various ways in which colors are lexicalized in different languages can be easily understood as purely arbitrary cultural options. As a result, color terms have been taken as evidence in favor of the linguistic relativity hypothesis, whose best-known formulation is the Sapir-Whorf hypothesis, according to which language and culture have the power to

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determine the way we conceptually perceive the world.
The reaction of universalists has been that of searching for the underlying regularities beneath apparent lexical variation, where such regularities are mainly thought of as consequences of physiological constraints in the process of vision. Berlin and Kay (1969), in particular, proposed the well-known and influential hypothesis, according to which basic color terms follow a rigid evolutionary pattern, that is, that there would be precise rules governing how color terminology expands from the minimal repertoire of two terms to eight or more terms. Moreover, each of the languages examined would select virtually identical focal hues for the same basic colors. What this means is that putting aside minor variations, languages would differ from each other just in the number of colors they give a name to, while universal preferences would dictate the sequence of lexicalized color categories and the focal hue for each category. Not long after Berlin & Kay published their paper on color universals, Rosch Heider and her colleagues (HEIDER 1972; HEIDER & OLIVIER 1972), put their proposal to the test in a series of experiments comparing: English speaking college students with non native English speaking foreign students; speakers of a number of different languages; and English speakers with New Guinea Dani speakers (whose language was reported to possess only two basic color terms). They found evidence that focal colors were in fact, given the shortest names and remembered quicker across languages, were recognized better by both English and Dani speakers, and could be paired with names with the fewest amount of errors. They interpreted these results as being consistent with B&K's hypothesis, including that the emergence of color lexicons followed a predetermined evolutionary course.

Berlin and Kay's conclusions, however, have also been called into question throughout the years from the relativist side, with several arguments, among which, that their findings were never objectively tested, that their assumptions and methodology led them to discard data that conflicted with their over-regularized picture, and that their data was obtained from primarily written languages and so possibly not representative of all languages (e.g., SAUNDERS and VAN BRAKEL 1997; LUCY 1997). In recent years, studies attempting to reproduce Rosch Heider's results, and looking for confirmation of the evolutionary nature of color terms hypothesized by Berlin & Kay, have been done on a variety of different languages. Several of these studies will be reviewed in the second section of this paper.
In the first section, we will provide a brief overview of the biology of the human visual system and how it might be influenced by the environment and by culture, by way of language, from a brain architecture point of view. The second section, will discuss in more detail, some of the recent evidence coming from anthropological studies on color terms that present a growing list of exceptions to the theory of color universals. The third section, will discuss evidence and exceptions coming from studies in the neurocognitive domain, with the fourth section instead, presenting challenges and exceptions to the theory coming from computational simulations.

1. Biology, environment and language

The mechanisms of color vision, while widely studied, are still far from being fully understood. Our ability to see colors derives from a chain of processes starting in the retina, involving the Thalamus, and several cortical visual areas, among which are V1, V2 and V4. As for other visual features, color perception is also affected by top-down projections from higher cortical areas. The neurophysiology of color is nothing

like a strict detector of the physical properties of the light projected onto the retina, and subjective perception is not only a complex elaboration of external information. It is also highly individualized by the history of visual experience, due to the plasticity of the brain. Even in the same individual, color appearance is affected by what has been previously seen, on a time scale of minutes.

1.1. Biology

The first mechanism of color vision begins in the three types of cones in the retina, referred to as L, M, and S cones, with reference to their long-wavelength, middle-wavelength, and short-wavelength sensitivity. Even at this very early stage, the exact determination of the spectral response of the three cones is tricky, since it overlaps extensively throughout the spectrum. It has been clarified only recently by Stockman (2000), recruiting a number of subjects, lacking one or more of the three cone types. The next fundamental mechanism is color opponency, which happens both in the retina and in the Lateral Geniculate Nucleus (CONWAY 2009). Cone-opponent neurons come in four varieties: L-on/M-off, M-on/L-off, S-on/(LM)-off, and (LM)-on/S-off, where on/off refers to the higher/lower intensity level of the center with respect to the surround of the receptive fields of the neurons.

The process of color becomes more complex in the cortex, because it is closely interweaved with other basic processes, like form and motion. In V1 and V2 there are cells that respond selectively to color opposition, but in a spatial asymmetric orientation rather than concentric (CONWAY 2009). Higher areas like V4 and VO are strongly involved in the most complex processes, such as color constancy (the tendency of the color of a surface to appear more constant than it should, by the physical composition of the reflected light under changing luminance conditions). Psychophysical experiments with human infants, have shown that this capacity is not present at birth, but develops somewhere between two and four months of age (DANNEMILLER 1989). The precise way in which colors are coded in higher visual areas is still largely unknown (BROUWER & HEEGER 2009).

1.2. Language

How language interacts with and/or affects the appearance of colors is also unclear. It is highly conceivable that the meeting between linguistic coding and the visual pathway takes place in the prefrontal cortex, because this is the area where categorization is represented independently from single specific sensorial modalities (FUSTER 2008). Recent experiments in color discrimination have confirmed the involvement of language processing brain areas (TAN *et al*. 2008; SIOK *et al*. 2009).

One of the most evident effects of language on color perception is the phenomenon known as categorical perception. While from a purely physical point of view, light is a continuum of wavelengths, the visible spectrum is perceived as discontinuous, split into categories that some believe are designated by the color terms used in a language. We will provide a detailed picture of these studies in Section 3.

Supporters of universals in color terms, do not deny categorical perception, they just explain it with a reversal from biology to language. According to their view, it is how colors are named in every language that reflects our neurophysiology, leading to the categorical split of the spectrum.

1.3. Environment

The role of the photic features of the environment in the evolution of the color visual system in animals, on a phylogenetic time scale, has been widely investigated and debated (BRISCOE & CHITTKA 2001). On the other hand, very little is known concerning the influence of the environment on human color perception. A good reason is that in most western cultures, individuals are immersed in a world of colorful manufactured objects, since birth, with marginal, if any, differences between countries.

However, there are studies (REIMCHEN 1987), that have discussed how Scandinavians have a significant higher level of a specific red-green deficiency, which might be accounted for by the photic characteristic of their habit, characterized by long twilight periods. Recent studies (LEANG *et al*. 2007), have revealed environmental influences at an ontogenetic scale. Norwegians born during summer months have a better discrimination in the green-blue range, compared with those born in winter. Moreover, differences in discrimination changed depending on whether the place of birth was located either above or below the Arctic Circle. Such a difference might be motivated by the fact that periods of darkness/sunlight lasting longer than the circadian cycle, only occur above the Arctic Circle.

In the cases of Berinmo and Himba, the environment might also have an impact on color perception, but for different reasons. The landscapes, in which these two groups live, are drastically different. One is immersed in the luxurious vegetation of Papua New Guinea, and the other, in the rocky desert lands of Northern Namibia. Moreover, their landscapes have very likely remained unchanged in color since their respective languages emerged and developed. There are no specific data available to support this hypothesis, but in the computational model described in Section 4 the possible environmental effect has been simulated.

2. Exceptions from anthropological studies

In the 1970's, Heider's work was influential in promoting the notion that language and cognitive experience were for the most part, independent from each other. The idea of focal colors has played an important role in this, having been considered the foundation upon which the universalist stance on cross-linguistic universals was based. To challenge them, has meant implicitly challenging the notion of universal color categories (KAY & REGIER 2007).

A research project also begun in the 70's, meant to validate and expand the findings of B&K's 1969 study, which originally concentrated on only 20 languages (and a survey of the available literature on about another 80), led to the World Color Survey (WCS), a data archive on color naming from speakers of 110 languages (COOK *et al*. 2005; KAY *et al*. 2010). The results and raw data made available by the WCS has provided a wealth of information to researchers currently working on understanding whether color nomenclature might influence or be influenced by cognition as well as culture. A number of these researchers have found a series of exceptions to the original hypotheses that motivated the WCS in the first place.

2.1. Exceptions from Berinmo

Roberson and her colleagues, in a series of cross-cultural studies, investigated how the Berinmo tribe of Papua New Guinea categorized color (DAVIDOFF *et al*. 1999). Through naming tasks using the 160 colors in the Munsell chart, they determined

that the Berinmo subjects used five basic color terms (English uses eleven). In a replication of Heider's earlier experiment with the Dani, the Berinmo's accuracy in remembering colors was evaluated, with surprisingly similar results: both groups were poor at this task, but upon statistical analysis, both studies showed a better statistical fit between Melanesian naming and Melanesian memory. This was taken to be consistent with the linguistic relativity hypothesis, but this was not how it had been interpreted in Heider's original study. Differences between English and Berinmo, were then used to test color universals vs. linguistic relativity. Categorical effects across color boundaries were investigated across blue and green (distinction exists in English but not in Berinmo), and between *nol* and *wor* (color boundary exists in Berinmo but not in English). English subjects proved to be better at cross-category decisions for blue-green, but not for *nol-wor* decisions, and the Berinmo showed no cross-category advantage for the unfamiliar blue-green stimuli, but instead showed cross-category advantage for the *nol-wor* stimuli. Thus, categorical perception was found to occur, but only for those speakers whose language marked the categorical distinction. This result is consistent with the linguistic relativity hypothesis.

Another universalist position tested in this study, regarded how categories are supposedly formed around natural fault lines in perceptual space. If this were true, then learning another language's color categories would prove to be fairly simple. English speakers were asked to learn the distinction between *nol-wor*, and Berinmo speakers the ones between blue-green and yellow-green. Subjects were also asked to categorize stimuli in a way that was consistent with their own language's color names, and to learn a distinction that was not marked in either language (two types of green: "green 1" and "green 2"). Berinmo subjects learned to divide green 1 and green 2 with no more difficulty than when asked to divide blue and green. English subjects instead, found the blue-green division easier, while the Berinmo found the *nol-wor* task easier than the yellow-green. With English subjects instead, the reverse happened. The results of these tasks indicate that when subjects are asked to divide stimuli that vary in hue, lightness and saturation, into two different color categories, they are more accurate when the division is compatible with a linguistic distinction rather than the supposed universal one. The conclusions these researchers have drawn based on their studies (e.g., ROBERSON *et al*. 2004; 2005), is that there is a considerable degree of linguistic influence on color categorization, that facilitates recognition and perceptual judgments even in languages with less abstract terms for color such as Berinmo. This linguistic influence would constrain underlying neural processes involved in color vision.

2.2. Exceptions from Himba

Examining linguistic relativity further, but using another method, Roberson et al. (2004, 2005), considered the question of whether two languages at the same supposed 'evolutionary' stage could have similar cognitive representations of color despite having different environments. If what Kay, Berlin & Merrifield proposed (1991), concerning the regular evolutionary pattern in which color terms would emerge in languages was correct, then this would be the case. Another aspect investigated, was the possible difference in cognitive organization between speakers of languages, despite the similar sets of color terms. Objects of study were the color terms used by the Himba people of northern Namibia, a semi nomadic culturally

isolated tribe, living in an arid desert-like environment, but that like the Berinmo of Papua New Guinea, have 5 basic color terms. The BCTs of Himba were studied and compared with the previously studied Berinmo and English. When recognition memory for color was examined in both Himba and Berinmo, results were consistent with Rosch Heider's results, as long as the arrays were ordered according to hue and brightness. When the arrays where randomized and the number of close competitors were instead likened to poor or best examples, neither the Himba nor the Berinmo showed memory advantages for the English best examples. What they did recognize, were the good examples of their own respective linguistic color categories, in a way that disregarded the status of these items in English color categories. A paired-associate learning task (colors to pictures of familiar objects) showed the same lack of advantage for supposedly universal examples in either Berinmo or Himba speakers. Results were interpreted as showing that no single set of prototypical colors are universally cognitively privileged. The color stimuli speakers seem to remember better are those that are the best exemplars of their own named categories.

Roberson et al. (2005), also investigated whether the Himba would show categorical perception at the English boundaries of green and blue, once again comparing them to speakers of Berinmo and English, and whether Himba (like the Berinmo) would show CP at boundaries within their own language that instead, do not exist in English. Subjects were shown a colored target and asked to choose, which one of two stimuli was the same as the target. Performance was facilitated in each language, when the target and the distractor had different color names (e.g. in English, a blue target with a purple distractor) as opposed to when they shared the same name (e.g. in English, two different shades of blue). All three groups showed CP, but significantly, only at the color boundaries that were clearly marked in their respective languages. Importantly, results indicated that no effect took place at the proposed universal boundary between green and blue for the Himba and Berinmo speakers, whose languages do not make this distinction.

How children acquire color terms presents an interesting and important test bed for universalist theories. Roberson et al. (2004), comparing color naming and memory of young children learning English in the UK and children from Namibia learning Himba, found that generally, the children from both cultures appeared to acquire the color terms of their language in the same gradual manner. Results presented no indication of any advantage English-speaking children might be having in learning their color terms compared to Himba children, even though English terms map directly onto the hypothesized innate set. Furthermore, no evidence was found to indicate that children of either group had pre-partitioned representation of color at three years of age, before the learning of color terms. The authors argue that this evidence thus suggests that:

> "if there is an innate set of cognitive categories present in young infants, then a) they are species specific and thus do not result from some property of the visual system that is shared with other primates and, b) they are not retained once adult linguistic categorization is in place."

Studies on early color term acquisition have noted how late children acquire competence with color terms, compared to the acquisition of words for other

dimensions (e.g. SANDHOFER & SMITH 2001; SMITH, JONES & LANDAU 1992; for neurocomputational models that deal with this topic see PLEBE *et al*. 2011, 2012, 2013), and have hypothesized a number of explanations for this delay. One thing is clear, learning color terms is a difficult task for children, more difficult than we might expect if what they are doing is just learning labels for innately determined universal color categories (ROBERSON *et al*., 2010).

2.3. Exceptions from Yélî Dnye

Stephen Levinson has played an influential role in the re-evaluation of linguistic relativity. Some of his more recent investigations have focused on how speakers of different language systems use different spatial systems, giving proof of linguistic relativity in the domain of space perception (e.g. LEVINSON 2003). In another well known study (LEVINSON 2001), on the language and culture of the Yélî Dnye, the inhabitants of Rossel Island, Papua New Guinea, he sought to test Berlin & Kay's theory of basic color terms in a culture where color turned out not to be salient at all. After using the procedures developed by Berlin & Kay (1991) and those of the WCS, Levinson found that the Yélî Dnye made limited use of basic color terms (BCTs), which were in part consistent with B&K's proposal, (that is, that terms for black and white and then red descriptors were the first to get lexicalized), but he also found that the data presented a number of challenges to BCT theory. One interesting result of the study, among others, was that while the Yélî Dnye made limited and inventive use of their basic color terms, they used them together with non BCT expressions to divide the color space. Levinson listed this and other exceptions he found to BCT theory in the following way:

> • The data do not support the fundamental assumption that all languages have dedicated terms that exhaustively partition and describe the perceptible color space.
> • They do not fit the predictions for composite categories in systems with only a few color terms.
> • Nor do they support the idea that a clean distinction exists between BCTs and referent-based similes for hue—instead the less canonical expressions may hedge in the more lexicalized ones.
> • Significant degrees of speaker variation exist, which do not, on the face of it, look like systematic sociolinguistic variation.

Moreover, the evolutionary trajectory of these terms seemed to be quite different to the one proposed by Berlin & Kay. Levinson went on to propose them to being more compatible with alternative evolutionary-philological theoretical views such as the Emergence Hypothesis (LYONS 1999). According to this hypothesis, in some traditional societies a fully systemized lexicon of color is not found because it is of minor communicational function. In other words, the cultural and technological pressures for color terms to emerge and evolve are not present, thus not making them necessary. According to this view, color terminology (and maybe even color cognition), could be seen as the result of bio-cultural influences, and not dictated strictly by universal perceptual constraints. In the conclusions of his study, Levinson says that EH recognizes that "for universal perceptual constraints to directly engender *semantic* universals of color terminology – it takes a culture of color to make a color terminology worthwhile" (LEVINSON 2001).

3. Exceptions from experimental studies

As already described, categorical perception is a vivid example of how language affects color appearance. It has been used to assess the phenomena on the *nol/wor* boundary in Berinmo (ROBERSON *et al*. 2000), and *dumbu/burou* in Himba (ROBERSON *et al*. 2005), as mentioned in Section 2. Here we describe a series of laboratory experiments, where it has been possible to obtain more detailed information than in the field.

3.1. Universalism on the left only

In a first experiment Gilbert et al. (2006), tested the green/blue boundary for categorical perception, but relying on reaction times instead of just the fraction of correct answers of the subjects. The same discrimination task was presented either on the right or the left visual fields, which are connected with the contralateral brain hemisphere. The results showed that discrimination of colors with different names is significantly faster than within-category discrimination in the right visual fields, not as in the left visual fields. The well-known lateralization of language was quickly invoked as the logical explanation of such a disproportionate influence on color discrimination in the two visual fields.

This rather schizophrenic tension between how colors are seen in the two visual fields led several universalist scholars to proposing a fair compromise: "Whorf was half right" (REGIER & KAY 2009). According to this view, half of our perceptual world might be viewed through the lens of our native language, and half viewed without such a linguistic filter. This hypothesis is of course at odds with our unitary perception of colors, which does not seem to change organization depending on which field it occupies, but this certainly would not be the first time our intuitive perception is fooled by brain mechanisms.

3.2. The Korean exception

This, however, is not the end of the story. Drivonikou et al. (2007), in replicating Gilbert's experiment (2006), confirmed that categorical perception is stronger in the right visual field. However, they did observe a smaller but significant categorical effect when targets were presented in the left visual field as well. They suggested that this category effect could be of an entirely different character, not linguistically mediated, and instead reflect presumably universal categorical distinctions.

Soon after, an experiment with Korean participants dismissed this interpretation. Roberson et al. (2008), used the boundary between the Korean categories *yeondu* (yellow/green) and *chorok* (green). This boundary is obligatory for Korean speakers, who have no single term that covers both *yeondu* and *chorok*, but falls within the green category for English speakers. English participants showed no categorical effect, regardless of whether the target was presented to the left or right visual field. On the contrary, reaction times for Korean participants where shorter for colors crossing the *yeondu/chorok* boundary, in both the right and the left visual fields. Roberson et al. (2008), gave a possible explanation for the lack of lateralized response in their study, noticing that in Gilbert's study, reaction times on average were much shorter, 450 ms, compared to around 1000 ms in Roberson's study. With

faster responses, there probably wasn't sufficient time for information from both visual fields to be available to language processing systems in the left hemisphere.
This explanation is in agreement with a recent replication of Gilbert et al.'s study by Witzel and Gegenfurtner (2011). They carefully controlled the rendering of the stimulus colors, which were not precisely specified in Gilbert's experiment, and ran ten different versions of the two original experiments with over 230 subjects. The results of this study revealed consistent categorical perception effects, with no difference between the right and the left visual fields.

3.3. Categorical variations

Several interesting studies that focus on a variety of aspects in color categorical perception are worth mentioning. Anna Franklin developed methodologies for testing color perception in pre-linguistic infants, based on the oddball paradigm. Infants were first familiarized with frequent presentations of one color, and later a different color was presented. Looking time is proportional to the amount of novelty in the unfamiliar color. Interestingly, pre-linguistic infants showed categorical effects in the green/blue boundary, but in the left visual field only (FRANKLIN *et al*. 2008). The results were confirmed measuring event-related potentials instead of eye movements, again for the green/blue categorical effect (CLIFFORD *et al*. 2009).
Franklin and her colleagues are conducting further research in order to investigate whether the change in lateralization of CP later in development, is related to the child's subsequent acquisition of color terms. This is something she does not rule out, considering there is evidence that suggests that color CP and language-mediated CP can exist alongside each other. There might even be two forms of CP: a non-lexicalized and right lateralized one in infants, and a lexicalized and left lateralized one in adults (FRANKLIN *et al*., 2009).

Other experiments, have investigated the flexibility of categorical effects, and the possibility of learning new categories, inside the blue and the green regions, with just a few days of training (OZGEN and DAVIES 2002), a result that clashes with the universality of color perception. In addition, Zhou et al. (2010), tested subjects that learned four new invented colors inside green and blue, named *ang*, *song, duan*, and *ken*, for lateralization, finding stronger categorical effects in the right visual field.

3.4. Seeing orange as *gelb*

A clever experiment by Mitterer et al. (2009), revealed a different and subtle influence of language on color perception. They used schematic shapes of objects, coloring one part of them with a hue varying from yellow to orange, and then asking subjects to name the hue. Half of the subjects were Dutch, the other half German. One of the stimuli was a traffic light, with the middle light being on. It turns out that Germans called the color within the traffic light more often yellow than Dutch speakers. This bias very likely comes from the fact that Germans call the middle light *gelb*, whereas the Dutch call it *oranje*. This is a clear demonstration of the influence of language on color perception, this time not due to the abstract partitioning of the color spectrum by lexical label, but by the common usage of a color name, for a particular object.

4. Exceptions from computational simulations

Computational models have been used as an alternative approach in exploring the relationship between the physical phenomenon of light and the linguistic categories of colors. One stream of research, started by Yendrikhovskij (2001), postulates that the peculiar way in which the color spectrum is split in categories by humans, simply reflects the chromatic statistics in the natural environment. He used the simple k-means clustering algorithm to cluster the color information of pixels drawn from images of natural scenes. All pixels have been projected in the Lu*v* CIE 1976 standard color space, using 11 clusters, their resulting position in the color space is not too far from the English color focal points. Studies on the statistical distribution of colors in natural images are highly relevant, and could indeed inform about the bias in categorization due to the natural distribution of colors in the environment. However, they clearly touch only one aspect of the matter, leaving aside all that concerns the physiology of vision and the relationship with language.

4.1. Seeking universal optimal partitioning

Regier et al. (2007), also used a simple abstract mathematical algorithm for partitioning the color spectra, but directly applied it to the Munsell color chart used in the world color survey. They introduced an arbitrary "well-formedness" measure of a partition in the chart, that takes into account how close together all the points in the chart under the same category are, and how far all the points of the other categories are. Using this measure as the optimizing function, they found theoretical optimal partitioning in a number of categories that looks quite similar to real partitions in selected languages with the same number of colors. The same measure has been applied to verify that the partition in the Berinmo language turns out to be "worst", if the color chart is artificially rotated among the hue axis. For the authors this indicates that the color naming used by Berinmo is more consistent with the universal structure of the perceptual color space, than all the other (artificial) ones. It is not clear how these results have advanced the debate since the model not only neglects any account of the physiology of vision, and its relationship with language, but also with the statistics of colors in the world.

4.2. Categorization from communicative behavior

A different stream of research is trying to model communicative interactions, from which color categories are established, using artificial agents. One of the best examples of this approach is the work of Steels and Belpaeme (2005), where virtual agents engage in two types of tasks. In the discrimination game, that does not involve language, one topic has to be discriminated from several distractor colors, and the agent in isolation develops categories in order to maximize the chance that each time, the topic belongs to a category different from all the other distractors. In the guessing game, the speaker wants to get something from the listener and identifies it through language. In this task, the agent uses categories learned during the discrimination game, modifying them and developing a lexicon at the same time. Their experiments have demonstrated that linguistic interaction is able to yield a finite number of categories in a population of evolving agents. While being very interesting for the aspect of simulated interaction, this research lacks an account of human color physiology and uses an oversimplified account of the interaction between perceptual categories and language. Recent extensions of this approach have tried to introduce

elements of the human perceptual system, in a very simplified way. An example is Komarova and Jameson's work (2008) simulating the presence of dichromats in a population of virtual agents.

4.3. Bringing the brain into the computation

While the modeling attempts briefly described above, have all brought something interesting to the debate, what they lack is a brain account of the phenomena they concentrate on. While jumping from no-brain-at-all models, to a model where all the details of the brain processes are perfectly reproduced is not feasible, considering that so much of what goes on in color representation in the visual cortex still remains unknown, we believe however, that an account that is limited to what is known of the brain processes involved in specific color-processing, and of general cortical mechanisms (e.g., plasticity, lateral connections, etc.), is still a good step forward in the attempt to understand what might be at play.

A model that has attempted a limited, yet biologically plausible simulation of human color processing, and a reasonable account of the interaction between color perception and language, is found in Plebe et al. (2011). It is a system of artificial cortical maps, built with a mathematical abstraction faithful enough in reproducing a biological learning mechanism, through the combination of Hebb's principle and neural homeostasis. Each artificial map is made up of an array of two-dimensional computational units that correspond to the vertical columns found in biological cortex. Each unit receives input from a neighboring receptive field in the model's simulated thalamic input, or from a lower cortical map. The cortical units connect laterally with cells of the same cortical map that can contribute in the activation of the receiving cell, with excitatory or inhibitory effects. The part of the brain simulated in this model comprises one path for the visual process and another for the auditory channel. In the visual path, retinal and thalamic connections are simulated by two main types of receptive fields: center surround, where two concentric areas have excitatory/inhibitory effects, connected to different combinations of chromatic signals, and coextensive, without a suppression area, but with one chromatic channel acting as inhibitory with respect to an opposite channel. The cortical process continues to the primary visual map V1 and the color center VO. In the auditory pathway, there is a first thalamic component that gives a spectrogram representation of the sound pressure waves, followed by the auditory primary cortex, and the superior temporal sulcus, the main brain area responsive to vocal sounds. The model map where the ventral visual path and the auditory path meet is the prefrontal cortex, for reasons discussed in Section 1. The model is exposed to a variety of stimuli, in different stages of its development that to some extent parallel periods of human development, from the pre-natal stage to the initial language acquisition stage. While the early developmental phase is common to all the models, in the linguistic phase three different models are developed, corresponding to English, Berinmo and Himba. The last stage of the experiment simulates events in which colored patches are viewed, and a word corresponding to its basic color category is heard contemporaneously. At the end of development, types of organization are found in the lower maps that enable the performance of processes that are essential to vision, and that are similar to those found in corresponding brain areas, and that are quite close for the three languages. In the upper map instead, populations of neurons are developed, which code for the color categories of the language-specific basic color terms.

4.4. Combining environmental and linguistic experience

In an extended version of the model described above, in the formation of color perception prior to language exposure, the separate effects of three different environments, Berinmo, Himba, as well as the typical, more varied and undifferentiated visual world of western cultures, have been included (PLEBE *et al*. 2011; 2013). In the pre-linguistic phase of development, natural images are used as stimuli for the visual pathway, with three variations. A neutral one lacks dominant hues, and is typical of many urban environments in modern cultures, where the most common objects and scenes seen by newborns are man made, with a wide range of colors, prevailing over the natural hue bias of the natural environment, if any. The other two environments are those typical of Berinmo and Himba that contrary to the neutral urban environment, are dominated by specific ranges of hues. The Berinmo environment is the luxurious vegetation of Papua New Guinea, along the large Sepik river, with villages under the shadows of tall trees. The Himba people live in the open rocky desert lands of Northern Namibia, dominated by warm hues. The most impressive result of this simulation has been the dominant effect of language over the influence of the environment, in the higher prefrontal cortex artificial map.

4.5. Artificial categorical effect

Finally, the same basic model has been used in simulating a psychological discrimination task, to check for an effect like that of human categorical perception. The Berinmo, Himba, and English versions have been exposed to sets of triads of color stimuli, where two of the stimuli lie within one linguistic category, while the third belongs to a different category. The activities in the artificial prefrontal cortex neural sheet are compared for similarity using all nodes, without taking into account their partition in population coding for categories, to prevent a biased judgment of similarity. The boundary categories are blue-green for English, *nol-wor* for Berinmo, and *dumbu-burou* for Himba. The exact values of the colors used match those used by Roberson et al. (2005). Results show a clear categorical perception effect for all languages, with the blue-green boundary, in particular, strongly affecting the English model, while having an indifferent effect on Himba and Berinmo.

5. Conclusions

The universal view on color perception has been an attractive theory, since it reinforced the view that human cognition shares a wide common basis, and for a while, seemed to be supported by empirical evidence. However, too many exceptions have emerged from several different domains, some described in this paper, which now make this position doubtful. Several theorists who have supported the universalist position in the past, now accept that linguistic differences between speakers of different languages influence color categorization (see for example REGIER & KAY 2009). A weaker version of universalism still defends the view that color terms, even if different in various languages, and producing different effects on color appearance, still derive from the biology of our visual system.

The cases of Himba, Berinmo, and Yélî Dnye are clear counterexamples. Moreover, computational approaches, when including a plausible account of the brain processes involved, confirm the relativist theory. We certainly believe that the neural

mechanisms of human vision, place important constraints on the construction of a lexical system of color terms, but these constraints would allow a large variety of color categories, which would depend on the history of languages as well as cultures. In the end, our perception of colors *is* affected by our language, in ways that are still far from being understood, and still worth finding out.

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