Journal of Theoretical Biology 253 (2008) 680–700

Contents lists available at ScienceDirect

Journal of Theoretical Biology

journal homepage: www.elsevier.com/locate/yjtbi

Population heterogeneity and color stimulus heterogeneity in agent-based color categorization

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ARTICLE INFO

Article history:
Received 22 October 2007
Received in revised form
21 February 2008
Accepted 25 March 2008
Available online 4 April 2008

Keywords:
Evolutionary game theory
Dichromat color naming
Population inhomogeneity
Environmental color distributions
Discrimination-similarity game
Learning algorithm

ABSTRACT

Investigating the interactions between universal and culturally specific influences on color categorization across individuals and cultures has proven to be a challenge for human color categorization and naming research. The present article simulates the evolution of color lexicons to evaluate the role of two realistic constraints found in the human phenomenon: (i) heterogeneous observer populations and (ii) heterogeneous color stimuli. Such constraints, idealized and implemented as agent categorization and communication games, produce interesting and unexpected consequences for stable categorization solutions evolved and shared by agent populations. We find that the presence of a small fraction of color deficient agents in a population, or the presence of a "region of increased salience" in the color stimulus space, break rotational symmetry in population categorization solutions, and confine color category boundaries to a subset of available locations. Further, these heterogeneities, each in a different, predictable, way, might lead to a change of category number and size. In addition, the concurrent presence of both types of heterogeneity gives rise to novel constrained solutions which optimize the success rate of categorization and communication games. Implications of these agent-based results for psychological theories of color categorization and the evolution of color naming systems in human societies are discussed.

1. Introduction

Human color categorization has a long history of empirical investigation by psychological scientists (see Hardin and Maffi, 1997 for a survey of perspectives), and is a research area that continues to attract active empirical interest (e.g., Davidoff et al., 1999; Roberson et al., 2000, 2005; Kay and Regier, 2003; Jameson, 2005a; Regier et al., 2005, 2007; Sayim et al., 2005; Lindsey and Brown, 2006). The empirical literature suggests that, on one hand, there is a good deal of universality in color categorization across cultures, whereas, on the other hand, a considerable amount of variation is also observed. A long-standing debate in the field has been whether specific universal tendencies exist in the ways different human linguistic societies categorize and name perceptual color experiences, and if so, to what factors (e.g., physical environment, human biology, perception, social features) might such tendencies be attributed. A major challenge for the area continues to be the development of a theory that would account for universal patterns seen in color categorization data while explaining any differences observed. This is a fascinating problem that has recently attracted the investigative interests of computational scientists (Belpaeme and Bleys, 2005; Steels and Belpaeme, 2005; Dowman, 2007; Komarova et al., 2007a; Puglisi et al., 2007).

1.1. Two perspectives on human color categorization

One widely held perspective is that the commonalities of color categorization across individuals and cultures are largely explained by human perceptual color processing, and universal features of individual psychological processing believed to underlie perceptual color experience. This "*universalist*" view implicitly places the causes for observed color categorization systems *within* the individual observer. The universalist view has historically been successful in characterizing color categorization similarities across a number of ethnolinguistic groups (Kay and Regier, 2003; Kay, 2005; Kuehni, 2005a, b; Regier et al., 2005; Lindsey and Brown, 2006), but less successful identifying the sources of the considerable variation in color categorization and naming that is seen across ethnolinguistic groups.

A different view is that socio-cultural factors contribute substantially to the ways color appearance is categorized and

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doi:10.1016/j.jtbi.2008.03.030

named by different ethnolinguistic groups (Davidoff et al., 1999; Roberson et al., 2000, 2005). This "*culturally relative*" view suggests that to the degree that two societies share similar environmental, pragmatic and social circumstances, two such societies are more likely to exhibit color categorization systems that resemble one another, unlike systems from two different societies which do not share any environmental, pragmatic or social circumstances. Thus, in contrast to the universalist perspective, this socio-cultural perspective places a large emphasis on factors outside the individual observer such as demands from social practices, environment, and so on. Also implicit in this latter view is the suggestion that at least some of the features that are shared among individuals in a given ethnolinguistic group, stem from commonalities *specific to human society* as it interacts with color in the world, rather than shared due to a common human individual perceptual processing basis.

Although historically these two views[1] have been put forth as somewhat mutually exclusive positions, scenarios necessarily exist in which the universal perceptual processing view and the socio-cultural view both play substantial roles during the development and use of color categorization systems in everyday communications among observers.

1.2. Some challenges in color categorization research

A specific challenge confronting human color categorization research is to model the phenomenon in such a way that both universal individual features and socio-cultural features can contribute in tractable ways to color naming and categorization behaviors in a given ethnolinguistic group. Building one such empirical theory, general enough to serve as a model across ethnolinguistic groups while convincingly demonstrating how the different features trade off in the process of naming and categorization, has historically proven to be a difficult task.

A different, equally important, challenge is to find methods that, essentially, *look across time*, permitting the investigation of the evolutionary dynamics that were present during the development of a society's color categorization system. For this an evolutionary approach seems needed to study dynamically imposed pressures and how those pressures are responded to by a system and by the individuals using that system. Historically, diachronic analyses have been used to address these issues (e.g., Kay, 1975), but such investigations are difficult as they depend greatly on the accuracy of very sparse, subjective historical sources of information.

These two challenges (the empirically based modeling of the interplay between universalist and relativist influences, and the need to examine the evolutionary dynamics of color categorization) are substantial obstacles to understanding human color naming and categorization phenomena even now. This article presents an investigative approach that addresses these challenges by idealizing two features inherent in human color categorization phenomena which have raised recent interest in the empirical literature: namely (i) color categorization under variation in individual color perception and (ii) color categorization under color space variation.

1.3. Idealizing two realistic influences on color categorization

The first feature, namely, potential variation in individual color perception and its influence on color categorization systems, originates from *within* the individual observer, representing what is generally viewed as a universalist type influence. Individual variation in color perception, while generally addressed in color vision science, has only recently played a role in the empirical color categorization literature (Sayim et al., 2005; Jameson, 2005d; Kuehni, 2005a, b), and the views on the impact of such variation are mixed. Jameson (2005a–d) recently discussed possible scenarios in which individual observer color perception variation might trade off with aspects of communication pragmatics arising outside observers in social situations of communicating about color. The present article explores such scenarios by formalizing simplified models of individual color perception variation and incorporating those models into individual category learning and population communication games. This provides a systematic way to assess the impact of idealized color perception variation on color category solutions.

The second feature idealized in our study, namely, the heterogeneity of color utility, potentially involves both cultural and environmental components, and therefore represents a relativistic influence. Realistically, several different sources may produce variation in color stimuli. Two such sources are: (a) environmental differences in color category exemplar frequency (i.e., frequency of green category exemplars may be greater in the rain forest compared to that for violet category exemplars), potentially expressed as a nonrandom sampling, or a heterogeneous "color diet"; (b) differences in pragmatically defined category ranges across the available color category exemplars (e.g., a nutritionally valuable reddish-orange exemplar may establish a trend for a more refined categorization, or a region of increased salience (RIS), compared to less valuable bluish category). Type (a) color stimulus variations were studied by Steels and Belpaeme (2005), Komarova et al. (2007a, b) and Dowman (2007). In the present article we introduce a novel investigation of type (b) heterogeneity and its effects on categorization.

The formal approach used here is based on the recent work of Komarova et al. (2007a, b), where our agent-based, evolutionary game-theoretic model of human color categorization was developed. We consider idealized populations of agents with different color perception abilities. Here individuals learn to categorize simulated colors by playing "discrimination-similarity games," and also learn to communicate the meaning of categories to each other. Population heterogeneity is introduced by varying, across agents, the "psychophysical transform" between the physical space of color stimuli and agents' perceptual spaces. The form of color stimulus heterogeneity used here is implemented by defining a RIS in the color stimulus domain.

1.4. Aims of the article

The present article aims to address several goals. First, using highly idealized models of real world phenomena, to develop investigative methods for examining possible trade offs in scenarios in which universal perceptual processing and socio-cultural factors both play substantial roles in the development and in the use of color categorization systems. Second, to examine the suggestion of Jameson (2005d) that nonrandom population heterogeneity will have a substantial impact on agent-based color category learning and on communicating population color category solutions, as well as figure prominently in the communication pragmatics (Jameson, 2005a, b). And third, to directly investigate the suggestion (Jameson, 2005a) that color salience (whether imposed by environmental scene statistics or through culturally imposed color sampling or salience) represents an important constraint on the development and use of a color

[1] Which typically appear in the literature as polarized extremes of the debate, but which are more akin to distant points in a continuum of possible explanations that involve a variety of potentially influential factors.