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Dynamics of Color Category Formation and Boundaries

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Definition

Dynamics of color boundaries is broadly the area that characterizes color categorization as a process that occurs over time.

Color Boundaries

A color category boundary is the area in perceptual color space where the labeling of one color transitions into another label. Color is a continuous wavelength dimension but distorted into nonlinearly perceived perceptual categories. A category boundary is fundamentally a distortion of continuous color space during perceptual and cognitive processing of color. There is no external signal in the wavelength dimension to tell the perceptual system to make this abrupt transition. This is called *the problem of invariance* [1]. The demarcation of color space has led to empirical work seeking to characterize color boundaries and discover their underlying dynamics.

There are various tasks that can be used to define a color boundary. One way researchers can do this is simply by presenting a color swatch and asking participants for the appropriate color label. Boundaries can also be measured by presenting two color swatches and asking whether they are the same or different, which is called *discrimination* (see "► Color Categorical Perception" for more details). The categorization graphs show a curve that can be classified as one of three types: step, sigmoid, or linear (Fig. 1). The step function is a theoretical ideal not found in empirical data. The discrepancy between the theoretical ideal and obtained data may be due to some meaningless noise in the perceptual system and appears in the data as a sigmoid, even though the actual underlying transition may be a discrete transition. Alternatively, the sigmoid may accurately reflect the boundary: The slope of the sigmoid is indicative of how gradual the transition is between categories. Finally, there could be a linear perception of the stimuli, which would indicate not having categories.

Human experimental data displays sigmoidal categorization boundaries, where stimuli near the boundary are not always reliably categorized into the same category. This area near the boundary is unique, because it represents a place in perceptual space where there is a distortion. This makes between-category distinctions a larger perceptual distance apart, effectively compressing within-category distances between stimuli and expanding between-category distinctions. One account states that categorical distortions are independent from and occur in parallel to continuous hue processing [2]. This issue bears upon whether categorical distortions have an effect on the perception of color or if they are a cognitive phenomenon induced by labeling rather than a warping of perceptual space [3].

Further support for the role of labels in the formation of category boundaries comes from comparative work on color perception. Color category boundaries do not arise from precortical processing, as there is no invariant signal coming from opponent process cells or the spectral

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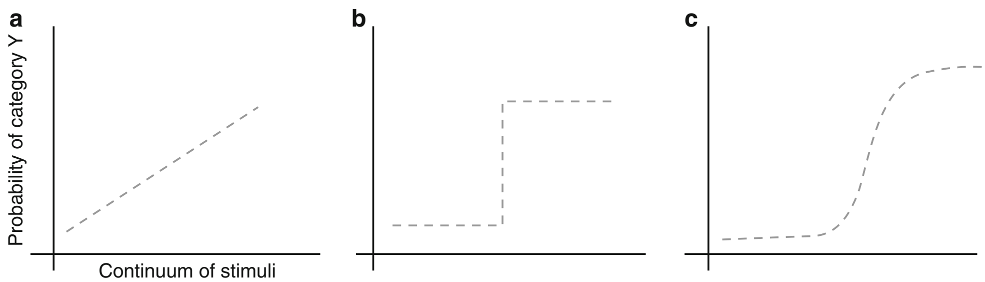

Fig. 1 Panel (**a**) illustrates a linear or identity function, panel (**b**) the step function, and panel (**c**) the sigmoid. A linear function represents sensitivity to continuity and a lack of categorization. The step function is the most extreme categorization, where there is an instantaneous transition from one category into another category. The sigmoid in panel (**c**) represents the more gradual transition from one category into another. In each panel, the *x-axis* represents a continuum ranging from category X to category Y, and the *y-axis* represents the probability or activation value for category Y

sensitivities of cones themselves. Thus, it is unlikely that boundaries arise from early low-level visual processes likely to be found in other primates. Baboons do not have color boundaries; rather, they perceive hue linearly, even though their retinal and opponent cell processing are similar to humans ([4]; also see "▶ Comparative Color Categories"). This evidence supports the role of higher level cortical processing and lends support to the Whorfian hypothesis (also called linguistic relativity). There is also evidence that color boundaries are learned and not innate further emphasizing a strong role for labels [5].

A dynamic view of color boundary formation is well supported by many already existing theories, including linguistic relativity (see "▶ Cultural Relativism and Color Categories" for more detail). This hypothesis acknowledges that the influence of language labels exerts some influence over the perception and formation of boundaries [6]. This influence could modify a boundary in many ways: Two labels could sharpen the boundary between them, making the sigmoidal slope steeper and expanding perceptual distances across the category boundary. One label could make the slope shallower or even linearly perceived (non-categorical). Finally, a label could translate the boundary, acting as an attractor or repellor for the boundary.

These kinds of dynamics are easily conceptualized as linguistic. However, many other factors could exert an influence on boundaries, such as biology, environment, or context. These alterations of the boundary could also happen at various timescales, on the order of minutes (adaptation; [7]), years (lifespan; [8]), or much longer spans (evolution; [9]). As opposed to thinking of color as something static and invariant, a dynamic view instead emphasizes the role of change and how those occur over time. The typical measurement of boundaries does not reflect influences of context that can alter the boundary [10].

Within a category hues are labeled the same. This could be because they are processed equivalently or because the task forces participants to place the stimuli into one of two categories. If they are processed equivalently, the underlying activation of the category should be all or none: For example, on a given trial, a given hue would be processed as entirely "green." Alternatively, both color categories may be active to various degrees. For example, the hue would be processed probabilistically as 0.8 "green" and 0.2 "blue." Over hundreds of milliseconds, the pressure of being required to put the hue in one of two categories would create competition between the two, finally resolving into a discrete answer of either "green" or "blue." This latter process is called gradient categorization and was shown to apply to color perception [11].

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One study demonstrated gradient categorization in color perception using a computer mouse tracking paradigm [11]. A color categorization task in which participants would begin moving vertically up the screen with a computer mouse and a color from a continuum of green to blue would appear briefly on the screen. The participants would continue moving up the screen and indicate their response by moving over a prototypically blue or green swatch in one of the top corners. The trajectories of computer mouse movements show subtle deviations toward the competing category response option – for example, veering toward green when the final response is blue. These deviations reflect the maintenance of continuous hue detail used to help make a discrete, categorical response. The categorical end goal and the gradation in processing coexist in the competition model and parallel human performance.

To demonstrate the maintenance of some form of continuous detail, whether that is in terms of raw hue value or in terms of distance to the category boundary, there must be evidence of a monotonic relation to the category boundary, as measured by some behavioral channel. This kind of signal is not seen in measurements taken only once per trial, as in typical naming tasks. A category boundary of some sort is mathematically guaranteed in a task requiring a decision between one of two items: Thus, within-category subtleties in processing are often neglected by measuring the boundary, which is informative about what is happening near the boundary (e.g., the steepness of the slope indicating the amount of distortion near the boundary).

Graded categorization can be computationally modeled as competition or even with an evolutionary algorithm emphasizing the role of motor movements [12]. Competition can be implemented with lateral inhibition, meaning that two representations are connected laterally and mutually inhibit one another (Fig. 2). This kind of a network shows gradations in performance during perceptual choices [13]. This network will cycle through the lateral connections, gradually taking the category with the highest activation and increasing its activation by stealing from the other node (Fig. 3). A mechanism like this is hypothesized to underlie the formation of discrete responses, and these gradations in initial activation can be seen in motor responses that are sampled at a very high density [11]. The competition model serves as a mathematical proof that one could accomplish a task such as categorical perception with minimally complex circuitry.

Category boundary formation is a dynamic phenomenon susceptible to context such as labels, objects, and the task being used. The typical color boundary is a relatively steep sigmoidal shape, and the steepness of this slope indicates the degree to which the perceptual or cognitive system has warped the continuous hue space. This could be due to competing labels or prototypes. The dynamic view emphasizes the characterization of these boundaries over many different timescales, and many different areas of color perception address these kinds of dynamic influences (Linguistic relativity, top-down influences, evolution of color categories, etc.) Future directions in this area may look more closely at these variables, and seek to characterize the process in real time, using dense-sampling methods appropriate to the timescale of the phenomenon.

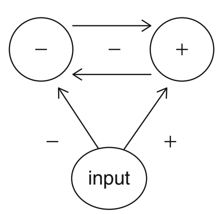

Fig. 2 The inputs range from −1 to +1 which represent a range of hues to be categorized. The second layer represents the two category options, and the lateral connections between them perform the competition

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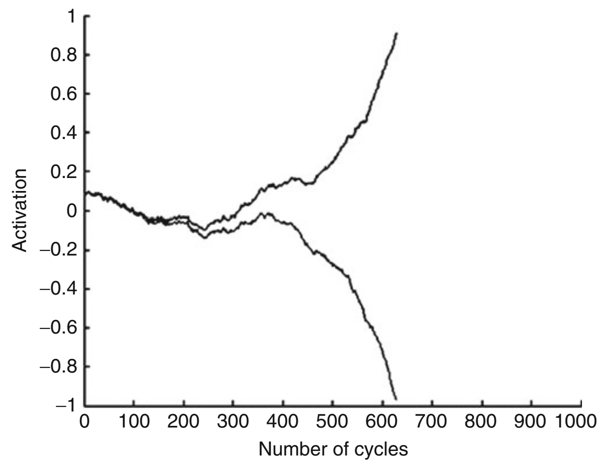

Fig. 3 Competition over time: the two nodes activations are plotted over a number of cycles. You can see the activations begin very similarly, and then gradually one begins to win, and it rapidly takes the activation away from the other node. This simulation contains a random noise term, which is responsible for the smaller fluctuations in each line, and can produce variability in the final response

Cross-References

► Color Categorical Perception
► Comparative Color Categories
► Cultural Relativism and Color Categories

References

1. Harnad, S. (ed.): Categorical Perception: The Groundwork of Cognition. Cambridge University Press, New York (1987)
2. Bornstein, M.H., Korda, N.O.: Discrimination and matching within and between hues measured by reaction times: Some implications for categorical perception and levels of information processing. Psychol. Res. **46**, 207–222 (1984)
3. Pilling, M., Wiggett, A., Özgen, E., Davies, I.R.L.: Is color “categorical perception” really perceptual? Mem. Cogn. **31**, 538–551 (2003)
4. Fagot, J., Goldstein, J., Davidoff, J., Pickering, A.: Cross-species differences in color categorization. Psychon. Bull. Rev. **13**, 275–280 (2006)
5. Özgen, E., Davies, I.R.L.: Acquisition of categorical color perception: A perceptual learning approach to the linguistic relativity hypothesis. J. Exp. Psychol. Gen. **131**, 477–493 (2002)
6. Roberson, D., Davidoff, J., Davies, I.R.L., Shapiro, L.R.: The development of color categories in two languages: A longitudinal study. J. Exp. Psychol. Gen. **133**, 554–571 (2004)
7. Bornstein, M.H., Korda, N.O.: Identification and adaptation of hue: parallels in the operation of mechanisms that underlie categorical perception in vision and audition. Psychol. Res. **47**, 1–17 (1985)
8. Raskin, L.H., Maital, S., Bornstein, M.H.: Perceptual categorization of color: a life-span study. Psychol. Res. **45**, 135–145 (1983)

DOI 10.1007/978-3-642-27851-8_64-6

9. Komarova, N.L., Jameson, K.A., Narens, L.: Evolutionary models of color categorization based on discrimination. J. Math. Psychol. **51**, 359–382 (2007)
10. Goldstone, R.L.: Effects of categorization on color perception. Psychol. Sci. **6**, 298–304 (1995)
11. Huette, S., McMurray, B.: Continuous dynamics of color categorization. Psychon. Bull. Rev. **17**, 348–354 (2010)
12. Beer, R.D.: The dynamics of active categorical perception in an evolved model agent. Adapt. Behav. **11**, 209–243 (2003)
13. Usher, M., McClelland, J.L.: The time course of perceptual choice: the leaky competitive accumulator model. Psychol. Rev. **108**, 550–592 (2001)