Combinatorics of Simultaneous Color Contrast

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Abstract

Simultaneous color contrast, the change in appearance of a color caused by surrounding colors, depends upon relationships of means and extremes in the color dimensions of value, intensity, and hue. In this paper, principles are defined and systematic methods are proposed for creating simultaneous color contrast. Combinatorial methods for simultaneous contrast effects are applied to value, intensity, and hue individually, then expanded to include combinations of these three color dimensions. Diagrams, formulas, and illustrations augment written descriptions, and examples of the author's artworks show creative applications of the ideas presented. A combinatorial approach to simultaneous color contrast offers the artist and designer a deductive method for producing color interactions, which can complement more traditional inductive, trial-and-error methods.

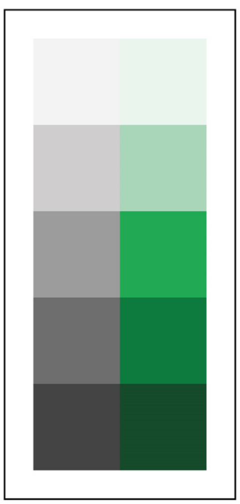
Introduction

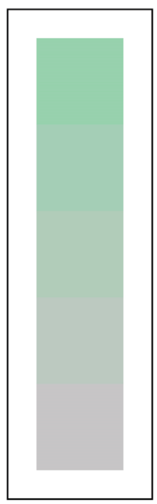
Although much has been done by artists and scientists over the centuries to produce color models that isolate, measure, and classify individual colors, the identity of any given color is ultimately elusive and changeable. Even when environmental lighting and all other variables are controlled, the identity of a given color in human perception depends on the context of other nearby colors. That is, the self-same physical patch of color can appear as many different colors—lighter or darker, brighter or duller, warmer or cooler—simply by changing the color that surrounds it. This phenomenon is called *simultaneous color contrast*, sometimes also known as *color interaction* or *color relativity*. Since a color is, for all practical purposes, always seen in the context of other colors, simultaneous contrast can be thought of as the organic, living reality of color. Color models, such as Munsell's "color tree," Ostwald's double-cone, and Küpper's rhombohedron, to name only a few, locate each color at a specific point in color-space but do not account for the range of appearances for any given color as a consequence of simultaneous contrast [2]. It is more accurate to consider a color as occupying not a point but an area of possible appearances that are determined by color contexts [4]. And yet, as elusive and relative as color can be, simultaneous color contrast is governed by structural principles and is largely predictable. This examination will use those principles to propose methods for combining colors and predicting results for simultaneous color contrast effects.

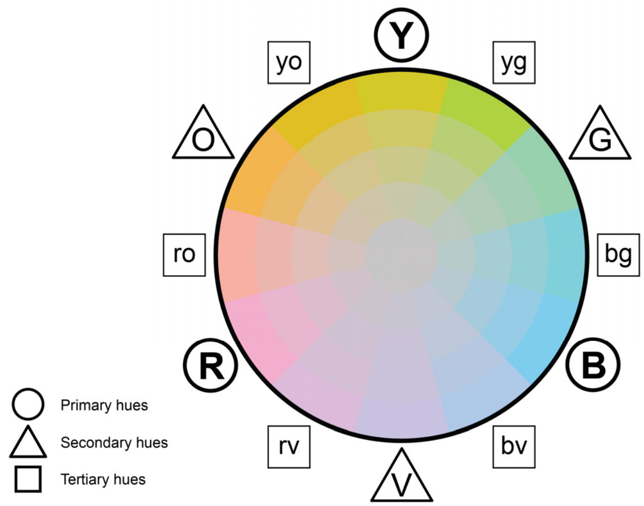
While this examination is grounded in empirical and repeatable color studies, neither the methods nor the purposes of this paper are scientific. Vision scientists are better positioned to explain physiological causes, collect data from multiple observers, and quantify results regarding light phenomena. Our perspective will be that of the artist or designer who can benefit from greater control and prediction of color relativity. We will assume our colors to be reflective (pigments) rather than projective (light), whose principles of mixture are subtractive rather than additive. Since this examination concerns the perception of color relationships, the reader is strongly encouraged to review the full-color digital version of this paper.

Color Dimensions and Terminology

It is important to the subsequent discussion to establish some color concepts and terminology. Human color perception distinguishes three qualities of any given color: (1) ***Value*** is the lightness or darkness of a color, sometimes also referred to as *light intensity* or *brightness* or *tints and shades* (see Figure 1a) In pigments, a color's value is usually changed by adding white to lighten or black to darken. Each color in its pure state (at its highest intensity) has a distinct inherent value. For example, a yellow lemon is naturally lighter in value than a red apple; thus, a black and white photograph would record a lighter gray from the lemon and a darker gray from the apple. (2) ***Intensity*** is the brilliance or dullness of a color; this quality is sometimes referred to as *saturation* or *chroma*. High intensity refers to the pure state of a color's intensity, its most brilliant state; low intensity (or *neutral*) refers to its dullest state, gray (see Figure 1b). For example, a red fire engine is more intense than a red brick, which in turn is more intense than gray concrete. In pigments, a color's intensity is reduced by the addition of its complementary color; the intensity of a bright red would be reduced by the addition of green. (3) ***Hue*** is the spectral identity of a color, that which distinguishes yellowness from redness from blueness, etc. In the arts, the traditional model of hues is the color-circle, obtained by joining the violet and red ends of the visible spectrum into a closed loop of continuously changing hue (Figure 1c, hues are shown at constant value). The color-circle offers a practical and generally accurate model for understanding not only hue but also intensity relationships. Hues change gradually around the circle, while intensities change gradually from high at the periphery to low (neutral) at the center, owing to the diametrical placement of complementary hues. As important, hues are also organized in classes: *primary hues* (yellow, red, blue) are unobtainable from mixtures; *secondary hues* (orange, green, violet) are mixed from equal portions of two primary hues; and *tertiary hues* (yellow-green, yellow-orange, red-orange, red-violet, blue-violet, blue-green) are mixed from equal portions of primary and secondary hues that are adjacent on the color-circle. The following hue abbreviations will be used below: primaries are *Y, R, B*; secondaries are *O, G, V*; tertiaries are *YG, YO, RO, RV, BV, BG*. In addition, we shall sometimes refer to the hue classes, primary, secondary, tertiary, as *P, S, T*. We shall call these three characteristics *dimensions* of color because all—value, intensity, hue—are simultaneously present in any instance of color.







(a) *(b)* *(c)*

Figure 1: *Color dimensions: (a) value; (b) intensity; (c) hue.*

Precedents and Principles of Simultaneous Color Contrast

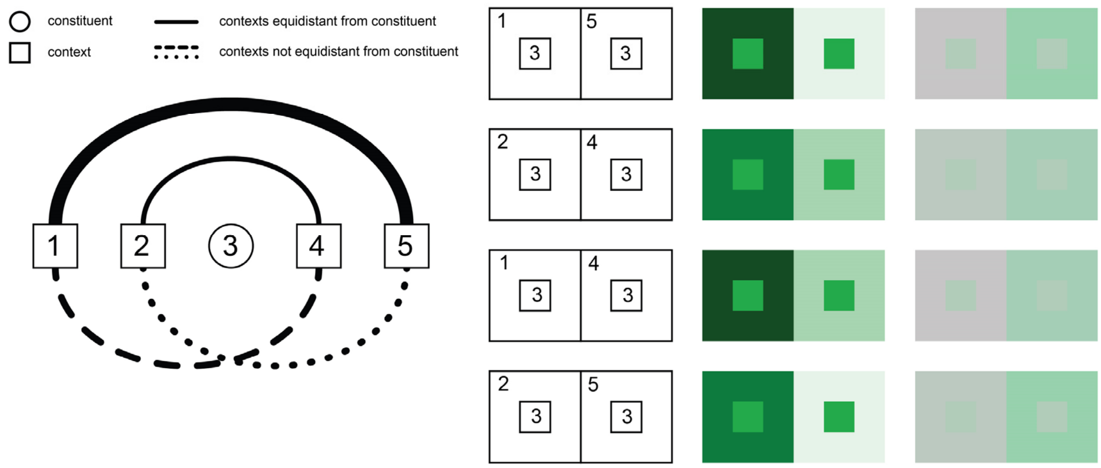
M.E. Chevreul (1786-1889), a chemist working on colored dyes in the production of tapestries, conducted the first systematic studies of how a color is modified by surrounding colors when he noticed perceptual color changes in tapestry threads viewed at a distance. Chevreul's 1839 book, *The Principles of Harmony and Contrast of Colors* influenced many artists in the late 19th and early 20th centuries, perhaps most notably the neo-impressionist Georges Seurat (1859-1891), whose paintings clearly show the simultaneous contrast of values (later known as Mach bands) occurring along the edges of forms. From the middle of the 20th century up to the present, the most influential book for artists and designers regarding simultaneous contrast has been Josef Albers's *Interaction of Color*, produced in 1963 as a portfolio of silkscreened color studies with an accompanying text. Although *Interaction of Color* shows a variety of excellent examples of simultaneous contrast, Albers (1888-1976) stops short of proposing a system or theory for achieving optimal color interactions and instead encourages inductive, empirical experimentation. This is not a criticism—far from it—because Albers rightly recognized that simultaneous contrast is a perceptual experience that constantly surprises, and he wanted to ensure that theory did not hamper the discoveries of practice [1]. Nevertheless, given enough inductive experimentation with color, one can recognize patterns of behavior in color interactions that point to general principles, which offer the possibility for deductive approaches to and predictive strategies for simultaneous contrast effects.

The following general principles are neither exhaustive nor final; instead, they are "working principles" distilled by the author from many years of working with this color phenomenon. In what follows, *constituent* refers to a smaller, surrounded square of color and *context* refers to a larger, surrounding square of color (see Figure 2 for examples). The principles of simultaneous color contrast important to this examination are: (1) ***Context color changes the appearance of constituent color.*** The larger principle at work in simultaneous contrast is that colors affect each other mutually. However, it is possible to tip this mutual influence in one direction more than another, making one color (*context*) exert the greater influence on another color (*constituent*). The context color exerts the stronger influence when: (a) it occupies the greater area; (b) it surrounds the constituent, and (c) there is no additional, comparative instance of the context color. (2) ***Color-appearance differences are comparative.*** Recognition of multiple appearances of a single color requires comparing—in the same field of view—two or more instances of the same constituent color, each in a different color context. This is the significance of the term *simultaneous* color contrast, which fundamentally differs from the temporal, before-and-after experience of *successive color contrast* (aka, *after-image*). Without comparisons, a single instance of a color has a single, static identity. (3) ***Actual color differences are perceptually exaggerated.*** Perception heightens the differences of value, intensity, and hue between the context and the constituent colors. This can be thought of as a perceptual "rebound" effect, where actual color differences become more contrastive, especially at the contact-edge of the colors. (4) ***Constituent color is intermediate between context colors.*** That is, on the spectrum of a given color dimension, the constituent color must reside between the context colors for an appearance change to occur in the constituent. For example, a constituent middle-value gray appears darker on a lighter gray, and it appears lighter on a darker gray—the "rebound" effects occur in opposite directions, resulting in two value appearances of the same-color constituents. Minimal to no difference in the constituent will be seen if both context colors lie on the same "side" of the constituent; for example, if both contexts are lighter than the constituent, the constituent would appear darker in both contexts—the "rebound" would occur in the same value direction. (5) ***Greater contrast yields greater illusory change.*** The degree of value, intensity, and/or hue contrast between context and constituent colors generally correlates to the degree of color-appearance change in the constituent. For example, a middle-value gray constituent appears even lighter on a black context than on a dark gray context.

Simultaneous color contrast is a complex phenomenon, with additional principles and implications, including compositional requirements [3], various magnitudes of appearance shift [4], and the convergent function, where two different constituents are made to appear the same (in contrast to the divergent function, where the same constituent has two appearances, which is our current topic) [2]. However, the above-stated five principles can guide us towards a systematic, exhaustive method of creating simultaneous color contrast effects, with the benefits of not only arriving more directly at colors that create the effect but also seeing a range of subtly different possibilities from which to choose the most appropriate version for a given purpose. Further, this combinatoric method splits the interactions into categories of value, intensity, and hue such that one may compare the differences among color dimensions for their specific effects, and for the selective combinations of constants and variables among the dimensions. In sum, a combinatorial approach to simultaneous color contrast intends both to broaden our understanding of the range of effects and to narrow our selections to those that optimally serve specific creative purposes.

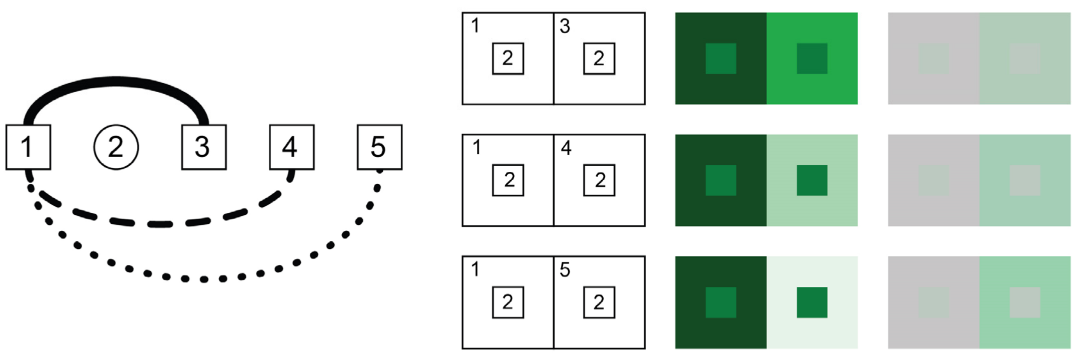
Simultaneous Value Contrast Combinations

We shall employ a value scale of five equal steps, extending from dark (value-1) through light (value-5). Any number of value steps could be employed, but five has the advantage of a clear-cut middle value (value-3) that is halfway between dark and light, and two intermediate values (value-2 and -4) that lie halfway between the middle and the extremes. That is, for combinatorial purposes related to the principle



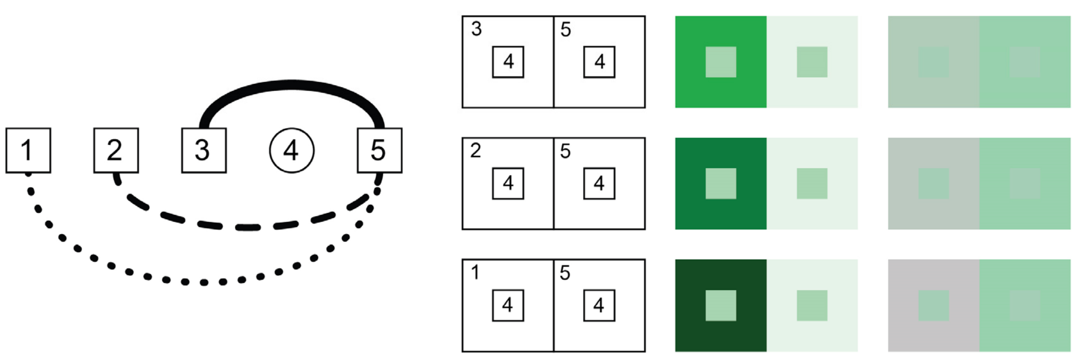
(a) (b) (c) (d)

Figure 2: *Simultaneous value and intensity contrasts, constituent-3: (a) combination diagram; (b) square-in-square-diagram; (c) value illustration; (d) intensity illustration.*



(a) (b) (c) (d)

Figure 3: *Simultaneous value and intensity contrasts, constituent-2: (a) combination diagram; (b) square-in-square-diagram; (c) value illustration; (d) intensity illustration.*



(a) (b) (c) (d)

Figure 4: *Simultaneous value and intensity contrasts, constituent-4: (a) combination diagram; (b) square-in-square-diagram; (c) value illustration; (d) intensity illustration.*

of intermediates and extremes (principle-4, above), we have three possible intermediate constituents: value-2, -3, and -4. Beginning with value-3, we can identify two combinations where the constituent value is equidistant from both context values (3 on 2 and 4, and 3 on 1 and 5), and two combinations where the constituent is closer to one context value than the other (3 on 1 and 4, and 3 on 2 and 5). Diagrams (Figures 2a, 3a, 4a) show the combinations graphically: constituents are indicated by a circle and contexts by squares. Pairs of contexts are connected by lines: solid lines denote contexts that are equidistant from the constituent, and broken lines denote non-equidistant contexts. Constituent-3 has four pairs of contexts owing to its two possibilities for equidistant contexts (Figure 2a, solid lines), as contrasted with constituents 2 and 4, each with one equidistant context pair (Figures 3a and 4a, solid lines). All resulting combinations are also diagrammed in the traditional square-in-square color interaction format (Figures 2b, 3b, 4b) and these are illustrated in color (Figures 2c, 3c, 4c). The sample color illustrations are limited to a single hue (green) at a constant intensity (intensity-5).

These ten value combinations may be applied to each of twelve hues (three primaries, three secondaries, six tertiaries), yielding 120 simultaneous value contrast combinations. Each hue also may appear in five possible intensities (see below), yielding a total of 600 distinct square-in-square value interactions. We can reduce this when we recognize that intensity-1 (neutral) is actually the same color for all 12 hues, meaning that there is only a single set of ten intensity-1 combinations rather than 12, yielding a final total of 490 value combinations (12 hues × 4 intensities = 48 + 1 neutral = 49 × 10 value combinations).

Simultaneous Intensity Contrast Combinations

As with value, the intensity combinations will employ a five-step scale, extending from low (intensity-1) through high (intensity-5). With five intensity increments, the combinatorial method for intensities is the same as that used for values. Thus, the combinatorial diagrams (Figures 2a, 3a, 4a), and the square-in-square diagrams (Figures 2b, 3b, 4b) for value apply also to the intensity combinations. The square-in-square color illustrations offer visual examples of the simultaneous intensity contrasts (Figures 2d, 3d, 4d). Again, the reader is encouraged to consult the full-color digital version of this paper since the intensity interactions do not vary values. The ten distinct intensity combinations may be applied to each of 12 hues, and each hue at five possible values, yielding a total of 600 distinct square-in-square intensity interactions. However, each of those 600 versions maintains a constancy of value and hue in any given interaction; the number of combinations becomes far larger when values are permitted to vary within the same square-in-square interaction.

Simultaneous Hue Contrast Combinations

Hue combinations are differently structured than value and intensity combinations. We derive the intermediates and extremes for hues both from the hierarchic relationships of primaries, secondaries, and tertiaries and from the circular organization (see Figure 1c). Hue combinations will be constrained by the following four rules: (1) ***Constituents are limited to secondary and tertiary hues only.*** This is due to the aforementioned principle that constituents are intermediate between more extreme contexts, which for hue means that constituents are *compound hues* and contexts are the *component hues* of the compounds. Secondaries are compounds made of primary components, and tertiaries are compounds made of primary and secondary components. Primaries are not compound hues, and so are not constituents. (2) ***Context hues are limited to the hue-classes (primaries or secondaries) of the component hues.*** Contexts for secondary constituents are primary hues (but not the complementary primary, see #3 below); contexts for tertiary constituents are all secondary and primary hues. (3) ***Hues that are complementary to the constituent cannot serve as contexts.*** This is for the reason that the simultaneous contrast effect of complementary hues affects the intensity appearance rather than hue appearance of the constituent. That is, the "rebound" effect of complementary hues is in a diametrical line across the color-circle (passing through neutral), which is the direction of intensity change, rather than around the color-circle, which is the direction of hue change. (4) ***The two context hues of any given simultaneous contrast combination must lie left and right of the constituent hue on the color-circle.*** This is for the reason that the aforementioned "rebound" effects must occur in opposite directions if the constituent is to assume different appearances on each ground. If the context hues lie on the same side (left or right) with respect to the constituent, the contexts will have parallel effects on the constituent, yielding little to no appearance change.

We can now define some general formulas for combining hues and examine the specific combinations that these formulas yield. Secondary constituents on primary contexts create only one general formula: S on P and P. Given three secondaries, we have a total of three specific simultaneous hue contrast combinations: O on Y and R; G on B and Y; V on R and B (see Figure 5). While three combinations may seem rather limited, we should remember that each of these has five value versions and five intensity versions, so there are in total 30 combinations of the secondary-constituent interactions. Further, we should remember that these 30 combinations do not vary the values or intensities in a given square-in-square interaction. As we will see below, the combinations vastly increase, as does the effectiveness of many interactions, when values and intensities are varied in a single square-in-square interaction.

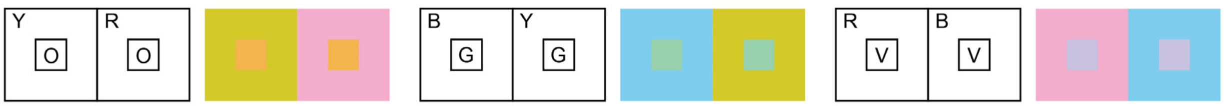


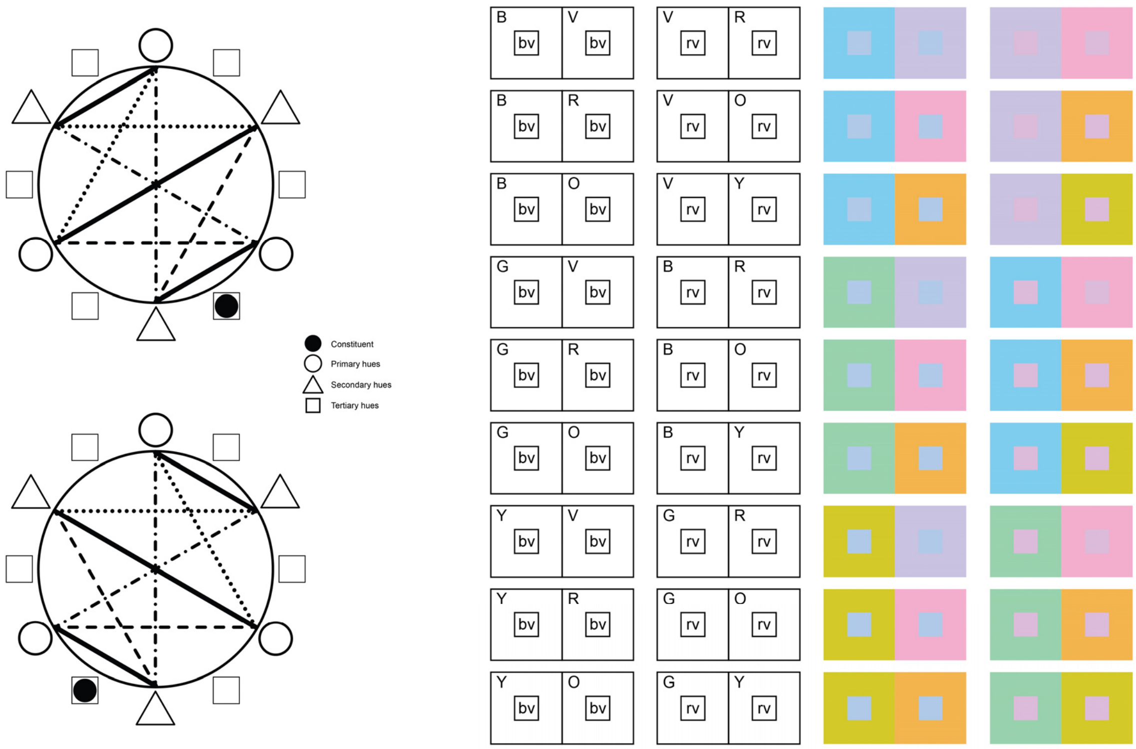
Figure 5: *Simultaneous intensity contrasts, secondary constituents on primary contexts.*

Tertiary constituents on primary and secondary contexts yield nine general formulas, the terms for which require some additional specification: abbreviations for context colors S (secondary) and P (primary) are followed by parenthetical designations R or L (right or left) and 1 or 2 (for first or second position relative to the constituent). For example, P(R2) is "the second primary to the right." Additionally, because of the disposition of tertiaries around the color-circle, there is a different number of primary and secondary hues left and right of half of the tertiaries (see Figures 1c and 6a), necessitating two related but alternate sets of formulas for the six tertiaries. We can refer to these as *formula set-A* and *set-B*; set-A applies to tertiaries positioned to the right of a secondary (YG, BV, RO) and set-B to those positioned to the left of a secondary (BG, RV, YO). The two sets of nine formulas are listed in Table 1a, and the corresponding specific combinations for tertiaries BV (set-A) and RV (set-B) are listed in Table 1c. The nine general combinations (both set-A and set-B) are diagrammed in color circles (Figure 6a). Diagram lines (Table 1b) correspond to context pairings in the color-circle diagrams (Figure 6a). The BV and RV combinations are shown as both square-in-square diagrams (Figure 6b) and square-in-square color illustrations (Figure 6c).

Table 1: *Simultaneous hue contrast combinations, tertiary constituents: (a) general formulas; (b) diagram lines (see Figure 6a); (c) specific combinations for BV and RV constituents.*

Set-A (YG, BV, RO)	**Set-B** (BG, RV, YO)	**Diagram Lines**	**Set-A** (BV constituent)	**Set-B** (RV constituent)
T on P(R1) + S(L1)	T on S(R1) + P(L1)		BV on B + V	RV on V + R
T on P(R1) + P(L1)	T on S(R1) + S(L1)		BV on B + R	RV on V + O
T on P(R1) + S(L2)	T on S(R1) + P(L2)		BV on B + O	RV on V + Y
T on S(R1) + S(L1)	T on P(R1) + P(L1)		BV on G + V	RV on B + R
T on S(R1) + P(L1)	T on P(R1) + S(L1)		BV on G + R	RV on B + O
T on S(R1) + S(L2)	T on P(R1) + P(L2)		BV on G + O	RV on B + Y
T on P(R2) + S(L1)	T on S(R2) + P(L1)		BV on Y + V	RV on G + R
T on P(R2) + P(L1)	T on S(R2) + S(L1)		BV on Y + R	RV on G + O
T on P(R2) + S(L2)	T on S(R2) + P(L2)		BV on Y + O	RV on G + Y

(a) *(b)* *(c)*

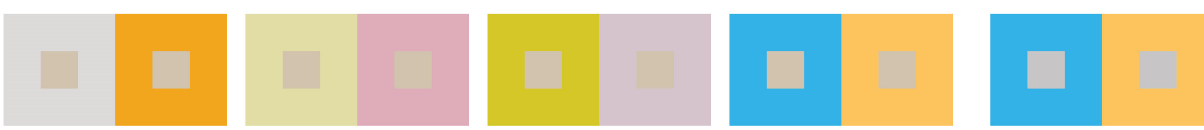


(a) (b) (c)

Figure 6: *Simultaneous hue contrast combinations, tertiary constituents: (a) diagrams of general formulas, set-A (above) and set-B (below); (b) BV and RV diagrams; (c) BV and RV illustrations.*

Combinations of Combinations

Each of the above three combination categories—value, intensity, hue—vary only one color dimension while holding the other two color dimensions constant. We can expand the combinatorial approach further by varying more than one color dimension in a given square-in-square interaction. There are four multi-variable combinations: (1) value and intensity variable (hue constant); (2) value and hue variable (intensity constant); (3) intensity and hue variable (value constant); (4) value, intensity, and hue variable. Figures 7a through 7d show these four combinations for a constituent that is orange at intensity-2 and value-3.



(a) (b) (c) (d) (e)

Figure 7: *Multi-variable combinations: (a) value and intensity variable; (b) value and hue variable; (c) intensity and hue variable; (d) value, intensity, and hue variable; (e) same as 7d with neutral constituent.*

Some of the most dramatic and surprising examples occur when all variables are in play (Figure 7d). Because all color dimensions are variable, this can include a combination that we have so far not addressed: complementary contexts, which can yield intensity interactions. For example, the orange constituent appears more intense on the complementary blue context in Figure 7d than it does on the neutral context in Figure 7a. This kind of interaction can go so far as to make the constituent hue itself appear as complementary hues, which often has a greater perceptual effect because it appears to be more a change of "kind" than of "degree." For example, Figure 7e shows a fully neutral constituent (orange, intensity-1, value-3) that appears blueish neutral on the orange context and orangish neutral on the blue context.

Figures 8 and 9 show recent artworks by the author that employ the last-mentioned type: variable values, intensities, and hues. The compositional arrangements, as well as the use of color gradients, expand further the possibilities presented so far. In these artworks, the colored lines are constituents, which change appearance in response to the context colors of the circles and annulus shapes. For example, in "Eccentric (YG)" (Figure 8), the yellow-green line appears darker and greener at lower left; yellower and lighter at upper right; lighter and more intense upper left; and darker, less intense, and warmer/oranger at lower right. While these multi-variable combinations are often desirable, any one of the types of combination mentioned in this paper (single- or multi-variable) could provide the ideal simultaneous contrast effect for one's purposes. I have employed each combination type in various artworks as the need has arisen.

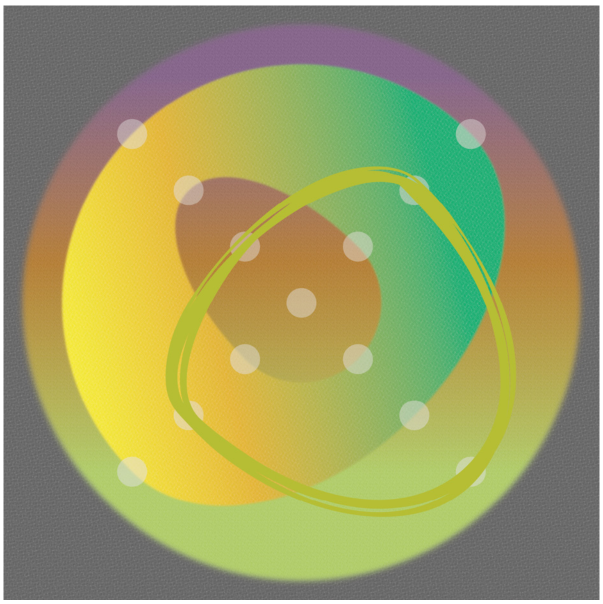


Figure 8: *"Eccentric (YG)" digital print, 14x14 inches, 2019.*

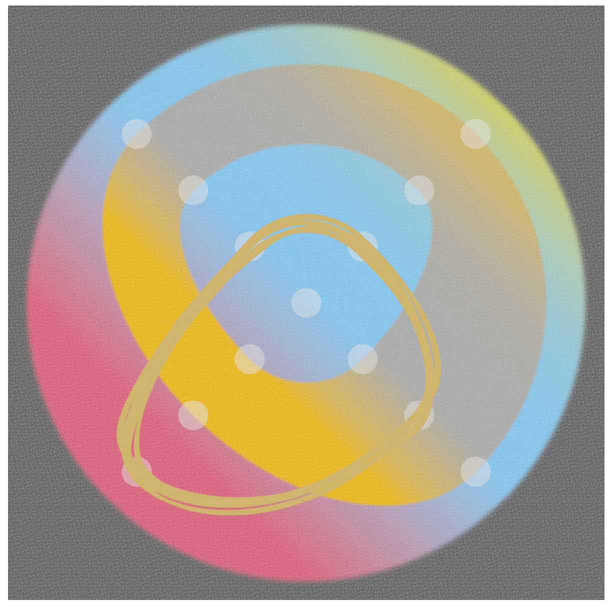


Figure 9: *"Eccentric (YO)" digital print, 14x14 inches, 2019.*

Conclusion

It is not realistic in this paper to create a catalog illustrating examples of every possible combination. The benefit of the combinatoric method to my studio work is that it provides not an inventory but a strategy for producing limited sets of color combinations for comparing and optimizing choices. That is, the combinatorial method serves as a map to navigate the vast terrain of all the possible color combinations. The combinatoric approaches presented here offer the dual advantages of a deductive, systematic means for producing a full array of interactions while also preserving the valuable role of inductive, empirical processes of fine-tuning colors towards new and specific simultaneous color contrast effects.

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