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RESEARCH ARTICLE

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Color order systems, color mixtures, and the role of cesia

José Luis Caivano

Universidad de Buenos Aires, and National Council for Research (Conicet), School of Architecture, Buenos Aires, Argentina

Correspondence
José Luis Caivano, Universidad de Buenos Aires, and National Council for Research (Conicet), Buenos Aires, Argentina.
Email: caivano@fadu.uba.ar

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Abstract
Two questions are mainly discussed in this article: (a) how the shape of color order systems is related to different types of chromatic mixtures, and (b) how the opacity or transparency (an aspect of cesia) of the coloring media involved in the mixtures define the results, beyond the established categories of additive, partitive, and subtractive mixtures. The degree of transparency, translucency, or opacity of the material used certainly has a great influence on these processes and in the results obtained, and we could also think that the degree of gloss or matte finish of the surfaces affects the mixtures as well. The underlying idea is that these processes are of a gradualist nature, and that a continuous sequence can be traced between two poles: additive mixture of overlapping lights, on one side, and subtractive mixture of transparent color layers, on the other one. Thus, instead of just three separate or unconnected types of color mixtures, we can postulate a model based upon a gradual sequence between additive and subtractive mixture, with partitive mixture as one of the steps in between. A schematic 3D model of gradual transformation is proposed to encompass different color systems that represent any possible mixture between additive and subtractive.

KEYWORDS
cesia, color mixtures, color order systems, gradualism, transparency and opacity

1 | INTRODUCTION: THE CONCEPT OF CESIA

This article offers an overview on how the shape of color solids of different order systems is related to various types of color mixtures, and how the degree of opacity or transparency of the coloring media involved in the mixtures defines the results, beyond the established categories of additive, partitive, and subtractive mixtures. The general hypothesis is that these processes are of a gradualist nature, and could be better understood as a continuum rather than being classified as separate categories.

Let us define some basic aspects. From the image of Figure 1A, we can take the features represented in the rectangles, and everybody will agree on saying that they are different colors. If the image is reduced to lines or borders built by color changes, we refer to shapes, that is, objects defined by their boundaries or spatial delimitations (Figure 1B). We can also pay attention to the different textures present in the image (Figure 1C). Finally, we may refer to aspects such as transparency, gloss, translucency, matte appearance of opaque objects, etc. For all these aspects, that have something in common, César Jannello coined the term cesia (Figure 1D).

Cesia is defined as an aspect of visual appearance that accounts for sensations that vary along three axes:

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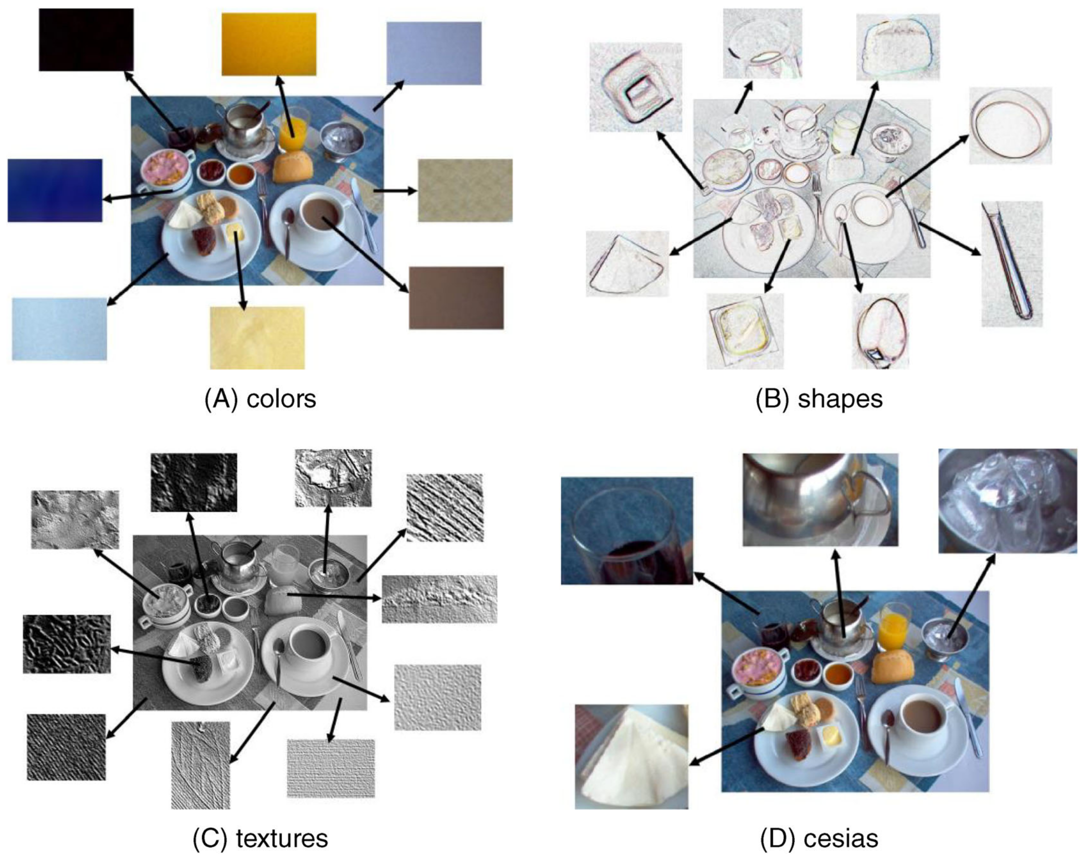


FIGURE 1 Four aspects of the visual appearance of an image

transparent vs opaque, glossy vs matte, and light vs dark.[1,2] Objects may produce different spatial distributions of light, and this constitutes the stimulus for the perception of cesia. A diffuse light reflection of an opaque object normally produces a matte appearance. A regular or specular reflection generates a mirror-like appearance. A regular transmission of light is normally seen as transparency, while a diffuse transmission of light, as translucency. Finally, if an object absorbs almost all the light that it receives, it will be seen dark or black (Figure 2).

Such as there are color atlases with physical samples, we have also the possibility to assemble an atlas of cesias.[3] The atlas shown in Figure 3 is made with pieces of glass. In the first plate of the atlas, opaque samples change in diffusivity, from mirror to matte, with intermediate steps of gloss, and produce a variation in darkness, toward black. In the last plate, transparent samples change also in diffusivity, from clear transparent to totally translucent, with intermediate steps of translucency, and also produce a variation of darkness toward black. Different plates of the atlas (each plate showing changes in diffusivity and darkness) display in turn the variation along the opaque vs transparent axis (Figure 3A). In Figure 3B, the plate of the atlas featuring transparent and translucent cesias, which also change in darkness, is used to make a comparison in order to establish a visual match with an object.

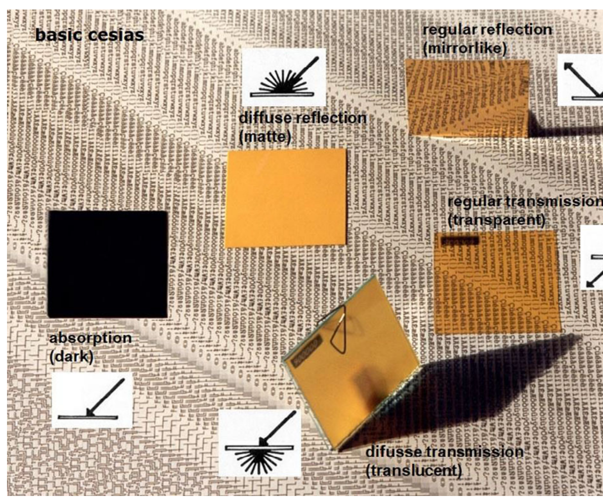


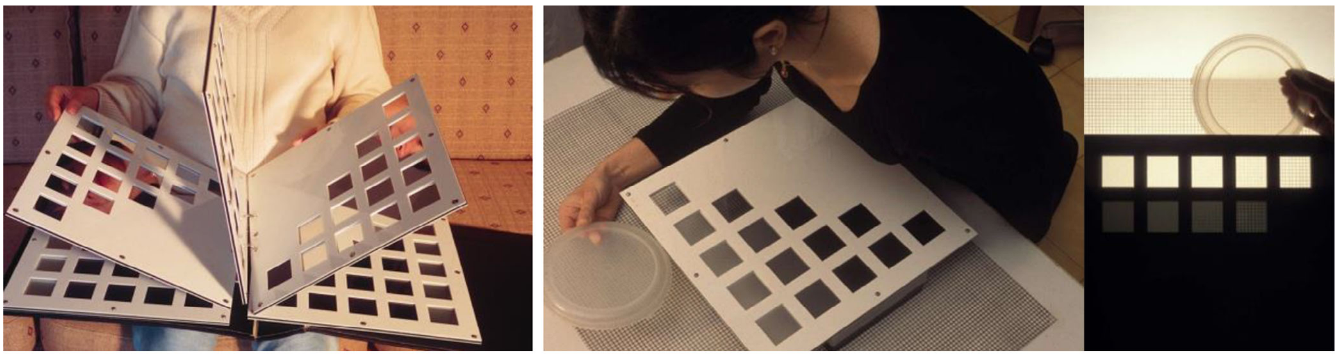
FIGURE 2 Five basic sensations of cesia (the perceptual aspect) and five types of spatial light distributions (the physical aspect)

What is the relationship of color with cesia? Every color may appear in all possible cesias. For instance, a yellow color may have a matte, transparent, mirrorlike or translucent appearance. And every cesia may appear in all possible colors. A transparent cesia, just to mention one case, may be seen in blue, green, yellow, red, or any other color. Cesia interacts with color in many processes, and one of them is color mixtures.

2 | TRADITIONAL CATEGORIES OF COLOR MIXTURE

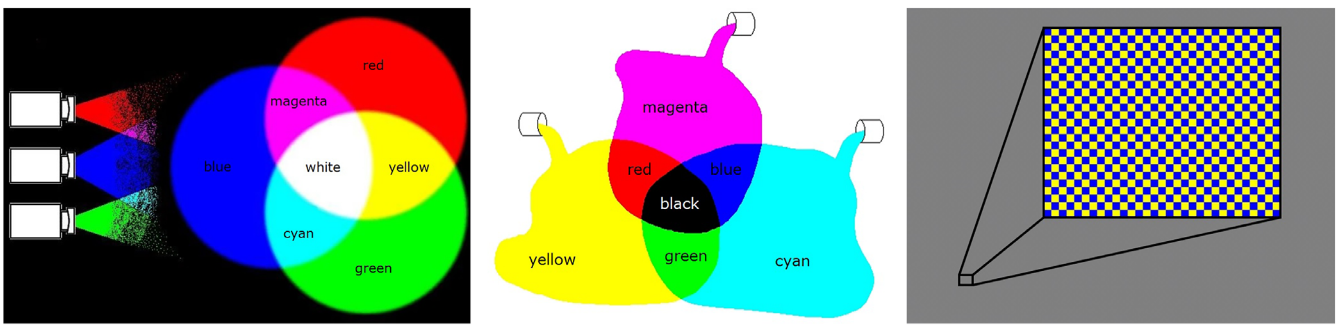
In regard to color mixtures, we usually take for granted that there are three categories:

1. Additive mixing (the sum of colored lights projected on a surface) yields colors that are brighter than the original colors. For example, in the additive mixture of red, green, and blue, magenta is brighter than blue and red, yellow is brighter than red and green, cyan is brighter than green and blue, and finally, white is brighter than all of them (Figure 4A).
2. Subtractive mixture produces colors that are darker than the original colors. For example, in the typical subtractive mixture of yellow, magenta, and cyan, red is darker than yellow and magenta, blue is darker than magenta and cyan, green is darker than cyan and yellow, and finally, black is darker than all of them (Figure 4B). This kind of mixture could be made with inks, dyes, or overlapping film layers that work as filters, and selectively absorb some spectral components of the light that is reflected or transmitted toward the observer.
3. The case shown in Figure 4C is different. We perceive a uniform gray field on the background, but if we enlarge a small sector of it, we can realize that it is composed of adjacent yellow and blue cells that are too small to be perceived individually. This is similar to the pointillist and divisionist techniques of painting.[i] The eye integrates the small dots, and the result is a partitive or optical color mixing, which produces a color whose lightness is an average of the original colors. The optical mixture of the yellow and blue dots in Figure 4C, generates the gray color, which is lighter than the blue one and darker than the yellow one. This kind of color mixture can also be made with



(A) (B)

FIGURE 3 A, A prototype of an atlas of cesia made with pieces of glass. B, Using the transparent/translucent plate of the atlas to make a visual assessment of an object in terms of permeability, diffusivity, and darkness (the three variables of cesia)



(A) (B) (C)

FIGURE 4 A, Additive mixture (lights): the resulting colors are always brighter. B, Subtractive mixture (inks, dyes): the resulting colors are darker. C, Partitive or optical mixture: the resulting color is intermediate in terms of brightness/lightness spinning disks. A blue and a yellow sector on a disk produce a grayish color when the disk is spun fast (see Figure 5B).

3 | ANALYSIS AND DISCUSSION OF THE TRADITIONAL CATEGORIES OF COLOR MIXTURE

Beyond these examples of additive, subtractive, and partitive mixture, things may be different if we consider particular cases that depart somehow from the typical situations. The tenet assumed in the additive mixture seems to verify in all cases, since the mixture works by adding light, and the result is always a higher brightness, or perceived luminance (Figure 5A). But there are some differences, for instance between overlapping lights and adjacent small light dots (as in computer or TV screens).

In Figure 5B, we present an optical mixture using spinning disks with matte-colored papers. The yellow sector has 96% lightness, or perceived reflectance, and occupies 25% of the total disk. The blue sector has 52% lightness and occupies 75% of the total disk.[ii] The resulting grayish color has a lightness of 63%, which is an area-weighted average of the yellow and blue sectors.[4] In short, the resulting gray has a lightness value that stands in-between the lightness of the yellow and blue sectors. But regarding this statement about partitive mixture we may consider: What happens if instead of using disks with matte surfaces we employ glossy surfaces? And what happens with translucent and transparent surfaces?

Another case is the trichrome process of printing with transparent inks (yellow, magenta and cyan), which produce a mixture that is halfway between partitive and subtractive. Where the printed dots overlap, the result is a darker color (that is, to say, a subtractive mixture). But where the dots are adjacent or separate, they will produce an intermediate color (which is a partitive mixture) when seen at distance.

For colorant mixtures, there are cases in which the subtractive rule is not fulfilled. In Figure 6, yellow and blue opaque pigments are dispersed in water. At the center, they mix in a brownish color with low saturation. But this color is not darker, as could be expected from a subtractive mixture. Instead, it has an intermediate lightness between yellow and blue, as we can see in the diagram with the numerical values below. Thus, it must be regarded as a partitive mixture, not a truly subtractive one. This issue has been explained in detail by David Briggs[5]: "The physical mixing of paints is often described simply as subtractive, but in reality a component of additive-averaging mixing is usually also involved." And it was also recognized seven decades ago by The Physical Society in its *Report on Color Terminology*[6]: "Pigment mixture is not entirely subtractive; it involves both additive and subtractive mixture."

Opacity, one of the aspects of cesia, is the key aspect here. The degree of opacity of paints is measured by extending thin layers on a black and white contrasting pattern. In the scale of cesia of Figure 7A, we can see the variable that changes along the axis going from transparent to opaque. On the left, a transparent layer of varnish allows one to see very clearly the contrasting black and white pattern of the background. The varnish is gradually mixed with a black opaque paint, and the scale increases in darkness, with decreasing degrees of transparency. Thus, the black and white contrast of the background

FIGURE 5 A, Overlapping lights produce an additive mixture: blue + yellow (red + green) = white; the resulting color is brighter. B, Spinning disks with color cardboards produce a partitive or optical mixture: blue + yellow = gray; the resulting color is an area-weighted average of both sectors' lightness: Yellow: 96% L × 0.25 = 24%. Blue: 52% L × 0.75 = 39%. The resulting grayish color is 24% + 39% = 63% L

gradually disappears, covered by the layer of paint. Another possibility is to gradually mix the transparent varnish with a white opaque paint (Figure 7B). And in this way, the scale increases in opacity toward the right end, passing through intermediate translucent steps, but keeping the maximum lightness (or the opposite, that is, darkness approaching zero). Again, the black and white contrast of the background tends to disappear step by step, now covered by the white paint.[7] The same kind of scale of cesia, from transparent to opaque white, is developed in Figure 7C, where clear water is gradually mixed with opaque milk.

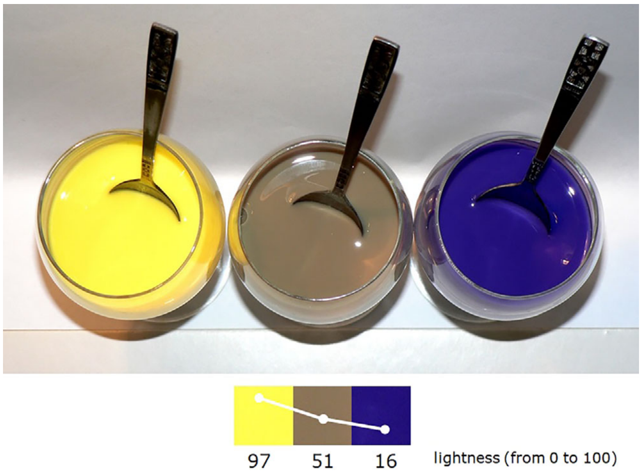


FIGURE 6 Mixture of opaque pigments dispersed in water. It is a partitive mixture; the resulting desaturated brownish color is intermediate in lightness

In Figure 8A, the same blue and yellow pigments of Figure 6, instead of being dispersed in water, are mixed in paste, with very little water content. Again, the resulting green color is intermediate in lightness, following the rule of partitive mixture. The conclusion is that pigmentary mixture should not be taken as a synonym of subtractive mixture. This is more evident when we mix the same pigments in powder form, not using water at all (Figure 8B). Here, it is clear that the green color is the result of a partitive mixture, where the blue and yellow small particles do not mix intimately but remain separate, adjacent to each other, being mixed by the eye of the beholder.

When transparent layers overlap, the result is certainly a subtractive mixture. In Figure 9A, the green color produced is darker than both yellow and cyan, as we can see in the numerical diagram below, with lightness indicated. But if instead of superimposing layers of perfectly transparent color films, they are somehow translucent, the result approximates a partitive mixture. Note that the green color in the middle of Figure 9B is still a little bit darker, but is closer in lightness to the cyan layer. With an increasing degree of translucency, we will obtain a lighter green color that will stand intermediate between yellow and cyan, becoming thus product of a partitive mixture.

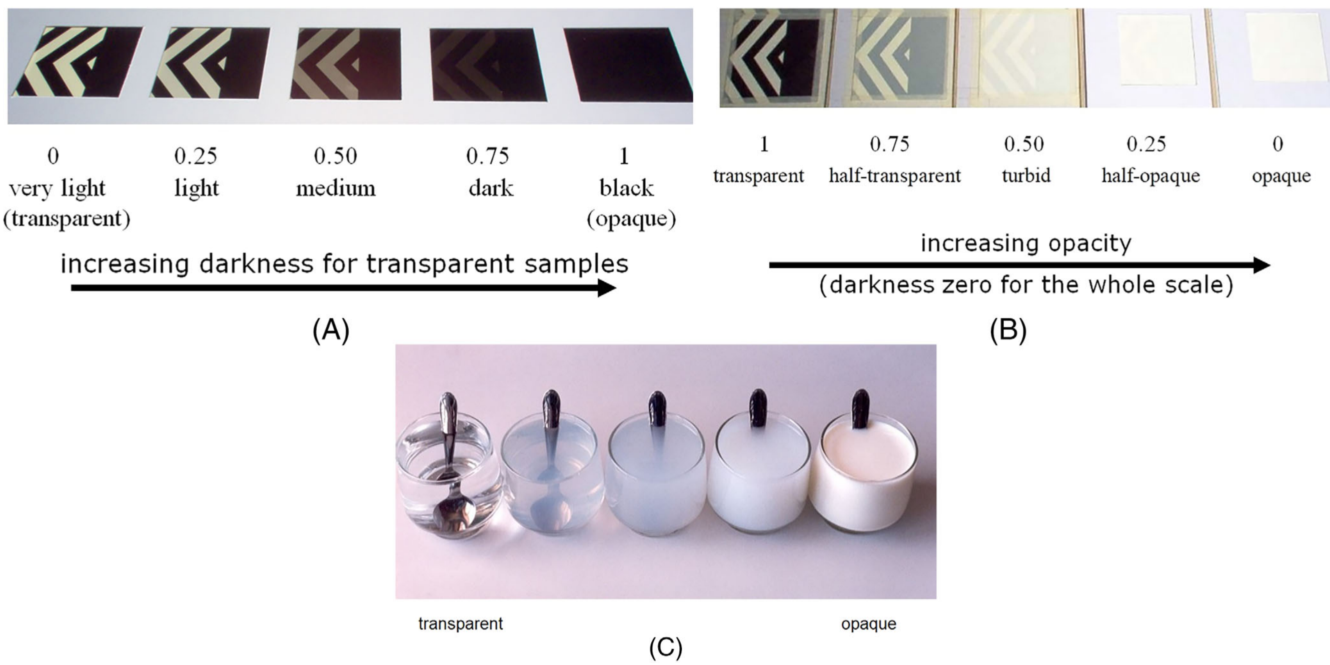


FIGURE 7 The transparent-opaque variable. A, Mixture of a transparent varnish with black paint; the transparent samples get darker. B, Mixture of a transparent varnish with white paint; the samples lose transparency and gain opacity. C, A scale from transparent to opaque obtained by mixing water with milk

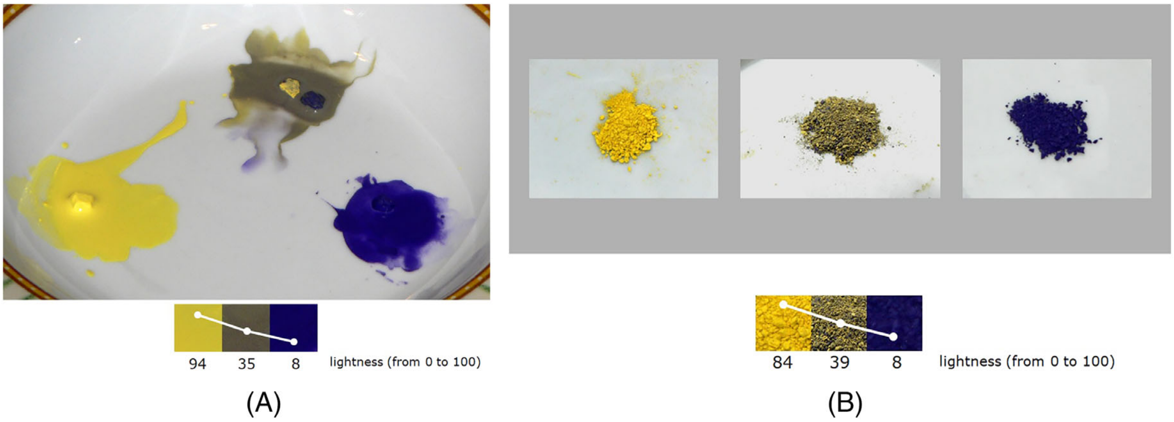


FIGURE 8 Pigmentary mixtures that are partitive; the resulting green color is intermediate in lightness. A, Mixture of pigments in paste (with little content of water). B, Mixture of pigments in powder

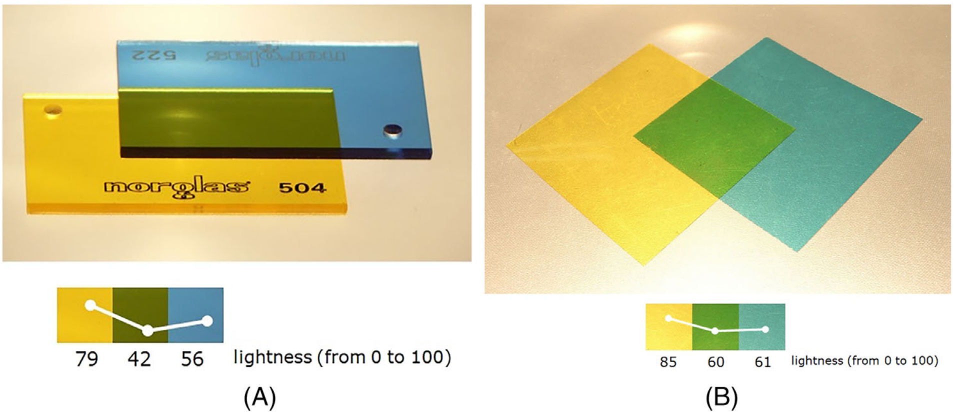


FIGURE 9 A, Overlapping highly transparent acrylic plates produce a subtractive mixture: cyan (absorbing red)/yellow (absorbing blue) = green; the resulting color is darker. B, Overlapping polyester films that are not perfectly transparent, but have a certain degree of translucency, still produce a subtractive mixture, but the lightness of the resulting green color approaches the limit where the mixture would become a partitive one

Helmholtz discusses in detail the results of using different procedures to mix colors.[8] One of them is mixing spectral lights by obtaining a full spectrum and then selecting three monochromatic lights by letting only three narrow sectors of the spectrum pass through slits made on a screen. He selects red, green, and violet, and obtains white by mixing all three. Then, he reports what happens with material substances, either transparent dyes, more translucent paints, and pigments in powder form. He explains the physical aspects involved, to arrive finally at the light that is directed toward the observer, which will elicit the color sensation. Finally, he mentions the spinning disks with radial sectors of colored papers, and an arrangement with a glass and two different colored papers, one seen by reflection and the other by transmission.

Harald Küppers is aware of these aspects when he develops his laws of color synthesis[9]:

- additive synthesis (for instance, color television),
- subtractive synthesis (eg, color photography),
- layers of translucent and opaque color (paints applied in overlapping layers),
- integrated mixture (opaque paints mixed with each other and then applied in a single layer),
- optical mixture (small color dots that cannot be perceived individually and are integrated),
- rapid mixture (color stimuli at very short time intervals).

Küppers asserts that "there are at least eleven laws of color mixture."

Our hypothesis goes a little beyond that. Instead of thinking of three, 11, or any other number of different color mixtures, let us consider them as a gradual or continuous sequence between two poles: additive and subtractive.

4 | COLOR ORDER SYSTEMS AND COLOR MIXTURES

What happens with color order systems in this context? In most cases, the shapes of color order systems are connected to the type of color mixture that they represent. The difference between additive and subtractive mixture begun to be understood just during the 19th century, after Helmholtz, Grassmann, Maxwell, and others. In 1852, Helmholtz describes his experiments on mixing colors by using lights or colorants, emphasizing the different results in both cases. This will be further developed in his *Treatise on physiological optics*, where he already uses the words "addition" and "subtraction" to differentiate the processes.[10]

Once this difference was clear, the systems representing light mixtures and those that respond to colorant mixtures started to adopt different shapes: conical shapes for the former (typically with one vertex, where black is located), and approximate double-cones or spherical shapes (with two poles, for white and black) for the second ones (Figure 10).

There are, however, some cases which are difficult to classify; for instance, Ostwald's double cone. Let us go back to Maxwell and Helmholtz for a while, in relation to Ostwald. One of the methods for mixing color used by Maxwell, and employed also by Helmholtz, in addition to other methods, was the device of spinning disks with colored papers in radial sectors.[11,12] We have seen the same device as an example of partitive mixture in Figure 5B.

Ostwald used the same method: spinning disks with three radial sectors: black, white, and a pure hue or full color. By this way, and following psychophysical scales, he calculated and obtained the intermediate colors in each monochromatic triangle around the circle of hues.[13] During the 19th century and the very beginning of the 20th century, this method was still regarded as a way of producing additive mixtures. The category of partitive mixtures was not yet established. Later in the 20th century, this method will be said to produce a partitive mixture, also called optical mixture, not a truly additive one.

5 | A GRADUAL MODEL OF COLOR ORDER SYSTEMS IN RELATION TO COLOR MIXTURES

Color order systems evolved during more than 2,000 years, from linear scales—one-dimension—,

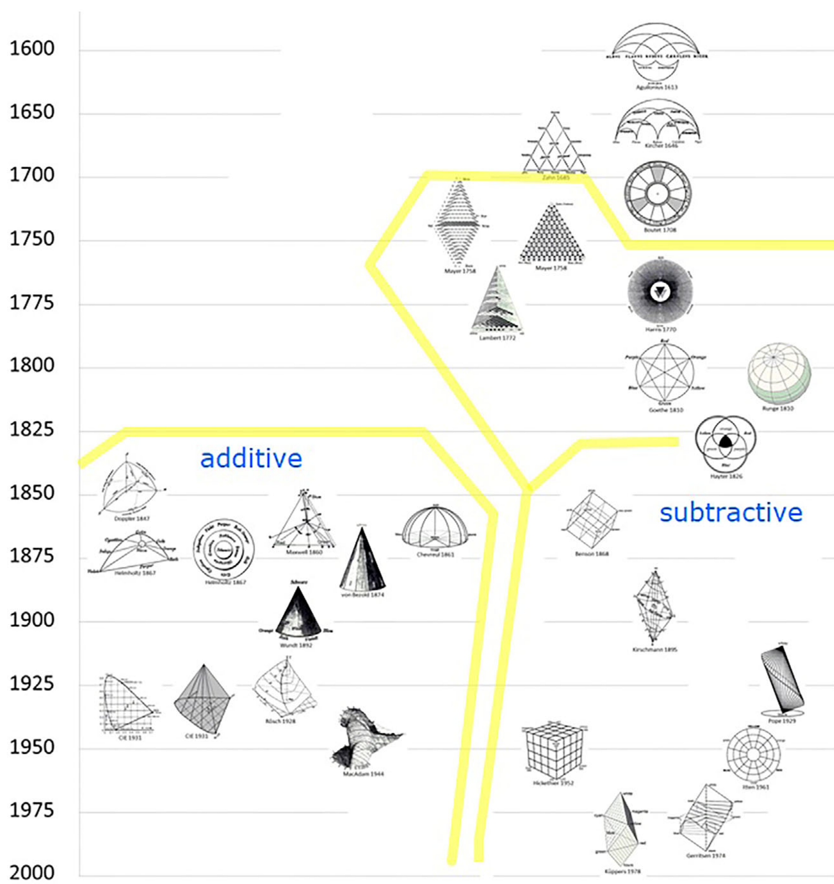


FIGURE 10 By the middle of the 19th century, the distinction between additive and subtractive mixing caused color order systems to begin adopting different shapes

progressively changing to two-dimensional schemes—circles, squares, triangles—and arriving to the modern three-dimensional models.[14-17] The 3D systems begin to appear in the 18th and 19th centuries, with the form of pyramids, cones, spheres, cubes, and other more complex and sophisticated shapes that have been devised in the 20th century. The evolution of these color order systems was produced in parallel to the changes in the theoretical conceptions of color, as well as in relation to the practical needs of producing colors through

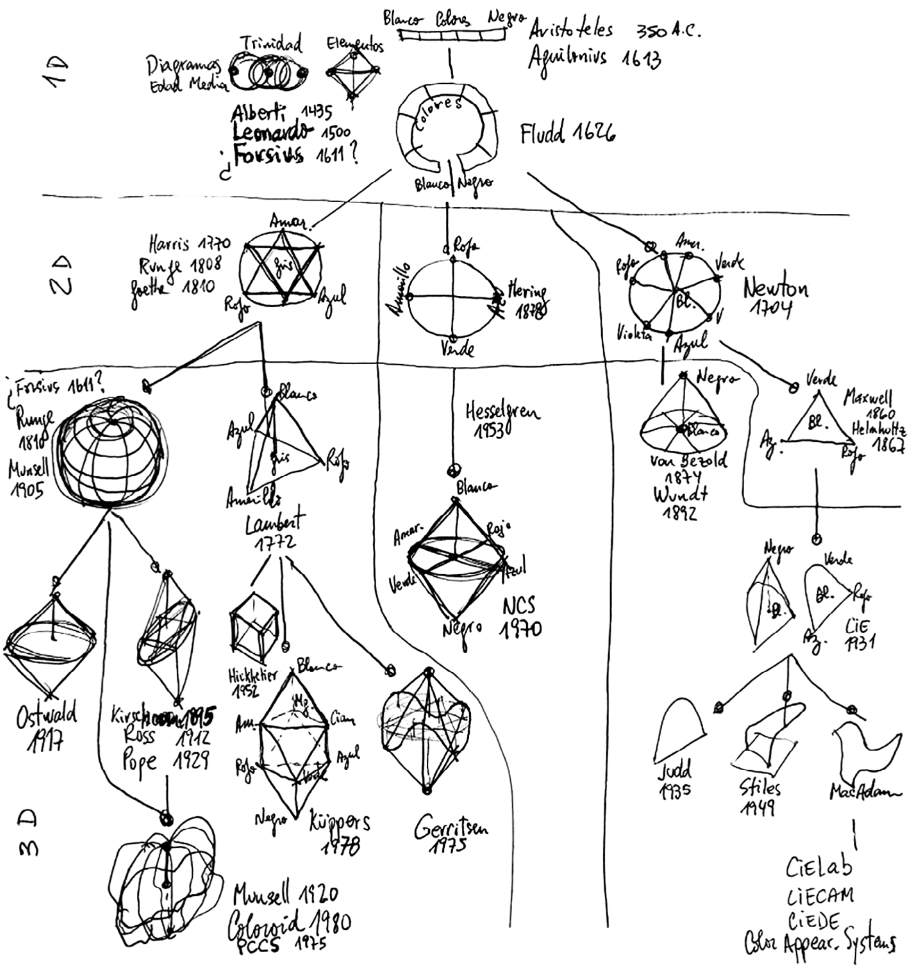


FIGURE 11 An evolutionary classification of color order systems (a sketch made in 2004)

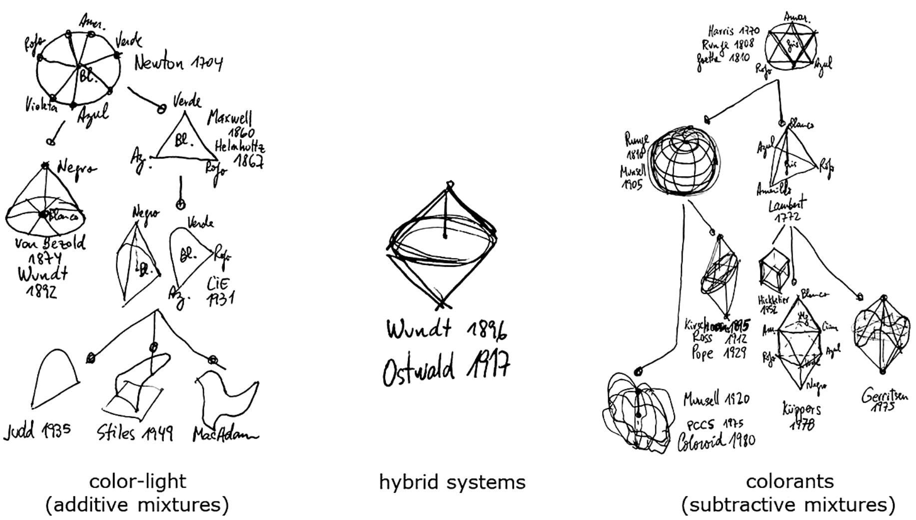


FIGURE 12 Typical shapes of color order systems representing additive light mixtures (left), subtractive colorant mixtures (right), and hybrid or intermediate systems (middle)

mixtures of dyes, pigments, lights, or other types of material means.

By 2004, I started to represent this panorama of color order systems as an evolutionary sequence or a tree, whose branches are divided according to the theories of color and to the practices of color mixing. The idea is that the shape adopted by color order systems is related to the color theory to which they ascribe and the type of color mixture they represent (Figure 11).

There are systems based on the trichromatic theory and the principle of additivity, devised to predict mixtures of color lights. They are useful for colorimetry, color reproduction in TV and screens, and lighting technology in general. Other systems are intended to explain colorant mixtures. They are mainly based on subtractive principles, and are useful in painting, graphic industry, design, architecture, etc. However, some models exhibit a certain ambiguity. They could be regarded as somehow hybrid systems, or intermediate steps representing other cases of color mixtures, since sometimes it is difficult to draw a clear separation between additive, partitive, and subtractive mixture (Figure 12).

A separate mention deserves the Natural Color System, based on Hering's theory of opponent colors, whose purpose is not to represent color mixtures of any kind. It takes color as a visual sensation, no matter how is it produced or what kind of mixtures are needed.[18,19]

Anyway, if we focus just on the relationship of color order systems with color mixtures, there are three basic cases (Figure 13):

1. Red, green, and blue primary lights mix additively in white at the base of a conic shape; brightness decreases towards black, which is placed at the vertex.

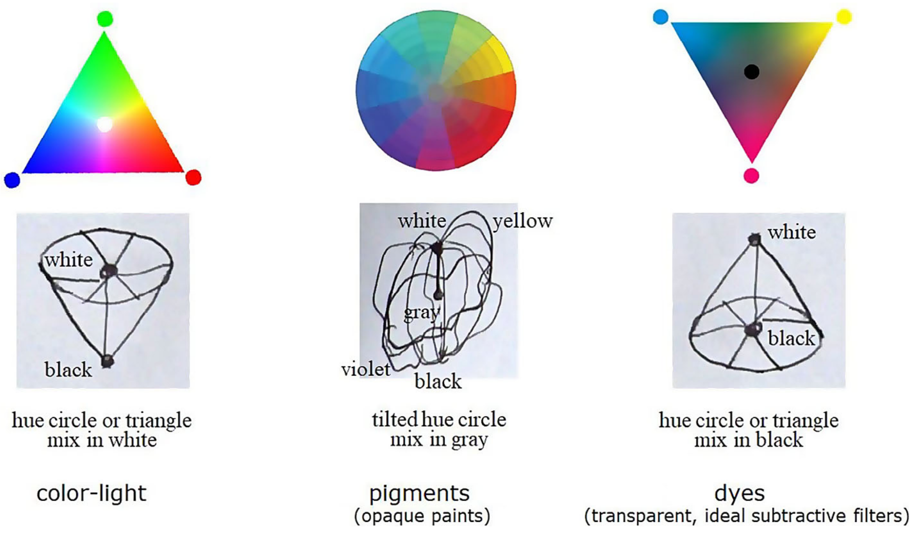


FIGURE 13 Three generic shapes of color order systems that account for light mixtures (left), opaque pigments (middle), and ideal transparent dyes or filters (right)

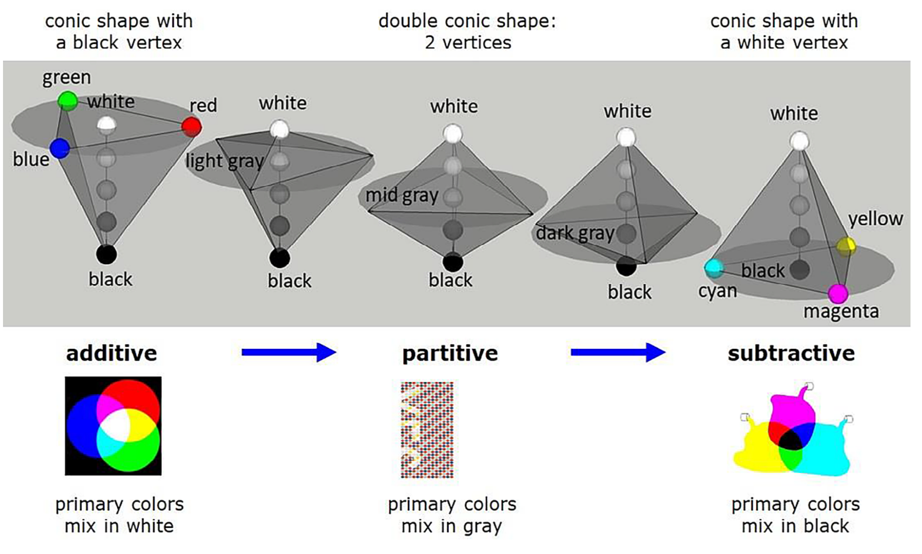


FIGURE 14 A schematic 3D model of gradual transformation of color order systems, from perfect additive synthesis to ideal subtractive mixture

2. Opaque pigments displayed around a tilted hue circle (with yellow closer to white and violet closer to black) mix in middle gray, which is located midway along the achromatic axis, in an approximate spherical shape (ie, usually irregular).
3. Cyan, magenta, and yellow, working as ideal transparent subtractive filters or dyes, mix in black at the center of the triangle; while white is located outside this surface, where the subtractive colorant layers have no influence at all.

With all this in mind, there are various cases of color mixtures that can be investigated, considering gradual steps between additive mixture (on one pole) and subtractive mixture (on the other one). Inspired also on Küppers' criteria,[9] this is a proposal for a gradual sequence:

Lights	• superimposed or overlapping • adjacent lights, in small size (without overlap) • intermittent lights, in fast sequence
Small color dots	• overlapping • adjacent • separate (on a white background)
Color surfaces spinning or moving fast	• with matte finish • with glossy finish
Opaque pigments	• mixed in powder • mixed in paste (graduating the amount of water) • totally dispersed in water
Translucent pigments	• with decreasing turbidity (from near opaque to near transparent)
Transparent inks Transparent filters	• previously mixed and applied in one coat • applied in successive coats, after the previous is dry • superimposed or overlapping

It is necessary to verify these cases experimentally, considering that the degree of transparency, translucency or opacity of the material, as well as the degree of gloss or matte finish of the surfaces, will have a great influence on the processes and the results. That is why cesia is important. And instead of three separate or unconnected types of color mixtures, we can postulate a model based upon this gradual sequence between additive and subtractive mixture, with partitive mixture as one of the steps in between. Actually, there is not just a single case representing each category, but a range of cases within each: perfect additive mixture, a range of additive mixtures approaching to partitive ones, a certain range within the partitive category, partitive mixtures approaching to subtractive ones, a range of subtractive mixtures, and finally a perfect one (even if it is an ideal case).

And thus, a schematic 3D model of gradual transformation can be proposed to encompass different color systems that represent any possible mixture between additive and subtractive. At one extreme, the mixture of three color lights (usually red, green, and blue) gives white as a result. In the middle, an optical mixing of primary colors results in a middle gray. At the other extreme, the subtractive mixture of transparent inks, acting as layers that absorb light (as used in color printing, for instance) yields a very dark gray, almost black, as the result. The base or the middle surface of these models may consist of triangles or chromatic circles, divided according to the number of primary or principal colors considered. And this surface gradually moves down (from white to black) along the achromatic scale (Figure 14).

This proposal is also somehow related to Paul Green-Armytage's idea of an elastic color solid.[20] If a particular 3D color order system can be "morphed" into another by stretching or compressing their dimensions in an elastic way, as he proposes (following the topological rule that, in order to maintain its equivalence, the space can be stretched, shrunk, bent or twisted, but without causing breaks or separations and without inserting aggregates), this means that there are numerous intermediate states along this transformation, that is, there could be a continuous or gradual transformation among systems.

This is a proposal, a scheme, or a hypothesis that needs further elaboration and experimental work. But this gradualist approach could be a way to advance our knowledge not only about color order systems but also color theory in general, if this idea is applied to different aspects of color research.[21]

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

ORCID

José Luis Caivano https://orcid.org/0000-0003-2047-4919

ENDNOTES

[i] A good criterion to explain a difference between pointillism and divisionism (if any) is offered by Hirschler et al, who based upon Floyd Rattlif, pose the issue as a matter of a variation of scale and viewing distance.[4] This is another example of how a gradualist conception provides a better understanding of two different aspects that may be considered as particular instances of a continuous sequence.

[ii] Even when in all our examples (Figures 5, 6, 8 and 9) we are dealing with different kinds of color stimuli and coloring media, in order to compare the results on a common ground, we consider the lightness values as reproduced and measured in our photographs.

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AUTHOR BIOGRAPHY

José Luis Caivano is a researcher at the National Council for Research, Argentina, and professor at the Buenos Aires University, School of Architecture, where he also leads the Color Research Program. Degree in architecture, PhD in theory of art, with more than 130 publications and 100 lectures worldwide, he holds the highest category in the National Research System of Argentina. He is a former research associate at the Center for Language and Semiotic Studies, Indiana University President of the International Color Association, International Association for Visual Semiotics and Argentine Color Group, and honorary member of Ad Chroma (France), the Portuguese and Mexican Color Societies. He is also a member of the editorial board of various international journals and associate editor of Color Research and Application.

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