COLOR AFTERIMAGES AS FILTERED PERCEPTION OF EXTERNAL PHYSICAL COLORS

Riccardo Manzotti

Color afterimages have often been considered an example of phenomenal experience that is ontologically independent from objective physical properties instantiated in the external environment. As a result, color afterimages have been presented as evidence of the psychological nature of colors. In contrast with this tradition, I will address color afterimages from a radically externalist perspective according to which colors are not the outcome of internal computational processes, but rather external physical properties that exist relative to our body. This hypothesis is coherent with a performative view of colors where the executive and motor components of behavior are key factors that single out the physical properties that are identical with one's experience. I will present empirical evidence in support of this view.

Keywords: Afterimage, Colors, Consciousness, Hering, Helmholtz, Perception, Performativity.

Are color physical properties in the external world? Are colors psychological or physical? According to the autoritative *Cambridge Handbook of Color Psychology* (Shevell, 2015, xxi), they are not of physical nature[1]:

> For generations, the school child's mnemonic – red, orange, yellow, green, blue, indigo violet – has undermined the scientific foundation of understanding color. What appears to be an innocent aid for recalling the sequence of spectral colors is instead *a misleading assignment of colors to physical wavelengths* of light. When the hues from red through violet are attached to wavelengths from 700 through 400 nanometers, it suggests that the colors we see are properties of the wavelengths themselves but that is not so. Physical wavelengths have no color; […] *Color is in the mind of the viewer (thus psychological), not in light (the physical)* or even in the eye's photoreceptors, which create from light the essential biological signals for seeing.

The notion that colors exist only «in the mind of the observer», while popular, is indeed startling for many reasons. First, it implies

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a dualistic ontology that may admit psychological entities over and above the physical ones. Second, it suggests a radical revision of the familiar world in which we live. The world would then be utterly devoid of colors. Third, if one is a physicalist, the notion seems to be self-contradictory insofar as, if the physical world is colorless and the brain is part of the physical world, colors cannot exist at all.

Yet, the notion of a colorless world is indeed very popular both in current neuroscience and in philosophy of mind – e.g., «colors are generate in the visual brain» (Zeki *et al.* 2017, 1). Yet, if colors are neither in the light nor in the objects, where are they? Why should it be any easier to locate them in neural processes (or, worse, «in the mind of the observer») than in the external objects? If we did not see physical colors, then what would we see? While the scholastic correspondence between wavelengths and hues is over simplistic, ruling out the physical nature of colors might be a hasty conclusion. No matter how complex is the nature of the properties that we call *colors*, as a physicalist, whatever they are, they must be physical properties (Byrne, Hilbert 1998).

However, both in philosophy and neuroscience, the notion that colors are not properties of the external world has gained increased acceptance. To justify such a radical notion, one might expect the existence of extraordinary and overwhelming evidence against the feeling that the world is indeed colored. Surprisingly, the available evidence amounts to the traditional argument from hallucination and a few sparse cases of color illusions. Here, I will skip cases of color hallucinations and I will focus on a familiar color illusion: color afterimages (sometimes called complementary afterimages). My aim is to show that it is possible to outline a physicalist account of afterimages that does not require any mental color. If my approach to afterimages has any merit, it will be possible to remove afterimages from the evidence in support of a mental nature of colors.

Color afterimages provides a good case because they have been routinely presented as cases in which color experience is generated internally either as a result of emergent properties of neural activity or as the outcome of yet-unknown computational process. The color of an afterimage is commonly assumed to be a mental concoction of either illusory or hallucinatory nature (Brown 1965; Hurvich 1981; Thompson 1992; Hardin, 1993; Tye 1995; Block 2002; Cohen, Matthen 2002; Langsam 2006; Laureys, Tononi 2009; Schwitzgebel 2011; Macpherson, Platchias 2013). In this regard, Ian Phillips observed that afterimages «have long formed a core part of the sensationalist's critique of purism» (Phillips 2013, 417).

In contrast with this tradition, I will defend an account of afterimages which is based on direct perception of existing physical properties of external objects. The line of attack will consist in revealing a systematic mistake in the accounts of afterimages. By doing so, it will be possible to interpret the actual data in a different manner and propose a realist and physical model for color perception. Given the importance of afterimages as alleged evidence that colors are mental or psychological, an account of them in terms of external physical properties will have philosophical and scientific relevance. This is precisely what I will try to accomplish here.

A color afterimage is a common phenomenon in which one sees a color (usually shaped in some way) that does not seem to belong to the scene one is staring at[2]. For example, when standard trichromats stare for several seconds at a colored patch – the *stimulus* –and then stare at a white or gray surface – the *ensuing surface*, they will briefly see another color – the *afterimage color*. The ensuing surface is the uniform surface that is shown *after* the stimulus is removed and *against which* the afterimage is seen.

The key point of contention will be whether the colors one sees in afterimages are physical colors or whether they are only «in the mind» of the perceiver. The gist of the proposal is that, in the case of afterimages, because of chromatic adaptation, one sees external colors that are otherwise be inaccessible but nonetheless that are instantiated by external objects (Byrne, Hilbert 2003). Afterimages will then be explained as perception of physical colors instantiated by external objects. If confirmed, such a hypothesis is philosophically relevant because afterimages will no longer be evidence for the mental nature of colors.

1. TRADITION *VS* SPREAD: WHERE ARE THE COLORS OF AFTERIMAGES?

For the sake of the discussion, let's focus on the red/green color case which is ideal to test the proposed hypothesis (other combinations will yield similar results). One stares at a green patch and then while staring at an ensuing gray or white background, one will see a colored afterimage (Fig. 1). What color will the afterimage be? There are two views in conflict here: TRADITION and SPREAD.

TRADITION maintains that colors are «in the mind» and thus that afterimages are mental colors generated regardless of the existence of the corresponding external properties. In contrast, SPREAD states that colors are physical properties instantiated in the external world and thus that afterimages should – and indeed can – be explained by physical colors in the world.

Remarkably, TRADITION and SPREAD lead to different predictions about the color one will afterimage. This is key because it will allow us to settle the matter by means of empirical evidence.

According to TRADITION, after staring at a saturated green patch, one will see a red afterimage. According to SPREAD, in the same circumstances, one will see a magenta afterimage.

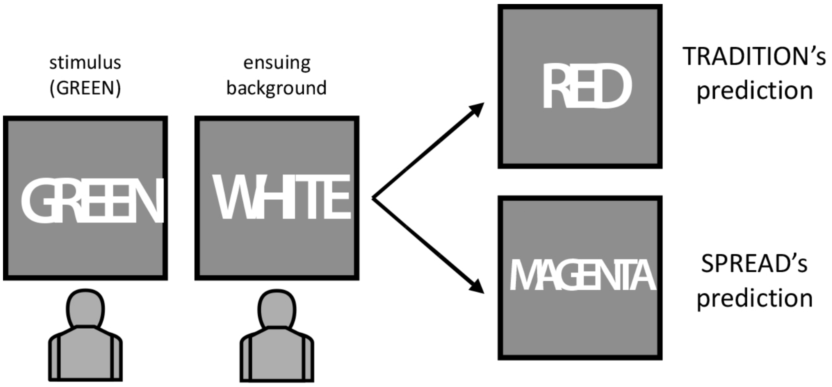

FIG. 1. Does a *green* stimulus cause a *red* or a *magenta* afterimage?

I hope I won't spoil the conclusions of the paper if I anticipate that, while the existing literature is practically unanimous in believing that TRADITION is right, this is not the case. On the contrary, overwhelming empirical evidence contradicts TRADITION and supports SPREAD (Brown 1965; von Helmholtz 1924a; Wilson, Brocklebank 1955; Conway, Livingstone 2006; Pridmore 2011; Manzotti 2017, 2019). Actually, the overwhelming majority of trichromats report seeing a magenta after image and not a red one. The same surprising results obtain after a red stimulus where TRADITION would predict a green afterimage, while subjects report a cyan afterimage (as SPREAD correctly states).

Yet, this remarkable contrast between the received view and the actual empirical evidence is completely neglected and dismissed both by philosophers and by neuroscientists. Let us analyze in greater detail the two models and the experimental results.

2. THE TRADITION MODEL OF COLOR PERCEPTION

TRADITION assumes that colors are psychological phenomena balancing pairs of internally generated opponent qualities. A signal can trigger, say, a certain amount of red and a certain amount of yellow but not, at the same time, any amount of green nor any amount of blue. Metaphorically, opponent hues are like a couple of internal springs that bounce back towards incompatible color qualities after a pull. In his authoritative textbook, the neuroscientist Stephen Palmer summarizes the model as such (Palmer 1999, 106),

> each hue produces its complementary hue in the afterimage. *The complement of a hue is the one located in the opposite direction with respect to the central point of* [opponent] *color space*. Thus GREEN's complement is RED, black's is white, and yellow's is blue.

Note *in passim* the confusion about opponent and complementary hues. Palmer refers to red/green as complementary hues, but they aren't; they are opponent hues. Leaving this oversight aside, the idea is that, in response to a colored stimulus, the visual system bounces towards the opponent hue and generates an opponent mental color as predicted by Hering's color system (Bidwell 1896; Wilson, Brocklebank 1955; Brown 1965; Jones 1972; Geisler 1978; Gordon 1991; Kelly, Martinez-Uriegas 1993; Palmer 1999; Churchland 2005; Goldstein 2010; Macpherson, Platchias 2013). Details may vary, but the underlying idea is that, because of color fatigue, the color system *generates* the afterimage color regardless of the external world. The colors one sees in an afterimage are then akin to hallucinations insofar as they are not assumed to exist in the physical world (Macpherson, Platchias 2013).

According to TRADITION then, colors are unconstrained by the external world, because they are «in the mind». In such an account, the color of the afterimage is not *out there* in the physical world, but it is rather occurring in some arbitrary mental space – whatever that might be. The model predicts that the fatigued and unbalanced visual system will concoct an illusory color – e.g., red – regardless of the ensuing surface which is colorless. This detail is key because it will lead to a further difference in the predictions that the two models put forward. According to TRADITION the afterimage color is independent of the ensuing surface color whose main function is only that of offering an inconspicuous background. The fact that the ensuing surface is almost always either white or gray is taken to be a detail of minor importance – an unobtrusive backcloth that ought not to distract from the afterimage. As we will see, far from being a minor detail, the monochromatic nature of the ensuing surface is a key element in explaining afterimages.

In brief, TRADITION articulates in four points:

– Afterimage hues abide a mental color space; usually some updated version of Hering opponent color space);

– Afterimage hues are a function *only* of the stimulus;

– The ensuing surface is an inconspicuous background;

– Afterimages are hallucinations that exist only in the mind.

As we will soon see, the first three points are empirically false as many scholars – colorimetrists mostly – have known all along.

3. THE SPREAD MODEL OF COLOR PERCEPTION

In contrast with TRADITION, SPREAD models afterimages in terms of perception of physical colors (a model I have elsewhere dubbed the *subtractive* model of afterimages, Manzotti 2016, 2017, 2019). The basic idea is that, when staring at a stimulus, our visual system adapts by becoming selectively blind to certain color components. As a result, after the stimulus is removed, one will filter off certain color components and one will see colors that are in the external world and that are normally masked by other color components. For instance, if one becomes red blind, when staring at a white surface, one will see cyan which is the sum of blue and green. I will soon provide more detail. This model is not original. Following Helmholtz, a different model of afterimages based on complementary colors has been around as of the mid-19th Century (Bidwell 1897; von Helmholtz 1924b; Wilson, Brocklebank 1955; Gage 1999; Livingstone 2002; Pridmore 2008).

SPREAD is based on Helmholtz's trichromatic color space – i.e., each color is the vector sum of three quantities each corresponding to a primary color (R, G, and B). Obviously, such a repartition of light frequencies depends the structure of our visual system that is based on three kinds of photoreceptors each sensitive to a different spectral distribution (L, M, and S). As a result, the light spectrum can be divided into three partitions roughly corresponding to the number of photons falling inside each absorption curve. For instance, $R=\int_0^\infty M(\lambda)\bar{r}(\lambda)\mathrm{d}\lambda$, $G=\int_0^\infty M(\lambda)\bar{g}(\lambda)\mathrm{d}\lambda$, $B=\int_0^\infty M(\lambda)\bar{b}(\lambda)\mathrm{d}\lambda$; where $M(\lambda)$ is the incoming light, and $\bar{r}$, $\bar{g}$, and $\bar{b}$ are directly related with L, M, and S cones absorption curves. In fact, R, G, and B express three physical quantities that approximate the amount of the light spectrum each kind of photoreceptor picks up from the external world (Frey, von Kries 1881; Stockman Sharpe, Fach 1999; Paula 2006). Thus, each RGB triplet does not point to a psychological content but it is the measure of a physical quantity, i.e., the amount of $M(\lambda)$ weighted by $\bar{r}$, $\bar{g}$, and $\bar{b}$. Such an account suggests that what we call color is a physical property instantiated in the external world.

Since colors are mapped onto vectors in the RGB space, color adaptation can be modelled in terms of a reduction in the absorption capacity of each component – i.e. a selective color component blindness. Various mathematical relations can be deployed. A feasible and simple method is vector subtraction. Similar formulations have been suggested elsewhere (Pridmore 2009, 220; Zaidi *et al.* 2012) and are compatible with von Kries' laws of chromatic adaptation (Frey, von Kries 1881).

If S is the color of the original stimulus, A is the color of the afterimage and B is the color of the ensuing surface, a simple relation can be devised

$$A = B - k \cdot S$$

A tuning parameter k ($0 < k < 1$) quantifies the strength of the adaptation. If k is close to 1, adaptation has been greatest; if k is small, almost no adaption has occurred (A = B); k depends on several factors – response times of one's visual system, duration of stimuli, stimulus intensity, environmental light, and so forth. I will not pretend high accuracy here. As confirmed by Yu *et al.* (2017) and Phuangsuwan (2018), the equation correctly predict afterimage colors when that $(B - kS) > 0$.

However, it fails to offer any predictions if $(B - kS) < 0$. To solve this problem, an alternative mathematical formulation which is not biased by the RGB color space might be modeled after von Kries's adaptation laws as follows:

$$A(\lambda)=B(\lambda)/(k \cdot S(\lambda)$$

$S(\lambda)$ is the stimulus spectrum, $B(\lambda)$ the ensuing surface spectrum, and $A(\lambda)$ the expected color of the afterimage. The two formulations are, in practice, almost equivalent. They both approximate the idea that, because of adaptation, only a subset of the existing spectrum is accessible. Multiplying by the inverse of the stimulus spectrum is akin to subtracting the stimulus spectrum from the ensuing surface spectrum in the logarithmic space of color sensation ($\log A = \log B - \log S^k$). Since all cases we will consider are such that $(B - kS) > 0$, in this article we will use the first equation because of its simplicity.

In sum, SPREAD outlines a *perceptual* and *filtering* model of afterimages that allows us to model afterimages in terms of the difference between the spectral density of the ensuing surface and that of the stimulus. It is perceptual because what one perceives is instantiated in the external objects. It is filtering because one selectively filters off certain color components. In this model, afterimages no longer support the notion of psychological colors. One sees an afterimage because one see less of the physical colors in the environment. Adaptation modifies the visual system so that it filters off, from the ensuing surface, the color components that were more prominent in the stimulus and that led to an adaptation.

According to SPREAD, color afterimages are cases of perception in which one is temporarily and to a certain extent blind to certain color components. One sees the afterimage color because such a color is contained in the external world and – because of adaptation which is a color-selective blindness – one sees only a subset of the existing colors. Subtraction is a quantitative way to model a *local color-selective* blindness. By *local* I mean that the adaptation is ego-centered *phenomenally* located where the stimulus was. Yet, this does not imply any mental level. No more than a local damage on the retina implies any mental existence although the resulting phenomenal experience will be akin to something moving together with the egocentric visual field. As regards the proposed model, the neural machinery of adaptation may take place anywhere it likes, no retinal commitment is implied. Although the final effect if phenomenally located where the stimulus was phenomenally, this does not commit to any specific neural locus of adaptation. By *color-selective* I mean that it filters off only selective color components depending on the stimulus spectrum. By *partial* I mean that the resulting blindness is only partial and depends on the duration and intensity of the stimulus.

In brief, SPREAD articulates three key points:

– Afterimage hues are physical colors unfiltered by RGB local selective adaptation (or L, M, S);

– Afterimage hues are a function of *both* the stimulus *and* the ensuing surface;

– Afterimages are modified perception rather than hallucinations.

The last point is tantamount to stating that colors are not generated in the cortex, or, at least, that there is no evidence requiring anything more than what occurs in the case of everyday color perception. As long as color is a set of external physical properties, the proposed model suggest that adaptation leads to a reduced capability to pick some of such properties, no matter what they are. In this model, I have assumed that the RGB components – taken as approximations of the LMS curve distributions – are an acceptable model of the physical components of colors. Of course, more detailed models, which include the environmental light or other factors, might provide more accurate results.

4. EMPIRICAL EVIDENCE

As mentioned at the onset of this article, TRADITION and SPREAD can be empirically checked against each other. This can be done with any available combinations of stimulus and ensuing background. Each model will yield different predictions as to the color of the after image. Because of its popularity, I will focus mostly on a green stimulus followed by a gray background. If TRADITION is right, after a green stimulus one will see a red afterimage. In contrast, if SPREAD is right, after a green stimulus one will see a magenta afterimage.

In the case of TRADITION, one will see the color that is opposed to the color of the stimuli in the chosen mental space, which very often is Hering space and thus green yields *red*. In contrast, in the case of SPREAD, one will see the colors that remain in the ensuing background once the colors of the stimulus have been subtracted. In this case, after a green stimulus S, a white ensuing surface B and maximum adaptation strength ($k = 1$), SPREAD yields

$$A = B - k\,S = \text{white} - \text{green} = (1, 1, 1) - (0, 1, 0) = (1, 0, 1) = \text{magenta}$$

This is coherent with subjective reports and Helmholtz's view. Crucially, the model extends to cases where the ensuing surface is colored – cases which have usually been neglected by the tradition. For instance, consider a green stimulus followed by a yellow surface. SPREAD yields

$$A = B - k\,S = \text{yellow} - \text{green} = (1, 1, 0) - (0, 1, 0) = (1, 0, 0) = \text{red}$$

The model predicts a different afterimage hue because the ensuing surface is no longer white. Since the afterimage color is a function of *both* the stimulus *and* the surface, by changing the latter, a change in the afterimage is to be expected. *The afterimage color is constrained by the external world of which it is a subset*.

In sum, SPREAD is to be preferred to TRADITION because it offers a better match with empirical evidence. Elsewhere, I tested the model by means of a series of simple experiments testing both afterimages against an achromatic surface and afterimages against a colored surface (Manzotti 2017, Table 1, 2).

The first experiment focuses on alleged red-green afterimages and employed a gray surface. Subjects stare at a *green* stimulus for 30 sec and then at a gray surface. Immediately afterwards, the subjects is shown a *red* patch and a *magenta* patch, side by side, and asked to assess which of the two was more similar to the previously experienced afterimage. In such circumstances, TRADITION predicts a *red* afterimage, while SPREAD predicts a *magenta* afterimage. Consistently with SPREAD, 99% of subjects report a *magentish* afterimage following a *green* stimulus, and 95% a *cyanish* afterimage after a *green* stimulus (Table 1). These findings are overwhelmingly consistent with SPREAD.

The second experiment addresses what happens when the ensuing surface hue is not achromatic – something that is seldom taken into consideration. Is the same afterimage hue or is it a different one? To test the dependence from surface hues, the previous setup has been applied to a number of combinations of color stimuli and colored surfaces. SPREAD predicts that, if the afterimage hue is equal to the subtraction of the stimulus hue from the surface (), given the same stimulus, different ensuing surfaces would yield different afterimages hues. For instance, given a *red* stimulus, the model predicts that a *white* surface will yield a *cyan* afterimage (cyan=white–red); a *yellow* surface will yield a *green* afterimage (green=yellow–red); a *magenta* surface will yield a *blue* afterimage (blue=magenta–red). Thus the *same* stimulus yields different afterimage colors – namely *cyan*, *green*, or *blue*. This is indeed what happens (Table 2).

TAB. 1. *TRADITION vs SPREAD: evidence*

Stimulus	TRADITION	SPREAD	Subjects' reports
Red	Green	Cyan	Cyan (98%)
Green	Red	Magenta	Magenta (96%)
Cyan	Orange?	Red	Red (92%)
Magenta	Yellowish green?	Green	Green (91%)

Tab. 2. *Afterimage hue dependence on the ensuing surface hue*

Stimulus	Surface	TRADITION	SPREAD	Subjective
red	yellow	green	greenish	greenish (91%)
red	magenta	green	bluish	bluish (97%)
red	cyan	green	cyanish	cyan (95%)
green	magenta	red	magentish	magenta (92%)
green	cyan	red	bluish	bluish (96%)
green	yellow	red	greenish	reddish (89%)

These findings back up convincingly SPREAD and show that the color of the afterimage depends *both* on the stimulus *and* on the ensuing surface. Moreover, they provide support for the fact that the color of the afterimage is a subset of the existing color components in the external world. In this regard, SPREAD suggests a dependence relation F with *two* arguments:

$$A=F(S,B)=B\text{-}kS\approx\frac{B}{kS}$$

In contrast, TRADITION suggests that the afterimage color depends only on the stimulus color – e.g., «the hue of an afterimage is determined *solely* by the hue of the stimulus color» (Wilson, Brocklebank 1955, 299). TRADITION states that the stimulus-induced chromatic fatigue causes an opponent hue that is *generated* internally no matter what one looks at afterwards. Thus TRADITION suggests a *one*-argument relation

$$A = F^*(S,B)$$

Where F^* has only *one* argument, which is the color stimulus. Yet the experimental evidence shows that the afterimage color depends *both* on the stimulus *and* the ensuing background – *two* arguments (Table 2).

A straightforward consequence is that one cannot afterimage anything by staring at a pitch-dark surface – a prediction that is at odds with the traditional model based on the generation of opponent colors in the cortex. In fact, this is precisely what happens in the case of a pitch-dark surface – one does not see any afterimage (Manzotti 2017). As a matter of fact, a positive afterimage might take place, but that is a different phenomenon than color afterimages. A positive afterimage is a case of persistence of perception and it might be explained in many ways, not all entailing mental colors. As regards color afterimages, it is a fact that no afterimage ensues simply by closing one's eyes, unless enough environmental light reaches the inner surface of eyelids. After staring at a color stimulus, if the room is suddenly plunged into complete darkness, no afterimage follows. This might be surprising but it might be easily verified. Once again SPREAD agrees with empirical evidence.

5. A SHORT HISTORICAL DIGRESSION

Remarkably, Helmholtz himself observed that ensuing colored surfaces – i.e., ensuing backgrounds – induce different afterimage colors (von Helmholtz, 1924a, p. 255):

> Corresponding results are obtained in observing negative afterimages of coloured objects on coloured surface. Invariably it is principally *those con-*

> *stituents which were predominant in the colour of the primary object that disappear from the colour of the ground.* Thus, a green object on yellow ground gives a red-yellow afterimage; and on blue ground, a violet afterimage.

Thus, in Helmholtz's account, the same green stimulus produces two different afterimage colors depending on the ensuing surface color (red-yellow on yellow and violet on blue). The same conclusion follows from Von Kries' adaptation laws. Remarkably, only a few authors have stressed such a dependence – e.g., «there is no single afterimage […] for a stimulus color» (Bagley, Maxfield 1986, 1003), against the majority of scholars (as seen before) who have described afterimages as though their color were a function only of the stimulus.

Likely, the culprit is the habit of inviting subjects to experience afterimages against *white* or *gray* surfaces thereby dismissing the role of the ensuing background hue: «look at a sheet of *white* paper» (Palmer 1999, 106), «viewed against a *white* surface» (Palmer 1999, 119), «stare […], with eyes unfocused, at the *white* disc.» (Gage 1999), «look at a piece of *white* paper» (Goldstein 2010, 213), «shift your eyes to the *white* rectangle» (Palmer 1999, 52), «look at a small, not-too-bright *achromatic* surface» (Hurvich 1981, 185-187), «look at a *white* wall» (Jones 1972, 154), «looking at a *white* wall» (Byrne, Hilbert 2003, 5), «looking at a *white* wall» (Macpherson 2013, 13), «hovering against that *gray* surface» (Churchland 2005, 541). By considering only achromatic and homogeneous surface, experimenters have discreetly set aside the dependence of the afterimage upon the surface. They have imposed situations where test subjects have always the complete solar palette at their disposal. In fact, *all color components are available to the same extent* a *inside white* and thus one can single out any hue.

As a matter of fact, as early as Helmholtz's days, many color scientists have reported that a red stimulus produces a blue-green – i.e., a cyan – afterimage (Kaisers, Boyton 1996; Pridmore 2011; von Helmholtz 1924b) and many artists and historians have reported the right color relations (Gage 2006). Yet, because both of the influence of Hering's work (Hurvich 1981; Jameson, Hurvich 1965) and of some optimistically-interpreted early evidence about the neural machinery of color opponency (Daw 1967; De Valois 1965; Svaetichin, MacNichol 1958), afterimages have been modelled in terms of opponent colors. Consequently, many scholars have assumed that *red* stimuli induce *green* afterimages and viceversa. The confusion spread and, in the field of philosophy, led to undeserved support for the notion that afterimages are illusory mental images concocted by the mind. This entangled story needed some rectification. It is informative to take a little detour to understand how pervasive and influential it was.

The RED/GREEN mistake was kickstarted by Helmholtz's archfiend Ewald Hering in the 19th Century (Hering 1964; Turner 1993). A hundred years later, in the '60s, Leo M. Hurvich fleshed out a similar model based on opponent colors (Hurvich, Jameson 1957) probably after Hurvich translated Hering's work into English (Hering 1964). Eventually, in his influential book on color perception (Hurvich 1981, 185-187), Hurvich stated explicitly that afterimages are ruled by red-green opponency:

> If the primary excitation in a small foveal field in an otherwise dark surround is produced by, say, 500 nm, it looks *green* while the stimulus is on. If we turn the stimulus off and look at a small, not-too-bright achromatic surface, we see a *red* afterimage.

Likewise, a few years before, Brown's influential review on afterimages stated that a «*red* primary stimulus» yields a «*green* afterimage» (Brown 1965, 483). Eventually, many neuroscientists have often assumed that «an intense *green* light induces a *reddish* afterimage; blue light induces yellow, and vice versa.» (Gordon 1991, 79). Werner and Bieber took as a platitude that «exposure to a bright field of one hue – e.g., *red* – Induces a nearly complementary colour in the afterimage – e.g., *green*» (Werner, Bieber 1997, 211). To date, in neuroscience, red and green are quoted together again and again. «Negative afterimages are modelled in terms of *red-green* contrast» (Tsuchiya, Koch 2005); «a *red* afterimage can be induced by a *green* color patch» (Robertson, Sagiv 2005, 142); «a *red* afterimage which is what would be predicted from viewing a GREEN surface» (Zeki *et al*. 2017, 2). Consistently, Stephen E. Palmer's claims that if you «stare at the *green* American flag, then quickly shift your eyes to the white rectangle beside it. You should see an afterimage of an American flag in *red*, white, and blue instead of *green*, black, and yellow» (Palmer 1999, 52). Likewise, Bruce Goldstein makes use of a *green* American flag stimulus to induce – as he claims – a *red* flag-shaped afterimage: «Notice that the *green* area of the flag […] created a *red* after image, and the yellow area created a blue afterimage.» (Goldstein 2010, 213). The recent *Cambridge Handbook of Color Psychology* states that «Color afterimages consist of the perception of a color (e.g., a *greenish* shade) in the absence of a corresponding stimulation that occurs after sustained fixation of an area with a complementary color (e.g., a *red* disk)» (Witzel, Hansen 2015, 644).

A similar confidence in red-green afterimages is widespread in the philosophical literature too. As of Goethe's and Schopenhauer's work, the notion that red and green were antagonistic hues gained popular acceptance (Goethe 1810). Franz Brentano stated that «after looking at a *red* surface, we see a *green* color» (Brentano 1874, 92). A hundred years later, O.R. Jones made the same point, «Suppose you stare at the glowing *red* bars of an electric fire for half a minute or so, and then look at a white wall so that the usual *green* afterimage appears» (Jones 1972, 154). More recently, William Lycan held that, «a *green* afterimage [is] a result of seeing a *red* flash bulb go off» (Lycan 2002, 18). According to Eric Schwitzgebel, «a *red* object will normally leave a *green* afterimage» (Schwitzgebel 2011, 48). Alex Byrne and David Hilbert wrote «Consider the experience of a *red* circular afterimage, produced by fixating on a *green* circular patch for a minute or so, and then looking at a white wall», write (Byrne, Hilbert 2003, 5). According to Paul Churchland if you «fixate for 20 seconds on the small cross within the *red* circle [then] you will see a circular *green* afterimage» (Churchland 2005, 541). In a recent collection of essays on hallucinations, Fiona Macpherson states: «You can have such a hallucination – of the afterimage variety – by staring at a patch of *green* for about a minute and then blinking a few times and looking at a white wall, whereupon you should experience an afterimage of a *red* patch» (Macpherson 2013, 13).

And yet, all such accounts have neglected the empirical evidence shown in the previous section and have not taken into consideration the possibility of an alternative view such as SPREAD.

6. DO WE NEED MENTAL OPPONENT COLORS?

If afterimages can be explained without opponent colors, do we really need them? Once we have provided a perceptual model of afterimage, many traditional reasons to believe in a mental space of colors will no longer hold. After all the notion of opponent colors is closely related with phenomena such as color contrast and afterimages.

First, consider the notion that the afterimage color is opponent to the stimulus. This notion, I have argued, is empirically and conceptually false. Afterimages are not based on opponent colors but on the subtraction of the stimulus from the surface in the complementary color space as a result of chromatic adaptation.

Secondarily, the notion of opponent colors is linked with that of unique hues, which is extremely problematic. As a matter of fact, if one looks at the CIE diagram as well as recent findings (Kuehni 2001; Stoughton, Conway 2008), no obvious evidence for unique hues – particularly for yellow – is available. The traditional data presented by Hering would yield identical results if applied to magenta and cyan (Hurvich, Jameson 1957) . It is fair to stress that the notion of unique hues has always been a source of conceptual and empirical concerns – their «special status remains one of the central mysteries of colour science» (Mollon, Jordan 1997, 381). Moreover, (italics mine, Wuerger, Atkinson, Cropper 2005, 3211),

> with recent advances in understanding the cortical mechanisms of colour vision […], *the unique hues have remained a mystery*. Neither neurophysiological studies with monkeys […] nor functional imaging studies with humans […] have revealed neurons with chromatic tuning similar to the unique hues. […] the unique hues do not seem to have a special status.

On the same issue, Valberg remarks that (italics mine, Valberg 2001, 1648),

> even if the elementary hues today are accepted as subjective references in phenomenal colour perception, it is necessary to emphasise that no opponent-cell correlates have been discovered. So far, *all attempts to determine the physiological nature of unique colours have failed*.

Thus, we may consider a tempting historical explanation of the origin of the space underwent a process of simplification that led to the opponent color space (Figure 2, left). In particular, the red-cyan and green-magenta axes might have been merged into the red-green axis (middle). This process of simplification paved the way to an opponent color space made of only two axes yellow-blue and red-green instead of red-cyan, magenta-green, and yellow-blue. The hunch is that the red-green axis is an amalgam of two axes: the red-cyan and the green-magenta axes (right).

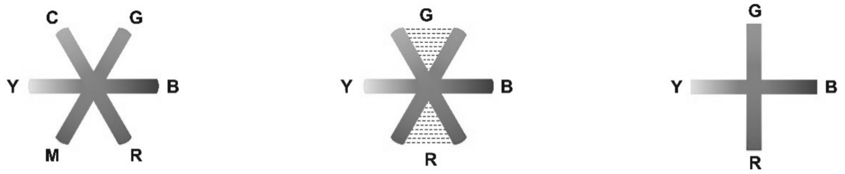

FIG. 2. How opponent colors simplified the trichromatic space.

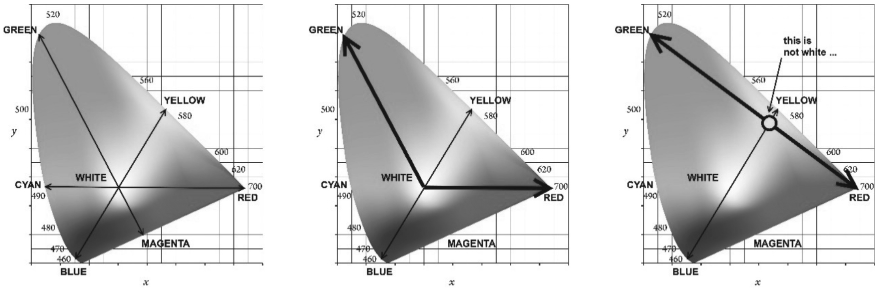

FIG. 3. Complementary pairs and opponent pairs in the CIE diagram.

After all, the notion that «there is no series of red-green intermediate hues» (Hering 1964, 49) and green has been called into question (Pridmore 2008). In fact, one of the main arguments for color opponency has been the lack of intermediate hues between green and red. Yet, is that so? On the one hand, complementary colors have no intermediate hue: yellow and blue do not have any intermediate hue in the trichromatic space either. Thus, yellow and blue cannot back up color opponency any more than complementary colors do. On the other hand, is it really true that there is no intermediate hue between red and green? Actually, if one draws a line between them (for instance in the CIE diagram or in other color space, RGB, HSV, and so forth), one finds a slightly unsaturated yellow (Figure 3); let alone that yellow is the combination of red and green in the RGB space. So why should we suppose that no intermediate hue obtains between red and green? Historically, the main reason might be that on the one hand yellow has been postulated to be a unique hue and on the other hand red and green were taken to be opponent hues. Yet, the former is questionable because the very notion of unique hues has now been called into question (Pridmore 2011; Romney, D'Andrade, Indow 2005; Stoughton, Conway 2008; Valberg 2001). And the latter is questionable too, because the red-green axis can be replaced by a pair of complementary color axes, namely red-cyan and green-magenta. Once this is done, each of the two axes have no intermediate hue – like the yellow-blue axis – and *unlike red-green*. In fact, the notion that «redness and greenness are mutually exclusive» (Hering 1964, 49) can be applied successfully both to green-magenta and to cyan-red.

Rather surprisingly, many authors who have embraced color opponency about afterimages and thus who should have claimed the absence of any intermediate hue between red and green have stated the opposite by reckoning the presence of yellow between red and green. Conveniently, though, they have often dismissed such a fact as though it were inconsequential. For instance, Valberg writes (Valberg 2005, 280):

> Unique yellow was viewed as an equilibrium state between a «red process» and a «green process». However, *the residual sensation (yellow in this case) did not need to be relevant*, since the judgements were based only on the absence of redness and greenness, independent of other color attributes of the stimulus (it could also be white or blue).

But whether relevant or not, is the presence of yellow (the residual sensation) between red and green not the crucial point? If red and green are balanced, should the standard theory predict that no hue will obtain? Yet, yellow does! Equal amount of red and green produces yellow. Does it not contradict the notion that they are unique and opponent? Likewise, Hering himself had observed that (italics mine, Hering 1964, 49)

from a color that is somewhat reddish we can arrive at a more or less greenish color through a continuous chromatic color sequence *only by a detour through primary yellow*.

Pace Hering, the detour he refers to is the shortest line both in the RGB space and in the CIE diagram (Figure 4, right). Red and Green are not separated by gray, but by yellow. The detour, if any, is the one that is required to pass through highly unsaturated regions (gray). In fact, if one moves from red towards green, one does not reach gray unless blue is added to the mixture so to avoid yellow. On the contrary, when one balances *yellow* and *blue*, no residual hue remains. Neither when one balance *red* and *cyan*, nor when *green* and *magenta*. Between complementary hues no hue obtains. No detours are needed.

The difference between, say, the yellow-blue midpoint (gray) and the red-green midpoint (yellow) derives from the fact that yellow and blue are complementary, while red and green are only an approximation of the red-cyan and magenta-green complementary pairs (Figure 4, middle). Thus, there are three pairs of colors between which no intermediate hue obtains – red-cyan, green-magenta, and yellow-blue; complementary pairs. Adopting the complementary color space allows us to have six antagonistic hues organized in three pairs, which are the three primary components and their complementary hues (Figure 4, right). The six hues so defined are an articulation of the three original quantities (Figure 4, left). There is no need to have opponent qualities. The three primaries, plus their complementary hues provides six hues and three complementary axes.

Fig. 4. Traditional representation of trichromatic space, opponent space, suggested trichromatic space.

6. CONCLUSIONS

In this paper I have contended that afterimages, which have been used to defend the mental nature of color experience, are amenable of alternative interpretations. In particular, SPREAD is a model of afterimages that locates the color of an afterimage in external objects. This solution is supported by the empirical evidence and is also ontologically more parsimonious. No mental color is needed. Colors are no longer in the mind. They are instantiated by the external objects.

In conclusion, SPREAD has several advantages that can be recapped as such.

1. It is supported by the empirical evidence.
2. It offers a more satisfactory model of afterimages based on *two* key variables: the stimulus *and* the ensuing surface, A = F(B, S).
3. Colors are not *in the mind* but rather in the external world.
4. Afterimages can be explained as a case of perception.
5. Phenomenal adequacy.
6. No need of emergent psychological properties.

Remarkably, such a view is compatible with externalist models of color perception and offers a physicalist ontology of colors to performative approaches. Color perception can thus be modelled in terms of a dynamic online relations between one's body, which is made by actuators and sensors, and the external objects with their actual physical properties. Changes in the structure of the body determine corresponding changes in the subset of properties that, at any moment, are identical with one's experiences. If we go back to the notion of performativity and the physicalist ontology proposed by the Spread Mind, we will see how they merge seamlessly and suggest a way to locate the mind in the physical world. Without the Spread Mind, performativity is a form of embodied functionalism lacking the resources to explain the nature of phenomenal experience. On the contrary, with the Spread Mind, performativity shows how the body carves out its personal world which is relative to the structure and the actions of the body (Pennisi, 2016). Performativity is the collection of processes by means of which a body carves out a collection of external relative properties that are identical to one's conscious mind.

Riccardo Manzotti
Università IULM
Via Carlo Bo, 8
2014, Milano

ENDNOTES

[1] All italics are mine.

[2] A couple of caveats will help me to set the discussion on the right foot. First, while it is well known that color perception varies between different subjects (Beau Lotto, Purves 2002; Hofer, Singer Williams 2005), for the sake of simplicity, here all subjects are taken to be standard trichromats. Second, here I will avoid a persisting confusion between the apparently overlapping notions of *opponent* and *complementary* colors (Bidwell 1897; Palmer 1999; Livingstone 2002; Tsuchiya, Koch 2005). Opponency refers to a psychological space of colors as devised by Hering, while complementarity refers to the fact that two colors together produce white. For instance, yellow and blue are both complementary and opponent; red and green are opponent but not complementary; red and cyan are complementary but not opponent.

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