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Monge

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Abstract

In 1789, when neither the physical basis of hue nor the retinal basis of color perception was established, the mathematician Gaspard Monge stated firmly that our color perceptions do not depend on the absolute value of the physical variable, but are influenced by the context and in particular by our estimate of the illuminant. He used this insight to explain color contrast effects and the Paradox of Monge (the desaturation of red objects seen through a red filter). He proposed that we can estimate the chromaticity of the illuminant in any scene because all surfaces reflect to us varying mixtures of (i) the body color and (ii) a specular component that represents the illuminant. He also realized that white objects have a special property: Provided that they are illuminated by a single illuminant, such objects exhibit no variation in chromaticity across their surface. Thus at least one of the unique hues exists as an external reference on which observers can agree. It is suggested that other unique hues may also have a basis in the external world.

Keywords: Color contrast, Color constancy, Colored shadows, Unique hue, Monge, Chevreul

The *Lycée Ampère* stands on the central peninsula of Lyon, beside the bank of the Rhône. Its modern name, dating from 1888, honors one of its most distinguished instructors, André-Marie Ampère, who taught physics there in the academic year 1804 to 1805 (Chabo & Charléty, 1901). Before 1888, the *Lycée* underwent many name changes and these changes conveniently trace the political history of modern France—a history to which I shall need to refer several times (Table 1).

From 1848 to 1888, during the Second Republic, the Second Empire, and the Third Republic the institution was called the *Lycée de Lyon* (Pouzet, 1984). From the Restoration of the Bourbons in 1814 until the fall of the July Monarchy of Louis Philippe in 1848, it was the *Collège Royal*. From 1804 to 1814, during the First Empire of Napoleon I, it was the *Lycée Impérial*. From 1796 to 1804, during the Directory and the Consulate, it was the *École Centrale*. In 1801, it had a moment in the spotlight of modern European history when delegates from the Cisalpine Republic met in its chapel and elected as their president, First Consul Bonaparte (who at once declared himself President of the Italian Republic and gave impetus to Italian nationalism). During the first flush of the Revolution, it was briefly the *Institut pour l'éducation publique* (1792–1793), but during and after the terrible siege of Lyon by Convention forces in 1793 it was closed to students and used first as a gun emplacement and then as a barracks.

Before the Revolution, during the *Ancien Régime*, it was the *Collège de la Trinité*. It had been established in 1527 by a secular city guild, the *Confrérie de la Trinité*, but from the middle of the sixteenth century to the middle of the eighteenth the College was run by the Jesuit Order (except for a brief period when the Jesuits were expelled from France). During this time, the College was distinguished for its learned teachers, its large library, and its musical traditions; but in 1762 the Jesuits were for a second time expelled from France, and another catholic society, the Oratorians, were asked to take over the College in 1763.

In 1762, the Oratorians of Beaune sent to the *Collège de la Trinité* a brilliant, 16-year-old student who progressed so rapidly in Lyon that within a year the College appointed him *Professeur* in physics. This young man was to be the founder of Descriptive Geometry and a collaborator of Lavoisier, but he was also to play a central part in the most turbulent years of French history. It is a mark of his genius that he held high office under almost every administration from the *Ancien Régime* to the First Empire; and the French have given him their ultimate accolade, a metro station in central Paris. He was a member of the Jacobin Club, and, as Minister for the Navy and for the Colonies in the Convention Government in 1792 to 1793, he was one of the signatories of the official record of the execution of Louis XVI. He was prominent in the commission that gave the world the metric system. His grasp of military technology was central to the early successes of France in the revolutionary wars. He was an intimate friend of Napoleon Bonaparte, accompanying him on the Italian campaign and on the Egyptian expedition. He was entrusted with carrying the text of the Treaty of Campoformio to the Directory in Paris. He was one

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Table 1. *The political history of modern France, illustrated by the history of an institution*

Political history	Collège de la Trinité, Lyon
Third, Fourth and Fifth Republics	Lycée Ampère, 1888–2005
Third Republic,1870	Lycée de Lyon, 1848–1888
Second Empire (Napoleon III),	
Second Republic, 1848	
July Monarchy, 1830 (Louis-Philippe)	Collège Royale, 1814–1848
Restoration of Bourbons, 1814;	
First Empire, 1804 (Napoleon I)	Lycée Impérial, 1804–1814
Consulate, 1799–1804	École Centrale, 1795–1804
Directory, 1795–1799	
Siege of Lyon, 1793. Terror.	
Execution of Louis XVI, January 1793	
National Convention, 1792	Institut pour l'éducation publique, 1792–1793
Legislative Assembly 1791	
National Assembly, 1789	
Ancien Régime	Collège de la Trinité, 1763–1791 (Oratoriens)
	Collège de la Trinité, 1565–1762 (Jesuits)

of the chief founders of the *École Polytechnique*, which remains today a prominent institution of higher education in France. In addition, he wrote one of the most intelligent papers on color vision that has ever been published. This was Gaspard Monge (Fig. 1).

The Oratorians of Lyon hoped that Monge would become a member of their order. For reasons that remain obscure, Monge declined the invitation and returned to his native Beaune in 1764 (Aubry, 1954). Soon, however, he was appointed to a technician's post at the Royal Engineering School at Mézières. Here he revealed his talent by developing a new geometrical method for solving the problem of defilade, that is, for determining from a relief map the elevation required in ramparts to shelter the defenders from fire or observation (Gillispie, 1980). Soon he was appointed as an instructor. His mathematical researches during his time at Mézières led to his election to the Royal Academy of Sciences in 1780.

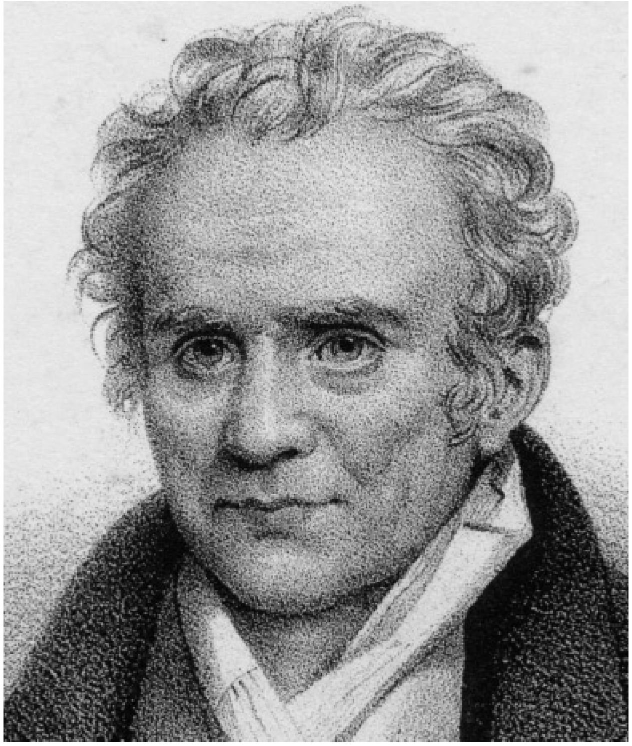


Fig. 1. Gaspard Monge (1746–1818).

Gaspard Monge gave his lecture on color vision to the Academy of Sciences in April 1789, on the eve of the Revolution. It was later published in the *Annales de Chimie*, with the title *Mémoire sur quelques phénomènes de la vision* (Monge, 1789) and a long extract was reproduced in the *Encyclopédie Méthodique* (Monge et al., 1816). The lecture might be seen as an isolated excursion into color science by a mathematician and physicist, but closer familiarity shows its intimate connection to the problems of Descriptive Geometry that were central to Monge's interests. He later returned to the issue in his lectures at the *École Polytechnique*, which were published after his death (Monge, 1838).

The paradox of Monge

The astonishing insights in the lecture of 1789 were probably lost on most of his contemporaries. Nevertheless, to one of them we are indebted for an eye-witness account of the striking demonstration with which Monge preceded his lecture (Gentil, 1791).

The Academy held its meetings in the Salle Henri II, the king's old antechamber in the Louvre. Monge had arranged a red paper to hang on the wall of a west-facing building that stood opposite the meeting chamber. He invited his fellow academicians to observe the red paper through a red glass. A red paper, as Monge well understood, predominantly reflects red rays. A red glass passes red rays and attenuates others. So we might expect the red paper through the red filter to look a saturated red, hinting perhaps at the bloodshed that was soon to touch even the members of the Academy. But it did not. It looked desaturated, even white. Our eye-witness adds: *Il y a plus, un habit rouge dont étoit vêtu ce jour-là un de nous, parut blanchâtre* (Gentil, 1791).

Similarly counter-intuitive was the appearance of a white object through the red glass. Such an object, Monge reminded his listeners, reflected rays of all colors, while a red glass would pass only the red rays. So there should be two changes in the appearance of the object when the red glass is introduced: it should be reduced in brightness and its color should change from white to red. In fact, the white object seen through a red glass continues to look whitish and it matches red objects concurrently in the scene.

The bleached appearance of a red or white object seen through a red glass, I shall call "the Paradox of Monge." Gaspard Monge himself identified some critical conditions for obtaining the phenomenon:

(i) There should be several objects of different colors in the scene. If the red glass is placed at the end of an opaque viewing tube, and if a single red or white object fills the field observed through the tube, then the object will appear red in both cases.
(ii) The scene should include some objects that are naturally white.
(iii) The illumination should be high.
(iv) The effect is most readily obtained with a red filter. Corresponding effects for other filters are difficult to obtain, al-

> though Monge mentions that he has had in his hand a yellow filter through which a paper tinted with *gomme gutte* (gamboge) looked absolutely white. With green, blue and purple filters, and corresponding objects, there is little effect. (Monge ventures that this is probably because such colors can be produced both by homogeneous rays and by mixtures.)

From informal trials, Robert Lee and I can confirm Monge's observations. For the modern observer, a suitable scene is offered by a sunlit car park, provided that it contains at least one bright and glossy red vehicle. Not all red filters work well. Suitable filters have no transmission in the short- and middle-wave region and have a cut-on near 600 nm. We have had good results with a gelatin filter 029 ("Plasa Red"), supplied by Lee Filters, (Central Way, Walworth Industrial Estate, Andover, Hants, SP10 5AN, UK; www.leefilters.com).

The Paradox of Monge can equally be obtained by placing the filter in front of the illuminant instead of in front of the eye. In a charming period piece, Judd and Wyszecki (1963, p. 342) describe how butter may look like lard when seen in a yellow illuminant.

Zeki (1980) described a possible physiological analogue of the paradox: in cortical area V4 of the macaque, he found cells that responded to a red patch in broad-band illumination but did not respond to the same patch when the whole scene was illuminated by red light. Distributed with Professor Zeki's article was a red filter that serves well for demonstrating the Paradox of Monge.

Colored shadows

Monge related his paradox to a second observation, that of colored shadows. The observation was already antique in his day. Monge attributes it to the Abbé de Sauvage, who had acquainted Buffon with it. A seventeenth-century description was given by Otto von Guericke (1672).

Suppose, Monge says, a little before sunrise on a fine day, one lets skylight enter a room through an open window and illuminate a sheet of white paper that is concurrently illuminated by a candle. If a small object is placed on the paper, then it will cast a blue shadow in the region where the surface is illuminated only by skylight. But now extinguish the candle. The entire sheet of paper is then illuminated purely by skylight, as previously was the shadowed area. We might reasonably expect the entire sheet to look blue, and of the same color as the shadow appeared previously. But no, the entire sheet of paper looks white.

Color constancy

Gaspard Monge relates both of these phenomena—the paradox of the red filter and the illusion of colored shadows—to a basic property of vision. This is the property that was later to be called "color constancy" (e.g., Koffka, 1935; Shevell, 2003; Smithson, 2005). Our color perception does not depend simply on the spectral composition of the light reaching on a local retinal area. Rather it is adjusted to take into account the spectral composition of the illumination, in such a way that an object of a given spectral reflectance remains approximately constant in its appearance.

"So our judgments of the colors of objects seem not to depend uniquely on the absolute nature of the rays of light that paint the image of them on the retina; our judgments can be altered by the context, and it is likely that we are influenced more by the ratio of particular properties of the light rays rather than by the properties themselves, considered in an absolute manner" (Monge, 1789, p. 147. See Fig. 2 for the French text).

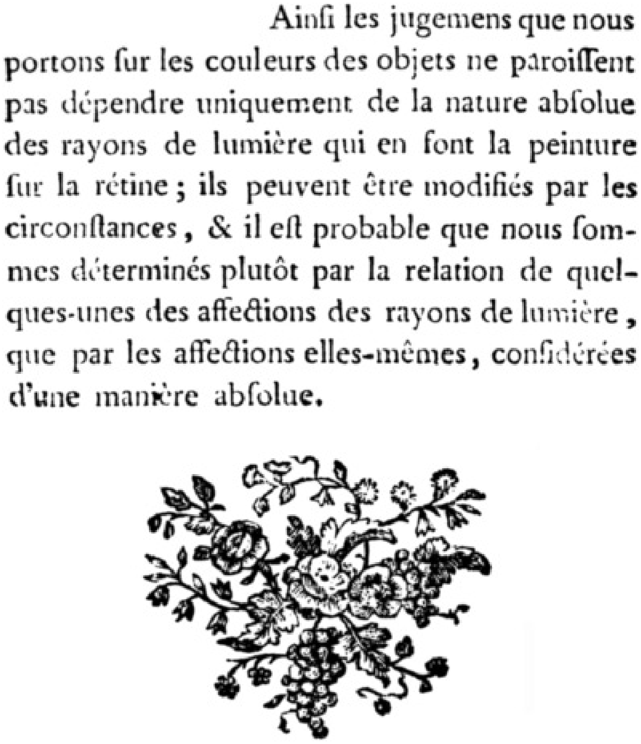
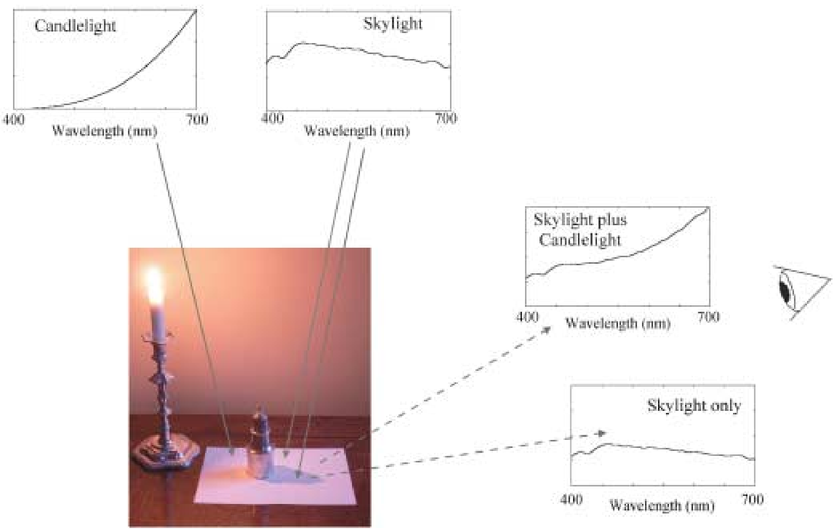

Ainſi les jugemens que nous portons ſur les couleurs des objets ne paroiſſent pas dépendre uniquement de la nature abſolue des rayons de lumière qui en font la peinture ſur la rétine ; ils peuvent être modifiés par les circonſtances, & il eſt probable que nous ſommes déterminés plutôt par la relation de quelques-unes des affections des rayons de lumière, que par les affections elles-mêmes, conſidérées d'une manière abſolue.

Fig. 2. The conclusion of Monge's paper of 1789. An English translation of this passage is given in the present text.

Monge allows that he does not know the physical difference that characterizes rays of different color. For he was writing in 1789, a decade and a half before Thomas Young offered evidence for the wave theory of light (Young, 1804). Some physicists suppose, says Monge, that there is an intrinsic difference in the nature of the rays, others that the different colors correspond to different speeds of light particles. Nevertheless, what his observations show is that rays of a given type do not have the power of exciting in us a sensation of one particular color. Rather our sensation depends on the ratio of some properties of the rays to the corresponding properties of other rays ("*. . . il paroîtroit . . . que la faculté qu'ont les rayons d'une certaine espèce d'exciter en nous la sensation d'une couleur particulière, ne tient à rien d'absolu, & ne depend que du rapport de quelques-unes de leurs affections aux affections analogues des autres rayons du système lumineux.*") Suppose for a moment, Monge says, that rays of light differ only in their speed. To excite in us the experience of red, it is not that the light would have a specific speed. Rather its speed would have a certain ratio to the speed of other rays that are present ("*. . . il suffiroit pour cela que sa vitesse eût un certain rapport avec celles des autres rayons du système*"). In insisting that color perception depends on a ratio (*rapport*), Monge anticipated Edwin Land, who was to write: "It is the ratio-making sense which keeps an apple looking like an apple in blue sky light when more blue light than red is coming from the skin of the apple to our eyes" (Land, 1974).

Monge proposes that color contrast effects are by-products of the normal process of color constancy. From surrounding objects the visual system infers that the scene is lit by a colored illuminant; and the target region is then seen as having the hue of a surface that

Case 1: **Coloured shadows, an example of colour contrast**



Case 2: **Colour Constancy. A blue object illuminated by candlelight and skylight.**

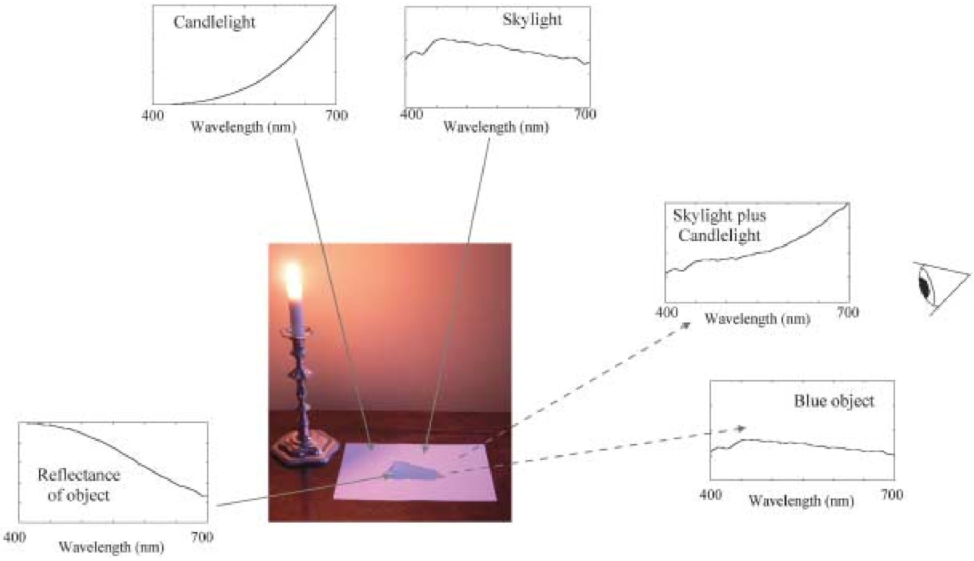


Fig. 3. The upper panel shows a case of colored shadows, which would conventionally be taken as a contrast effect. The image is an unmodified digital photograph taken just before dawn in a Cambridge college room. The white paper is lit by candlelight and also by skylight from a north-facing window: It delivers a combination of these illuminants to the observer's eye. The sugar caster throws a blue shadow in the region where the paper is illuminated only by skylight. Yet if the candle is extinguished, the same region looks white. In the lower panel, a photograph has been taken of the same scene without the sugar caster. The only manipulation of this image is that the shadow from the upper image has been transposed to the table in the lower image, where it represents a blue object with the reflection spectrum shown to the left. The spectral signals reaching the eye from the paper and from the object are the same as those that reach the eye from the paper and the shadow in the upper case. In both cases the observer interprets the illuminant as yellowish and so judges the shadow/object to be blue.

would deliver the same spectral signal to the eye if it were under such an illumination. This hypothesis has been a recurrent one in color science (e.g., Jaensch, 1921) and has recently, for example, been favored by Cunthasaksiri et al. (2004), but it has not been given an explicit name. Because Monge was the first, as far as I know, to put the hypothesis forward, I shall refer to it as the "Mongean conjecture." Fig. 3 illustrates his argument. Consider first the case of the colored shadow. Most of the white paper is illuminated by candlelight and by skylight, but one region, in the shadow of the sugar caster, is lit only by skylight and (as long as the candlelight is present) looks vividly blue. Now consider the second case where there is no sugar caster, but rather, a blue object lies where the shadow formerly was. The blue object is illuminated with the mixture of candlelight and skylight that illuminated the unshadowed area in the first case. If the spectral reflectance of the blue object were suitably chosen, it would reflect to the eye the same spectral flux as the shadow in the first case. It is reasonable that our visual system should interpret as blue the shadow in the first case, because the shadow delivers to our eye the same spectral signal as would a truly blue object in the inferred illumination. Yet if the candle is extinguished, the inferred illumination changes and we then see as white the entire paper, including the region that sends the same spectral signal to our eye before and after the candle is snuffed.

To ask whether colored shadows are objective or are visual illusions—to ask, for example, whether the shadow lit by skylight is truly blue—is to ask a mistaken question and is to miss the point that Monge is making. There is no absolute mapping between spectral power distributions and hues. A given spectral stimulus has meaning only by its ratio to surrounding stimuli.

Monge offers the same type of explanation for another contrast effect, which had been described to him by Jean-Baptiste Meusnier. A fellow academician, Meusnier had been a pupil of Monge at Mézières and is remembered in aeronautical history for his design for a dirigible airship. Sharing Monge's political radicalism, he earned a reputation for bravery as a Major-General in the revolutionary Army of the Rhine and died from wounds sustained during the Prussian siege of Mainz in 1793. (The Prussians allowed a two-hour cease-fire for his funeral.)

This is the illusion that Meusnier described. A room is illuminated by sunlight passing through a red taffeta curtain. There is a tiny gap in the curtain through which a shaft of direct sunlight passes. If this unfiltered sunlight is allowed to fall on a sheet of white paper, the illuminated area of the paper reflects to the eye nothing but white light. And yet it looks a most beautiful green. If the curtain is green, and the conditions otherwise the same, the spot looks an equally fine red.

The explanation that Monge gives for Meusnier's illusion is again in terms of color constancy. When the room is illuminated by sunlight passing through a red curtain, we are constrained to take as beams of white light the rays of homogeneous light reflected by all points on the surfaces of the many objects in the room. The patch of sunlight must then appear of a different color, because it stimulates our visual system differently and because the colors that we see depend not on the absolute properties of the light but on their ratios (*v*. Fig. 2). In modern terms, the visual system is assuming that the illuminant is reddish; and the dapple of unfiltered sunlight delivers to the eye the spectral signal that would be produced by a greenish object in such a reddish illumination.

Discovering the spectral composition of the illuminant

But if the spectral flux from a local patch is to be reinterpreted according to the illumination falling on a larger area, then how can we know the spectral composition of the illuminant? This has ever since been one of the central issues in the field of color constancy, and the answer that Monge gives is clearly inspired by his longstanding interest in the geometry of natural scenes.

All objects, Monge argues, reflect to us a certain proportion of white light, that is, light that corresponds to the unmodified illuminant. Consider a cylinder with a polished surface, for example, a stick of sealing wax. Along the axis of the cylinder, one typically observes a narrow band, a highlight, where the unmodified illuminant is reflected to our eye. Today, we should call this specular reflection (Fig. 4): The specular component is reflected at the same angle as the angle of incidence and is not altered by pigments within the surface of the object (Lee, 1986). Elsewhere the cylinder exhibits to us its body color: the illuminant has been spectrally shaped by selective absorption by pigment molecules within the surface and the signal that reaches our eye is the product of the spectral power distribution of the illuminant and the spectral reflectance of the surface. Between the regions exhibiting the highlight and the body color, there will be a gradient of regions that exhibit different mixtures of the illuminant color and the body color.

So far we have considered a polished cylinder, but Monge invites us to consider the microscopic structure of natural materials. The fine structure will consist of individual surfaces lying at different angles. Some of these will reflect a specular component to the observer's eye. So the light reflected by the macroscopic object will always contain a specular component. Consider a scarlet woolen fabric, suggests Monge: Each of the individual strands of wool can be thought of as a little cylinder and will deliver to the eye not only the red rays that define the color of the object but also rays of white light—which indeed allow us to recognize the cylindrical form of the strand if we inspect it under the microscope.

The proportion of the two components will depend on the angle that a given region presents to the illuminant and to the eye. We can use the gradients, Monge suggests, to learn about the shape of objects: nowadays we might call this "shape from chromaticity." It

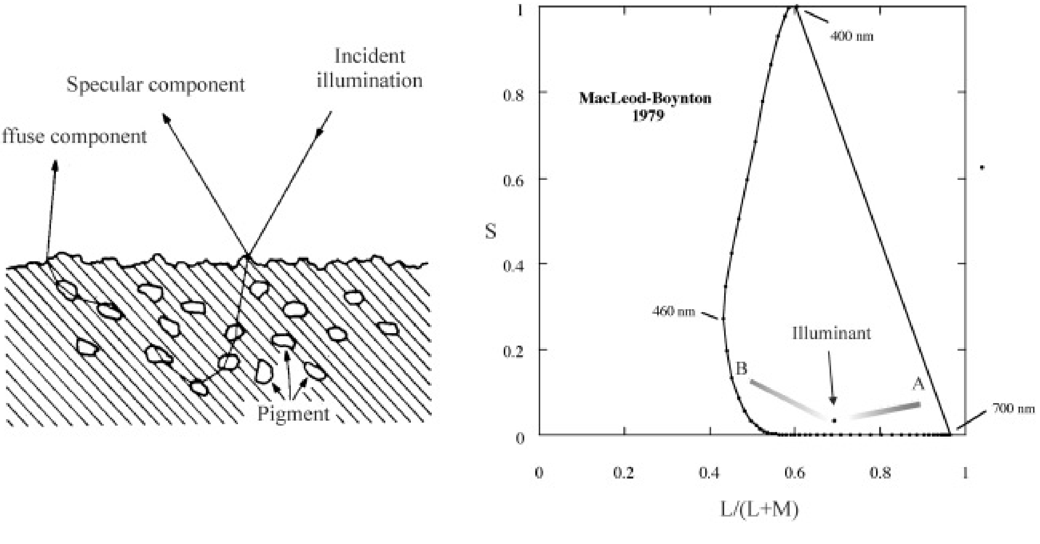


Fig. 4. Left-hand panel (after Lee, 1986). The light reaching the eye from any surface consists of two components: Firstly, a specular component, which is reflected at the same angle as the angle of incidence and often is spectrally unmodified; and secondly a scattered component, which has been spectrally shaped by selective absorption within the surface. Right-hand panel: The light reaching the eye from any point on a colored surface will be a mixture of the body color (the scattered component) and the illuminant. According to the inclination of the surface to the illuminant and thus the proportion of the specular component, the chromaticities of the mixture will lie along a line that runs between the chromaticity of the illuminant and the chromaticity of the body color. If two surfaces, A and B, are present in the scene, a line projected through the set of chromaticities reflected from surface A will intersect a line projected through the set of chromaticities reflected from surface B, so identifying the chromaticity of the illuminant even if no direct sample of the illuminant—no highlight—is visible.

Fig. 5. A detail from David's painting of Lavoisier and Mme Lavoisier, illustrating the use of chromaticity and lightness gradients to indicate three-dimensional structure. Lavoisier was executed in May, 1794, together with other tax farmers. Gaspard Monge, his scientific collaborator, did nothing to save him. The Metropolitan Museum of Art, Purchase, Mr. and Mrs. Charles Wrightsman Gift, in honor of Everett Fahy, 1977 (1977.10). Photograph © 1980 The Metropolitan Museum of Art.

is important to realize how closely his color theory is related to his descriptive geometry. He writes:

> "When we cast our eyes over a range of objects of different colors, every visible part of the surface of these objects, at the same time as it sends to the eye rays of the characteristic color of the corresponding object, also sends rays of white light. It is by means of these rays of white light that we judge, not the contour of the objects, since this contour is established by the shape of the image painted on the retina, but rather the depressions, the protrusions, and in general the degree of obliquity of different parts of the surface of the objects" (Monge, 1789, pp. 137–138).

The recognition of shape from chromaticity is illustrated well by David's celebrated painting of Lavoisier and his wife (Fig. 5): by mixing the illuminant color with the body color, David shows us the fall and folds of the scarlet tablecloth.

Monge comes very close to a hypothesis that was advanced by Lee (1986) and D'Zmura and Lennie (1986). It has been named the "chromatic convergence hypothesis" by Hurlbert (1998). Even if a scene contains no explicit highlights, any given surface will exhibit some variation in the proportion of specular and body colors. In a chromaticity diagram these mixtures will lie along a line (Fig. 4), a line that must point toward the chromaticity at which only the specular component is present (i.e., the chromaticity of the illuminant). Suppose now a second surface is present in the scene, a surface of a different body color. The light reaching the eye from this surface will in its turn consist of mixtures of the body color and the illuminant, again falling along a line in the chromaticity diagram. Even though no highlight is present, the intersection of the two lines identifies the chromaticity of the illuminant, and this information could in principle be used to achieve a degree of color constancy (D'Zmura & Lennie, 1986; Lee, 1986). (This cannot of course be the only method of achieving color constancy, because a Mondrian array of chromatically homogeneous patches, simulated on a monitor screen, exhibits a degree of constancy. And the method estimates only the chromaticity of the illuminant, not its spectral power distribution.)

Monge, of course, did not have available to him a modern chromaticity diagram, although he would almost certainly have been aware of Newton's color circle, which can be taken as a primitive chromaticity diagram (Mollon, 2003). How close he comes to the chromatic convergence hypothesis must be judged from passages such as this:

> "So, even when amongst the objects of our gaze there be none that are white, we always have the awareness, not of white strictly speaking, but of white light, as a result of the brilliance that in general it gives to colors, and by the differences that it produces among tints, according to the obliquity of the surfaces" (Monge, 1789, p. 142).

It is curious that Monge was not himself tempted to a geometrical representation of colors, but his geometry was very much the geometry of the external world (see, for example, Gillispie, 1980, p. 526).

The unique property of a white surface

Monge had a related insight that is of some importance. He realized that a white surface has a unique property: provided there is only one source of illumination (and no secondary reflections from colored surfaces), there can be no variation in chromaticity across a white surface, because the chromaticity of the body color and the chromaticity of the illuminant are the same. We may add that this is also true for grey surfaces. In both cases, although there is no variation in chromaticity, there may well be variation in luminance across the surface.

If this is how we identify a white surface, then—Monge argues—we can explain the whitening of a red object seen through a red filter. When the red surface is observed through the red glass, it has the property of a white object (i.e., there is no variation in chromaticity across its surface). The specular component reflected from any point on the surface has now the same color as the component that has undergone selective absorption. The same result will occur if, instead of viewing through a chromatic filter, we illuminate a scene with one predominant color:

> "For these homogeneous rays, being reflected to the eye from all the visible parts of the surface of colored objects, as is white light under ordinary conditions, we are led to take them for the white rays whose function they now perform, and thus to consider as white all those objects that reflect to the eye only rays of this type." (Monge, 1789, pp. 144–145)

Monge's insight has a corollary: a chromatically variegated surface cannot represent the illuminant. Now, if the Mongean conjecture about contrast (see earlier) is correct, we might expect uniform and variegated fields to behave differently in studies of contrast: the visual system may take an extended uniform surround to represent the illuminant, but a variegated field can never represent the illuminant. Jenness and Shevell (1995) indeed showed that adding sparse white or green dots to a red background field greatly weakened its power to induce a color shift in a central target, even though the randomly added spots occupied only 5% of

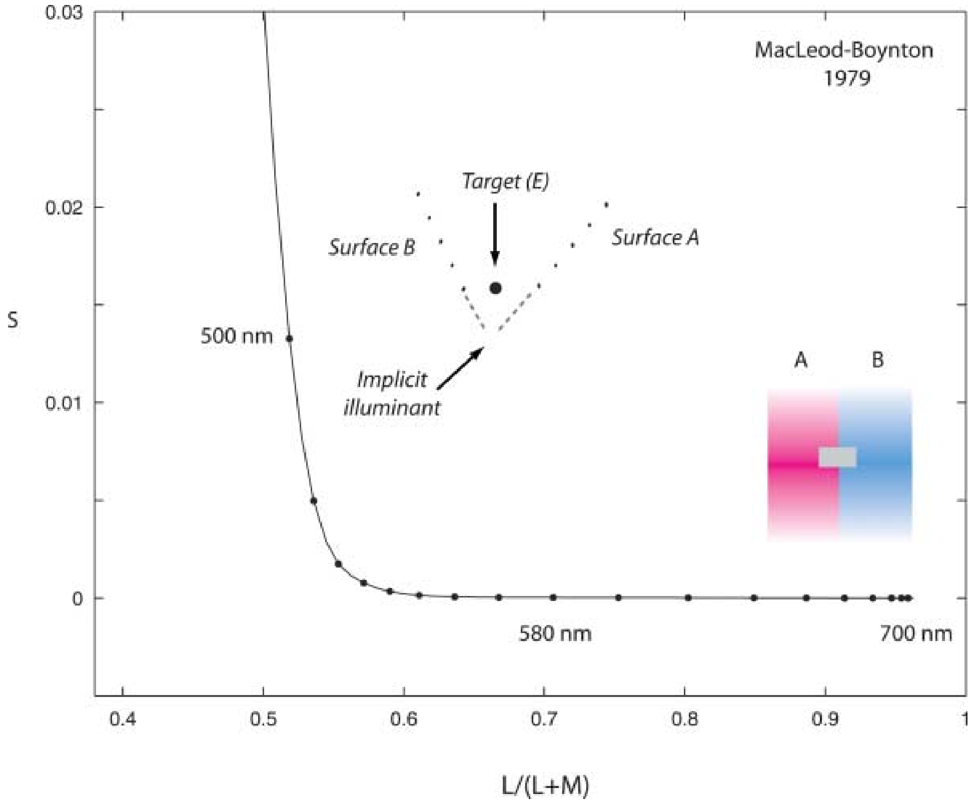


Fig. 6. A proposed experimental test case, where the color shift expected from conventional contrast is opposite to the shift expected from color constancy. The inset shows the target stimulus embedded in a scene that contains two sets of chromaticities. Each set of chromaticities corresponds to varying mixtures of body color and illuminant and lies along a line in color space. Although all these chromaticities have higher S values than the target, the two lines intersect below the target and thus imply an illuminant with a lower S value than the target. The spatial configuration of the surround need not, of course, be that suggested in the inset. Different results might be expected according to the degree to which the spatial configuration suggests a three-dimensional scene with a directional illuminant.

the area of the field and did not substantially change its space-averaged chromaticity. Similarly, Hurlbert and Wolf (2004) showed that a variegated—finely textured—surround induced less color contrast in a uniform target patch than did a surround of the same space-averaged chromaticity and luminance. However, their results cannot wholly be recruited in favor of the Mongean conjecture, because induction was weakest when the target patch was variegated and the surround was uniform.

A possible test of Monge's conjecture

If the visual system does exploit chromatic convergence to estimate illuminants, an interesting test of the Mongean conjecture suggests itself (Fig. 6). Suppose that the subject is asked to judge the color of a target with the chromaticity, say, of equal energy white. The target is embedded in a context that contains at least two surfaces, A and B. The body colors of all surfaces have higher S (short-wave cone) values than does the target surface. The implicit illuminant in the scene, however, has a lower S value than the target surface. Each of the surfaces exhibits some variation in chromaticity, corresponding to varying mixtures of the illuminant and the body color, and so these variations offer information about the illuminant: in the chromaticity diagram, a line projected through the chromaticities presented by one surface will intersect similar lines representing other surfaces, and the intersection represents the chromaticity of the implicit illuminant. However, no point on any of the surfaces has a lower S value than does the target. There are no actual highlights.

So, here we have a nice test of the relationship between color contrast and color constancy. A conventional account of contrast would predict that the embedded target would be displaced in its appearance so as to match a stimulus of lower S value. For all the surrounding regions have a higher S value than the target. On the other hand, if spatial induction effects are secondary to a mechanism of color constancy, and if chromatic convergence is exploited by that mechanism, then the embedded target should be displaced in appearance so as to match a stimulus of higher S value. For the target delivers to the eye a stronger S signal than does the implied illuminant. It would be straightforward to generalize the experiment to include the L/M axis of color space.

It is possible, of course, that there are two underlying processes, one of pure contrast and the other a constancy mechanism. If this is the case, we might expect the outcome to favor the Monge prediction when the target is embedded in a three-dimensional scene that implies a realistic illuminant but not when it is embedded in a two-dimensional geometric array such as used in traditional studies of simultaneous contrast.

Unique hues

I should now like to turn to the topic of unique hues, a topic that is often discussed in isolation from the topic of color constancy. There exist four *Urfarben*, or unique hues, that appear phenomenally unmixed to most normal observers (Hering, 1878). These are red, yellow, green, and blue. In the case of other colors, we judge that we can identify more than one component quality within our sensation—for example, redness and yellowness in orange, or redness and blueness in purple. The unique hues are grouped into opponent pairs, red–green and yellow–blue, so that, in everyday conditions, we do not experience reddish greens or yellowish blues.

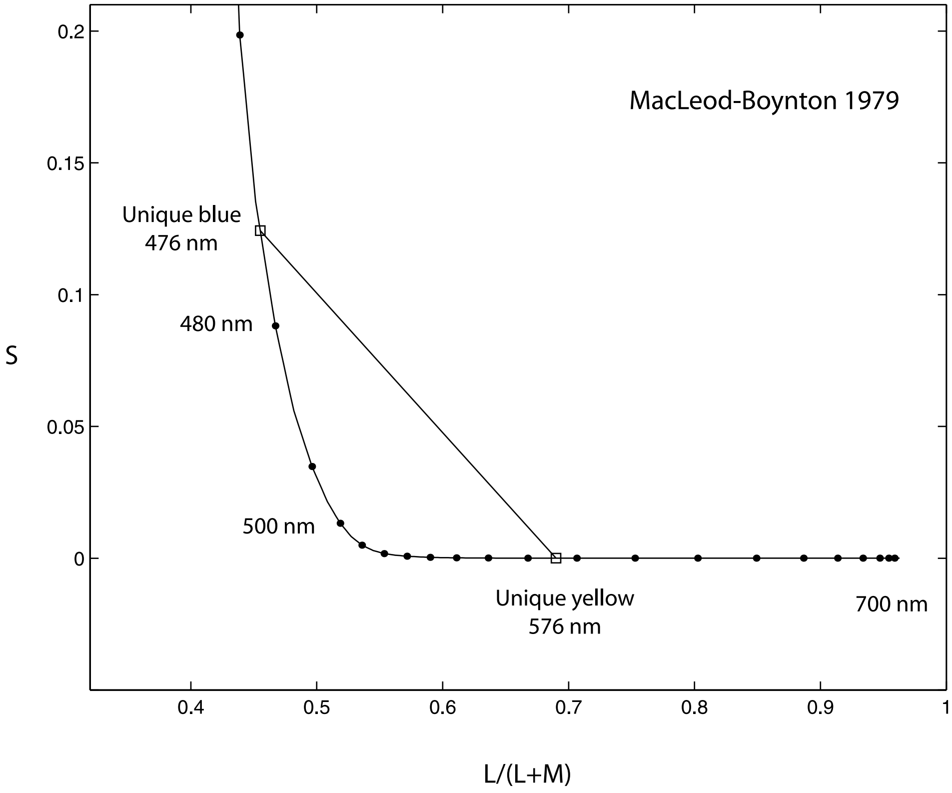


Fig. 7. Unique hues plotted in the MacLeod-Boynton chromaticity diagram. A line between unique yellow and unique blue is oblique in this space.

A central problem in modern color science is that the axes of phenomenological color space defined by the unique hues do not correspond to the two channels identified physiologically in the early visual system (Derrington et al., 1984) or to the two cardinal axes identified psychophysically by means of contrast adaptation (Krauskopf et al., 1982). This is readily apparent if the unique hues are plotted in the MacLeod-Boynton chromaticity diagram (Fig. 7). The ordinate of the diagram corresponds to the phylogenetically ancient subsystem of color vision, which compares the signal of the short-wave cones with some combination of the signals of the long- and middle-wave cones; and the abscissa corresponds to the phylogenetically modern subsystem of color vision, which compares the signals of the long- and middle-wave cones (Mollon, 1989). If we plot in this diagram a line that runs from unique blue (*c*. 476 nm) to unique yellow (*c*. 576 nm), it is very far from being a vertical line that would correspond to a simple variation in the signal of the short-wave cones. Rather, a blue-yellow line represents a large modulation of the ratio of the long- and middle-wave signals. Such a line simply does not correspond to exclusive modulation of the phylogenetically ancient subsystem of color vision.

Judgments of whether or not a hue is unique are paradigmatic examples of what Brindley (1970) called "Class B observations." We require more of the observer than a match or a detection: we require that he or she reports on the quality of a private sensation. To this day, we do not know what status to give to Class B observations.

So, what are the unique hues? Are they determined within us, by the organization of our visual system? Or are they ecologically significant, identifying for us particular subsets of spectra in the world? Let us call answers of the former type "constitutional" hypotheses, and answers of the second type, "ecological." The two types of account are not necessarily exclusive, because our visual categories may have evolved to match some feature of the world.

An example of a constitutional hypothesis is that of Cicerone (1990), who proposed that the wavelength of unique yellow depended on the relative numbers of long- and middle-wave cones in an individual's retina. To be in equilibrium, the "red-green process" needs a certain ratio of input from the long- and middle-wave cones. The more long-wave cones that an observer has, the greater the relative long-wave signal at a given wavelength. So an observer with an excess of long-wave cones should set unique yellow at a shorter wavelength than will an observer who has fewer long-wave cones.

Gabriele Jordan and I have offered two tests of this hypothesis. Firstly, we asked whether the wavelength of unique yellow is correlated with the relative flicker-photometric sensitivity to red and green light. The latter measure has traditionally been taken to reflect the ratio of long- and middle-wave cones in an individual retina (De Vries, 1947). In a sample of 50 color-normal males, instead of the negative correlation predicted by Cicerone's hypothesis, we found a non-significant relationship ($r = 0.066$) between flicker-photometric sensitivity and unique yellow (Mollon & Jordan, 1997). Secondly, we measured the wavelength of unique yellow in obligate carriers of X-linked color deficiency. Owing to random inactivation of one or other X-chromosome in every cone (Lyon, 2002), the retinal mosaics of such heterozygotes will exhibit abnormal ratios of long- and middle-wave cones: Carriers of protan defects should have low numbers of long-wave cones and carriers of deutan defects should have low numbers of middle-wave cones. By Cicerone's hypothesis, therefore, protan carriers should place unique yellow at a longer wavelength than normal, and deutan carriers should select a shorter wavelength. In this

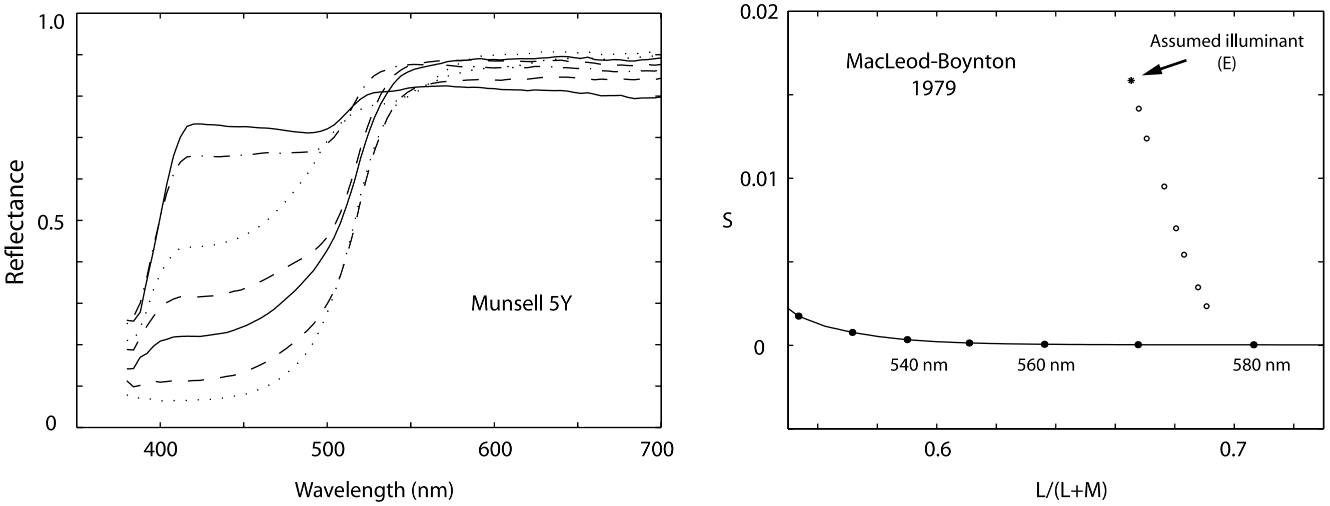


Fig. 8. A set of real-world surfaces that appear unique yellow. These are Munsell papers with a hue of 5Y and varying degrees of chroma. The lefthand panel shows the reflection spectra of these papers, measured with a PhotoResearch 650 spectroradiometer. The righthand panel shows the chromaticities of these papers when illuminated by an equal-energy white illuminant. Notice that the chromaticities run obliquely in the MacLeod-Boynton diagram: They do not lie on a tritan line.

experiment, luminance was held constant at 20 td as wavelength was varied, and unique yellow was measured by a method in which four staircases are randomly interleaved, to avoid any systematic bias. The two types of carrier did not differ significantly from normals or from each other (Jordan & Mollon, 1997).

So we have been led to ask whether unique hues might have their basis in the world rather than in the hard-wiring of the visual system. If we are correct in looking for unique hues in the external world, perhaps we should be measuring them not with the traditional monochromatic lights but with broad-band surface colors. Fig. 8 illustrates how very different from monochromatic lights are the surface stimuli that give rise to the sensation of a pure, light yellow.

In favor of an ecological explanation are the suggestions, going back to Donders (1884), that observers show less variation in judging colored papers than they do in judging monochromatic lights. In an unpublished study with M. Lwin, Dr. Jordan and I have compared unique yellow settings for monochromatic lights and for surface colors (prepared with a dye-sublimation printer). Twenty-two subjects were tested, using closely similar psychophysical procedures—four randomly interleaved staircases—for the two conditions. The dominant wavelengths of the surface colors were measured with a spectroradiometer. Both for the lights and for the papers, luminance was held constant as wavelength was altered. For monochromatic lights, the standard deviation of the settings was 4.03 nm, whereas the standard deviation of the dominant wavelength for the surface colors was only 2.31 nm. The difference is significant ($F = 3.05$, $P = 0.02$).

An interesting observation made by Jordan and Mollon (1997) would be consistent with an ecological hypothesis. In a study of 97 color-normal males, we found a very significant relationship between the lightness of the subject's iris and his settings of unique green: Observers with lighter irises judged a shorter wavelength as unique green. The measurements were made with monochromatic lights. We took the lightness of the iris as an indirect index of the degree of pigmentation of the fundus. Yet all that an ocular pigment can do to a monochromatic light is attenuate it. It cannot change the *relative* effects of the light on the three classes of cone. So if unique green corresponds to a particular set of ratios of cone absorptions, it is difficult to understand why it should be affected by inert pigments. Suppose, however, that the different observers all acquire their concept of unique green by interacting with surfaces in the world. Suppose they agree on the broad-band green surface that is neither yellowish nor bluish. In those whose fundus contains a stronger density of melanin, the retinal absorption at short wavelengths will be reduced: when the broad-band green surface is viewed, the relative excitation of the three cones will be different from that in observers with little pigmentation. If now, in the unusual conditions of the laboratory, the observers are asked to find the wavelength that produces the same relative cone excitations as did the broad-band green, then they must necessarily differ from one another.

To explore further the idea that there is something in the world corresponding to unique hues, let us return to Gaspard Monge and the case of white.

White is a unique hue

Discussions of the unique hues rather seldom include white as one of the unique hues. Yet white is the mother of all unique hues, and its phenomenological purity and simplicity were historically an obstacle to the acceptance of the Newtonian theory of the physics of color. We cannot identify multiple qualities in our sensation of white: white is neither reddish nor greenish, neither yellowish nor bluish, and in Opponent Colors Theory unique white represents the chromaticity that places in equilibrium both of the chromatically-opponent processes. Walraven and Werner (1991) have shown that a given observer's unique white—measured as the ratio of two monochromatic components—remains constant over a 4-log unit change in radiance.

Now, if we accept that white is a unique hue, then we do have an example of a unique hue that corresponds to a particular class of surfaces. For white surfaces in our world can be identified by two properties:

(a) First, if we neglect fluorescent surfaces, white surfaces are necessarily the lightest of surfaces, because physically they are surfaces that reflect all wavelengths near maximally.

(b) Second, Gaspard Monge has shown us that the white surfaces in our world have a further special property: (Provided there are not multiple illuminants falling on the surface), an achromatic surface is one that exhibits no variation in chromaticity across its surface. Conversely, a chromatically variegated surface cannot be achromatic.

When unique white is measured with combinations of monochromatic lights in the laboratory, different subjects make different settings, and they will reject each others' settings in confrontation tests (Walraven & Werner, 1991). Yet in the real world, when they are asked to judge surfaces, we may expect two observers always to agree on what are white surfaces, owing to properties (a) and (b) mentioned earlier. This should especially be the case if we allow the observers to handle the object, varying the tilt of the surface relative to the illuminant.

It is interesting that the two properties of white surfaces will in principle allow observers of different phenotype to agree on what is white in the world. A surface that is judged as white by color-normal observers can equally be identified as white by anomalous trichromats and dichromats—provided only that the surface has close to 100% reflectance throughout the visible ranges of the phenotypes being compared. Note, though, that I am claiming only that different phenotypes can all *identify* this special class of surfaces. I make no claim about their private sensations. And the agreement across phenotypes does not extend to grey surfaces: a surface with a non-flat spectral reflectance curve may, for a particular observer, be metameric with a surface that has a flat reflectance; but these two surfaces may be distinguishable for an observer with different photopigments (see, for example, Bosten et al. (2005)).

Do other unique hues correspond to properties of the world?

I have argued that at least one of our unique hues, white, does correspond to a special class of surfaces in our world. But what could be the surface properties that correspond to other unique hues? I shall concentrate here on the case of unique yellow.

White surfaces are ones that show no variation in chromatic signals across their surface in a single illuminant. Could yellow surfaces be ones that show no variation in the L/M signal across their surface? No, for we have already ruled out this possibility. It would require that yellow surfaces lay along a tritan line in color space, that is, a vertical line in the MacLeod-Boynton diagram (*v.* Fig. 8).

Could it be that unique yellow surfaces are, after white, the lightest surfaces in our world? Such surfaces differ from white only in absorption at short wavelengths (Fig. 8) and so we might expect little loss of luminance as we depart from white in a yellow direction. The hypothesis cannot be tested with Munsell colors, since the lightest available Munsell chips have been selected to have a constant lightness, corresponding to value 0.9 in the Munsell system. MacAdam (1935), however, calculated the maximum lightness that could be achieved for a surface of a given chromaticity. He showed formally that such surfaces must have a reflection factor that is zero or unity at each wavelength of the spectrum and must have no more than two transitions between zero and unity within the visible spectrum. Fig. 9 shows his results, as contours in the CIE diagram. There is indeed a ridge in the diagram, corresponding to the hues of maximal theoretical lightness. It runs from the white point in a yellowish direction. But close inspection shows that it does not run towards unique yellow. For a reference white of Illuminant C, the ridge runs in a tritan direction, cutting the spectrum near 570 nm, a yellowish green.

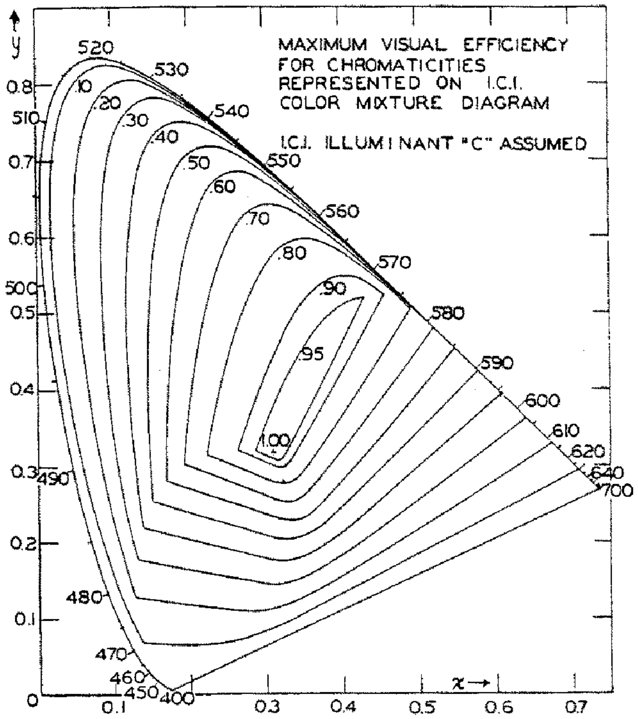


Fig. 9. The maximum lightness that can be achieved for surfaces of a given chromaticity. The surfaces are assumed to be illuminated with CIE Illuminant C, and the data are plotted in the CIE 1931 chromaticity diagram. (From MacAdam, 1935).

So should we look above us for unique hues? And are we misleading ourselves by considering scenes lit with a single illuminant?

Historically, it has often been asked why the sky is blue, but the question has rarely been asked in the sense that I should like to ask it here. Most observers would agree that the normal blue of the sky, the result of Rayleigh scattering, is neither reddish nor yellowish. Sky blue is a unique blue. This is a rather provocative coincidence. It is true that at sunrise, when Aurora leaves the saffron bed of Tithonus, the sky may be tinged with orange or red. And it is also true that occasionally, when thunder threatens, a lowering sky might be yellowish or purple. But most of the time, the sky exhibits a unique blue, without the slightest hint of red or of green. And it remains a unique blue as the observer ages and the lens of the eye becomes less transparent to short wavelengths.

Shepard (1992) has explicitly proposed that the yellow-blue axis of human color experience corresponds to the two predominant illuminants in our world. One of these is skylight; the other is the yellowish light of direct sunlight. In Fig. 10, plotted in the MacLeod-Boynton (1979) chromaticity diagram, are measurements that Robert Lee and I made in Cambridge in July, using a PhotoResearch 650 spectroradiometer. The crosses show the northern sky, measured directly. The open circles show the chromaticity of light reflected from a plaque of barium sulfate. At one extreme

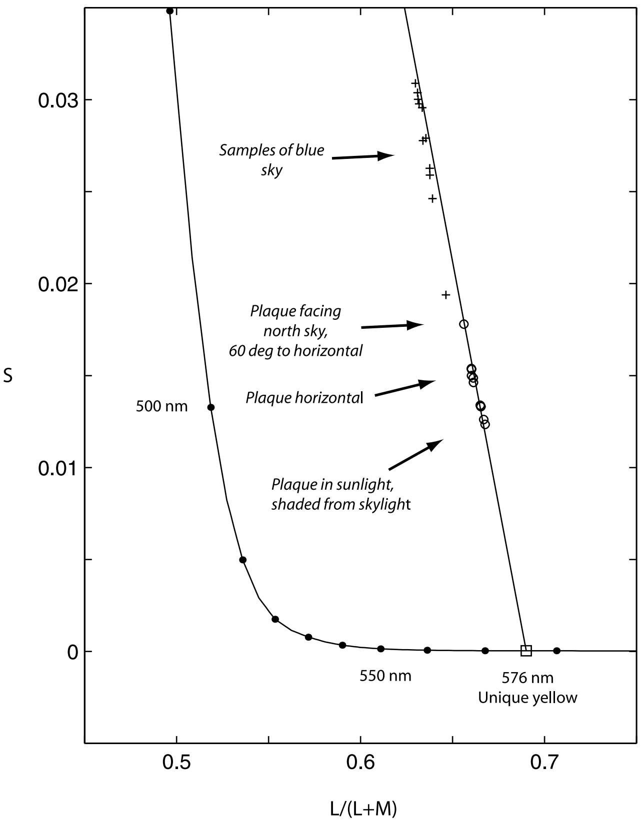


Fig. 10. The crosses show the chromaticities obtained by direct spectroradiometric measurements of northern sky on a clear day in July in central Cambridge. The circles show the chromaticities of light reflected from a white (barium sulfate) plaque. At one extreme (the rightmost data point), the plaque is illuminated by sunlight and is shaded from skylight. At the other extreme (the leftmost data point), it is exclusively illuminated by northern skylight. The intermediate circles represent the chromaticity of light reflected from the plaque in intermediate positions, when it is illuminated by both sunlight and skylight.

(rightmost circle), the plaque was facing the sun and primarily illuminated by direct sunlight. At the other extreme (leftmost circle), the plaque was facing the northern sky and was not illuminated by direct sunlight. As the plaque is rotated between the two positions, the measured chromaticity moves along a line in color space that is rather close to the yellow-blue axis. The line that I have superposed on the data runs between the monochromatic lights that correspond to unique blue (476 nm) and unique yellow (576 nm). The estimates in the literature would allow some variation in the wavelengths chosen (e.g., Dimmick & Hubbard, 1939), but it is very suggestive that the natural illumination in our world varies along an axis that is so close to the locus of lights that appear neither reddish nor greenish.

It is less obvious that unique red and unique green can be directly related to properties of illuminants as such. Even in the case of yellow and blue, what may prove to be critical is the way surfaces change in chromaticity as they are manipulated in a natural world containing two illuminants.

A contrast of politics and the politics of contrast

In the traditional history of French color science, a much more central figure than Monge has been Michel-Eugène Chevreul (1786–1889), whose writings on simultaneous color contrast had wide influence on both scientists and artists (Chevreul, 1839; Roque et al., 1997). Chevreul read his first paper on color contrast to the Academy of Sciences within a decade of the death of Monge (Chevreul, 1832). Neither in that paper nor elsewhere in his writings did Chevreul ever cite Monge, whose insightful conjecture, published in a prominent journal, seems so relevant to any discussion of simultaneous color contrast. It is difficult to believe that Chevreul was unaware of Monge's conjecture. In the *Annales de Chemie et de Physique* for 1828—the year that Chevreul gave his first paper on contrast—a theory very similar to that of Monge was attributed to Bénédict Prevost, and the editor of the *Annale*s appended a detailed précis of the original paper by Monge (Prevost, 1828). The *Annales* was the primary chemistry journal in France, and Chevreul—a chemist—served on its editorial board, briefly in 1816 and from 1853 to 1889 (Crosland, 1994). I have long been curious about Chevreul's reluctance to cite Monge, and had previously attributed it simply to Chevreul's self-centered personality (Mollon, 1997); but a brief survey of the career of Gaspard Monge after 1789 may suggest a fuller explanation.

Monge embraced the Revolution with enthusiasm and became a member of the Jacobin Club, serving indeed as its Vice-President (Aubry, 1954). His father had been a peddler at the time when Monge was born in 1746, and Monge had resented his own lowly role—preparing materials for well-born cadets—when he first came to the military school at Mézières (Pairault, 2000). From the 1770s, he was a close and long-term friend of Jean-Baptiste Pache, who was to become Mayor of Paris during the Terror (Gillispie, 1980, ch. 6). It was partly through the influence of Pache that, two days after the fall of the monarchy on August 10, 1792, Monge was elected Minister for the Navy and for the Colonies in the new *Conseil Exécutif Provisoire*. He held the post until resigning in April 1793.

Monge did not sign Pache's *Addresse au Peuple*, calling for the death of "Louis Capet" in December 1792. However, as a Minister of the executive council, Monge was an official witness of the execution of the king on January 21st, and his signature, with that of Pache, is on the report to the Convention (Aubry, 1954).

In 1792, while Monge was Minister for the Navy, he was called upon by a young Corsican artillery officer seeking a command. Monge received the young officer with courtesy (Pairault, 2000). The incident may have been forgotten by Monge, but was recalled by the officer—Napoleon Bonaparte—when they met again in 1796 in Milan (Aubry, 1954). The two became good companions. "Monge loved me as one loves a mistress," Napoleon is reported to have said on St. Helena. During the Italian campaign, Monge was officially responsible for the systematic plundering of art, books, and manuscripts for transfer to the museums of Paris and to the library of the *École Polytechnique* (Gillispie, 2004).

The letters that Monge wrote to his wife from Rome in 1797 reveal a fierce anti-clericalism. He characterizes the Pope as a "charlatan impudent," priests as "terroristes abominables qui empoisonnent notre vie entière" and religious processions as "farces pitoyables" (De Launay, 1932*a*). The Oratorians had given Monge a fine education, but they did something to alienate his soul.

Monge was made a member of the Senate in 1799 and President of the Senate in 1806. In 1807 Napoleon, now Emperor, gave him a gift of 200,000 francs, with which he bought a large chateau and estate at Bierre-les-Semur (De Launay, 1932*b*). And in 1808, only 15 years after he had signed the report of the execution of Louis XVI, Monge accepted from Napoleon the title of Comte de Péluse (Fig. 11), together with an income of tithes from an estate at

Fig. 11. Gaspard Monge, Comte de Péluse.

Eimbeck in Westphalia. When he visited the Emperor at Fontainebleau, the carriage of this former Jacobin was drawn by six horses.

Nemesis watched. In December 1812, reading the account of the disasters in Russia, Monge let fall his newspaper and collapsed in apoplexy. With the final exile of Napoleon in 1815 after the Hundred Days, the restoration of the Bourbons brought a white terror to France. Monge was one of its victims: he was stripped of his honors and was expelled from the *Institut de France*. His final years were sad ones and he died on July 28, 1818.

The allegiances of Michel-Eugène Chevreul were very different from those of Monge. He was a royalist and he came from a fervently catholic family. As a child in Angers, he had been deeply affected by the excesses of the Terror and by the sight of the guillotine being erected: "I see forever," he wrote, "the winter of 1793, a somber sky, an expanse of snow and patches of blood" (Chevreul, 1997). In 1824, Louis XVIII nominated him as Director of Dyeing at the Gobelins Factory, which was a royal institution. We can readily see that Chevreul, holder of a government post under a restored Bourbon monarchy, would not readily cite a man who—fairly or not—was judged a regicide. What went for Monge, would go too for most of those who wrote in French on color theory and simultaneous contrast in the period 1780 to 1805: it is a curious and perhaps unnoticed fact that Gaspard Monge (1789), Jean Paul Marat (1780), Jean Henri Hassenfratz ("H. F. T.", 1782), and Claude-Antoine Prieur (1805), together with Jean Meusnier (*v. supra*), all concerned themselves with colored shadows—and all were prominent members of the Jacobin Club.

If Monge is little remembered now amongst color scientists, his name is well preserved in mathematics, and an odd coincidence links him forever to another instructor from the *Lycée Ampère* of Lyon. The class of partial differential equations, for which he is best known, are the Monge-Ampère equations.

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