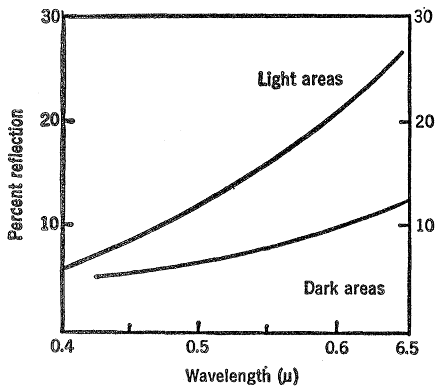

Fig. 2. Spectra of Martian light and dark areas, compiled by Loomis (7).

a very low percentage of trans-opaque material present in the soil, the spectral curves for different sizes of particles may not cross.

Thus, although we have shown here that the two hypotheses are mutually exclusive, there is insufficient evidence available to allow a choice between the particle size–albedo hypothesis and the hypothesis that the Martian soil consists in large part of limonite. Whatever the cause of the albedo differences on Mars, we believe that the most likely soil, from the standpoint of geology, is one composed of silicates lightly stained or coated with ferric oxides, as advocated by Van Tassel and Salisbury (3). This belief is consistent with the conclusions of Adams (11), based upon the suspected Martian band near 1 μ.

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27 May 1968

Vision: The Additivity Law Made To Work for Heterochromatic Photometry with Bipartite Fields

Abstract. *Additivity failures are common in heterochromatic photometry when the usual criterion of equal brightness is used. Using instead the criterion of a minimally distinct border between two precisely juxtaposed fields, we found that the additivity law holds.*

The photometric quantity called luminance (L) is derived from the physical quantity called radiance (N) by taking into account the spectral sensitivity of the eye (V_λ) (1). If the radiance of a surface is known as a function of wavelength, luminance may be calculated by evaluation of the definite integral

$$L = K\int_{380\text{ nm}}^{750\text{ nm}} N_\lambda V_\lambda d\lambda \qquad (1)$$

Equation 1 states that superposed lights, of differing spectral compositions, should have luminances that add linearly (Abney's law); such additivity is true by definition and international agreement. The assumption that fields of equal luminance are also equally bright holds only when additivity is demonstrated and brightness judgments are used as a criterion. Despite Abney's claim, such additivity is generally not found; in particular, the superposition of lights that are complementary, or nearly so, results in clear cancellation of brightness as well as of chromaticness (2).

We now show that one can make a direct side-by-side comparison of photometric fields in a manner that causes the additivity principle to be obeyed. This experiment is performed by juxtaposing two fields with high precision and then asking the observer to set the radiance of one field relative to the other until the border between them is minimally distinct. Our search of the literature has found no evidence of such an experiment; nearly all writers refer to an equal-brightness criterion, making no reference to the quality of the border between the fields (3).

We measured the residual contrast between two heterochromatic fields when the contrast between them was at a minimum (4). We found that, when two such fields are precisely juxtaposed, a minimally distinct border generally does not occur between them when the fields are equally bright. When one field is white, the chromatic half must be brighter than the white half for the border to be minimally distinct. If the brightnesses of the fields are equated (by reducing the radiance of the chromatic field, for example), the border between the fields becomes clearly more distinct than it was before.

This finding led to development of a model of visual brain activity. The key idea is the supposition that there are chromatic and achromatic neural elements in the visual brain that can be in either an active or inactive state (5). When active, a given chromatic element provides one unit of chromatic signal and one unit of brightness (6). Chromatic signals are related to sensations of red, green, yellow, or blue; other bright colors (7) are blends of some of these within a receptive field. The more the units of activity within a receptive field and period of temporal integration, the more intense is the sensation. A given element can give rise to only one kind of chromatic sensation (8). Moreover there are achromatic brain elements which, when active, give rise to sensations of whiteness and brightness.

An example of how the model is applied is shown in Fig. 1 for a blue (B) versus a yellow (Y) field. The blue field is assumed to activate 10 B units for every 10 W (white) units; this is shown on the left of the inset circle. The yellow field (right), being less saturated, is assumed to activate 1 Y unit for every 10 W units.

Contrast (C) (Fig. 1) is determined by the sum of the absolute differences between the numbers of active elements of each type on the two sides, divided by the total number of elements active on both sides. In the example, ΔB is 10, ΔY is 1, and ΔW is zero—a total of 11. In the denominator, the total number of active units is 31: 20 on the left plus 11 on the right. Curve C is calculated in this way and is plotted as a function of the ratio of white units active on the left to the number of white units on the right. We assume that minimum contrast yields a minimally distinct border. It is exactly true that the minimum contrast always occurs when the numbers of active white elements are equal on the two sides, regardless of the assumed ratio of chromatic to achromatic elements. Thus the minimum of curve *C* occurs above an abscissa value of unity. Brightness (β) depends on the ratio of the total numbers of active elements in the left and right fields; it is unequal at this point of minimum contrast.

If it were true that equal achromatic activity, due to each half of the field, implies a minimally distinct border between them, we might expect the additivity law to hold when such a criterion is used to test it. But, for this prediction to be made explicitly from our model, one must also assume that the achromatic units receive their inputs from a system containing only one type of receptor or two or more receptor types (or both) whose outputs sum linearly (*6*).

For performance of our experiments we were forced to construct a bipartite field having precisely juxtaposed borders. Our criterion for this border was that, when the spectral distributions and luminances of the two independently supplied fields were equal, there would be no visible border between them. Finding that this criterion was impossible to achieve in the standard Maxwellian-view system, we projected our fields onto a magnesium carbonate block. The left field was a reference white of 17 trolands, produced by a xenon arc filtered by a pale-yellow (Wratten CC05Y) filter and a neutral density wedge; it was delivered to the block by way of suitable optics that allowed a sharp edge to be formed by a razor blade placed at a conjugate focus of the system. The right field was provided similarly by two chromatic channels. Wavelength and luminance were controlled by precisely calibrated interference and neutral density wedges. The two fields together formed a circle, subtending 1 deg 40 minutes, divided vertically.

The observers maintained steady head position by means of a bite board. The fields were viewed through a 5-mm artificial pupil and an achromatizing lens that corrected for chromatic aberration of the eye. A shutter occluded the field for approximately 250 msec every 4 seconds to prevent fading.

In the first experiment the observers adjusted the radiance of the chromatic side of the bipartite field until a minimally distinct border, with respect to the white reference field, was obtained. The wavelength was then changed, and another set of minimum-border judgments was made. The two wavelengths were then mixed together, and the observer adjusted the radiance of each

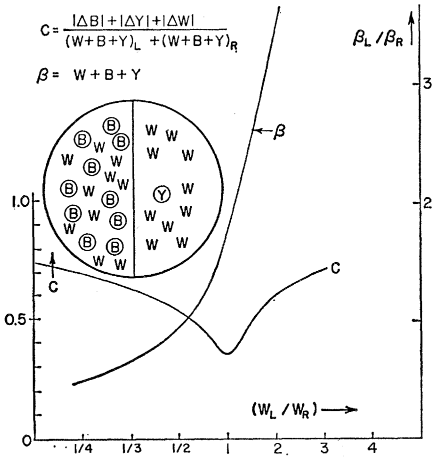

Fig. 1. Contrast (*C*) and relative brightness (β) between juxtaposed fields as functions of the ratio of achromatic (white) brain elements active because of stimulation of the eye by the left field to those activated by the right. The circle (inset) shows hypothetical ratios of brain activity for a blue field activating equal numbers of *B* and *W* units, and for a yellow field activating many more *W* than *Y* units. Formulas for calculation of the contrast at the border, and for the brightness of one-half of the field, are shown at the top.

until a minimum border was achieved (*9*). In these experiments, because we used complementary wavelengths, minimization of border with the mixture field resulted in an exact match and disappearance of border.

The calculations for the test of additivity were accomplished as follows. The relative radiance value, of each chromatic field required for a minimally distinct border with white, was defined as unity. If the additivity law is obeyed, the sum of the values, required of the wavelength components in the mixture condition, also should be unity. Columns 1 and 2 of Table 1 show the results of these experiments for observers RMB and PKK.

In the second experiment we created an artificial border, about 10 minutes of arc in width, between the bipartite fields. The observers repeated the experiments, using matching of brightness as a criterion. (Since there was always a border between the fields, the observers could not use a minimally distinct border as a criterion.) The data were collected and analyzed in the manner described for the minimum-border experiments; the results for RMB and PKK appear in columns 3 and 4 of Table 1. It is clear that the additivity law is obeyed to a close approximation when a minimally distinct border is used as a criterion. When the classical equal-brightness criterion is used, on the other hand, deviations from additivity are found [as in previous studies (*10*)]—often as high as 50 percent or more.

Walsh (*11*) discusses the well-known unreliability of matches of heterochromatic brightness. This unreliability, relative to the reliability of minimum-border judgments, is manifest in the great difference between the standard deviations of results for the two methods (see Table 1).

In a third experiment we asked a slightly different question. After determining the radiance values for each of two wavelengths (492 and 595 nm) that result in minimally distinct borders with respect to the reference white, we fixed 595 nm at various proportions of

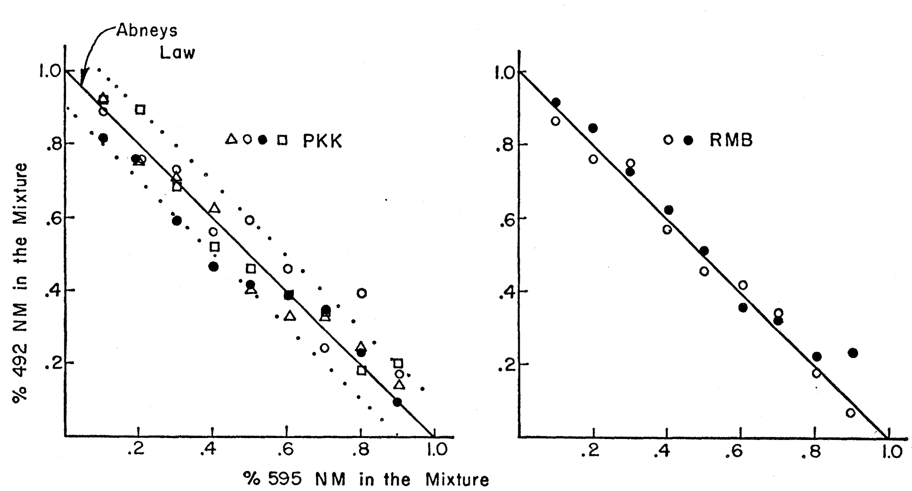

Fig. 2. Percentage of relative luminance at 492 nm, in a mixture field, as a function of the percentage of relative luminance at 495 nm, 100 percent (1.0) being based on minimum-border comparisons with a reference white when each component is used alone. The straight line is the predicted outcome if the additivity law obtains. The dotted lines (*PKK*) indicate ± 10 percent; the different symbols indicate data collected in separate sessions.

Table 1. Results of an additivity experiment. Perfect additivity would yield a value of 1.0. Two observers: RMB and PKK.

Minimum border		Equal brightness	
RMB	PKK	RMB	PKK
Wavelengths 492 and 595 nm			
0.975	1.030	1.419	2.012
.976	0.965	1.523	1.344
.981	1.009	1.475	1.309
1.060	1.040	1.647	1.205
1.044	1.094	1.549	1.587
0.990	1.026	1.362	1.377
Means			
1.004	1.027	1.500	1.472
Standard deviations			
0.027	0.037	0.092	0.267
Wavelengths 480 and 580 nm			
1.014	1.048	1.512	1.224
1.010	1.011	1.238	1.309
	0.980		1.126
	1.030		1.238
	1.063		1.100
	0.933		1.290
Means			
1.012	1.011	1.375	1.215
Standard deviations			
	0.043		0.077
Wavelengths 480, 540, and 630 nm			
0.925	0.961	1.160	1.392
1.028	.973		
0.969	.991		
.988	1.026		
Means			
0.978	0.988	1.160	1.392
Standard deviations			
0.038	0.025		

unity (unity defined as the radiance value for each component yielding a minimally distinct border). The observer then added light of 492 nm to this value of 595 nm to achieve minimization of border. We used proportions ranging from 10 to 90 percent of unity for the wavelength 595 nm. We should point out that border minimization of the mixture did not usually result in complete disappearance of the border as was the case in the first series of experiments. The calculations in this experiment were the same as those already described (*12*).

This experiment allowed us to make a series of precise predictions of the percentage of 492 nm that should be mixed with the set percentage of 595 nm (*13*). One can see (Fig. 2) that for both RMB and PKK the points fall close to the predicted (solid) line that defines the additivity law. The predicted line accounts for 96 percent of the variance for RMB and 92 percent of the variance for PKK.

Thus we have shown that, when the minimally distinct border criterion is used, the additivity law is obeyed for a side-by-side comparison. This finding is true whether the proportions of the mixture lead to complete cancellation of hue (first experiment) or to only partial cancellation (third experiment). As did other experimenters we have found that the additivity law is not obeyed when equal brightness is used as a criterion (second experiment).

One implication of our results is that additivity failures in heterochromatic photometry could be avoided by use of the criterion of minimally distinct border without placement of any restrictions on the chromaticities of the fields to be compared. Whether this procedure would lead to the same spectral-sensitivity functions as does flicker photometry (which also has been shown to eliminate additivity failure (*14*) remains to be seen (*15*).

Our results also have implications for the class of experiments in which one wishes to deal with visual effects produced by chromatic differences alone. Equation of stimuli for brightness (or luminance) provides little assurance that only chromatic differences will remain: since it is probable that the achromatic components of the visual system are unequally activated, such stimuli probably will not yield minimum visual acuity, minimum contrast, or minimum electrophysiological response.

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References and Notes

1. The term V_λ does not represent the spectral sensitivity of any real eye; it is a function based upon averaged data obtained in 1923 [K. S. Gibson and E. P. T. Tyndall, *Bull. Bur. Std.* **19**, 131 (1923)]. It was sanctioned in 1924 by the 6th session of the Commission Internationale de l'Éclairage.
2. Heterochromatic photometry and Abney's law are summarized by Y. LeGrand, *Light Colour and Vision* (Wiley, New York, 1957). Although Abney's law has been repealed many times for direct brightness matching, it is true to a good approximation in the flicker-photometry method (*14*).
3. Helmholtz [*Physiological Optics* (Dover, New York, 1962)] mentions that Fraunhofer wrote of a minimally distinct border that could be achieved between areas of different color, but Fraunhofer was not concerned with photometric measurement.
4. In a series of experiments to be described elsewhere.
5. A two-state neural element is hypothesized for the sake of simplicity. We could hypothesize a three-state neural element as implied by DeValois's findings in the lateral geniculate nucleus of the monkey, but the mathematical statement of the model would not be altered.
6. See R. M. Boynton, *J. Opt. Soc. Amer.* **50**, 929 (1960), for an earlier discussion of some of these ideas.
7. As opposed to dark colors. At the present stage of development our model does not incorporate the effects of induction generated by stimulation by the surrounds.
8. If a three-state element were hypothesized, the model would have to be altered to allow for a given element to give rise to either of two chromatic sensations when the element is not in a neutral state.
9. In the first two series of experiments the observers made six judgments of minimum border (or equal brightness) for each single-wavelength condition and six judgments for the mixture condition. Additivity was calculated from the mean values of these judgments. All determinations of minimum border (or equal brightness) were made by the method of adjustment.
10. Deviations of this magnitude for complementary wavelengths have been reported by S. L. Guth, *Vision Res.* **7**, 319 (1967); R. Morrocco and S. L. Guth, before Midwestern Psychol. Assoc., May 1967; M. Tessier and M. Blottiau, *Rev. Optiques* **30**, 309 (1951).
11. J. W. T. Walsh, *Photometry* (Dover, New York, 1958).
12. In this experiment we used the method of adjustment. Five determinations were made at each step, and the median value was used in the calculations because, on receiving the settings for 595 nm against white, the experimenter had to calculate immediately the setting of the neutral density wedge required for a certain percentage of unity. This determination was made separately for each set of data collected.
13. This method is similar to the test of additivity used by Tessier and Blottiau (*10*) with equal brightness as a criterion; they found large additivity failures.
14. For example: H. E. Ives, *Phil. Mag. Ser. 6* **24**, 845 (1912).
15. F. H. C. Marriott [in Davson, *The Eye* (Academic Press, New York, 1962), vol. 2, p. 241] states that different functions are obtained by the three methods (flicker, side-by-side, and step-by-step). Therefore it is reasonable to assume that the minimally distinct-border criterion may yield a still different function.
16. Supported by NINDB grants NB00624 and 2F2 NB 12, 980-02.

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Dielectrically Heated Sensor of Water-Vapor Pressure

Abstract. *Existing psychrometers of small dimensions cannot provide accurate long-term measurements of water-vapor pressure without frequent maintenance and recalibration. A small, simply constructed instrument employing dielectric heating and avoiding many of the problems of available sensors is described. The calibration curve depends only on the pressure-temperature curve for saturated lithium chloride.*

Of many available hygrometric sensors, one frequently favored for micrometeorological work is the dew cell. This device is rugged and has good short-term stability, and its range is limited only by lithium chloride triple points which correspond to water-vapor pressures of 1.3 and 30.0 mb (*1*). However, the dew cell is bulky and is susceptible to problems associated with the resistive dissipation of widely varying power, which rises to high levels under conditions of high vapor pressure. The conductive path is an extensive thin layer, the resistance of which may be required to vary repro-