The Binocular Fusion of Yellow in Relation to Color Theories

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IN 1928 HECHT REPORTED A DEMONSTRATION OF THE BINOCULAR FUSION OF YELLOW from monocular red and green stimuli, and explicitly developed the implications of this fact for color theory (*1*). Hecht's demonstration has been widely reported and discussed and has frequently been cited as a crucial experiment with respect to the two major classes of color theory—namely, three-component and four-component theories (*2–9*).

If we take the Young-Helmholtz view as illustrative of a three-component theory, then we assume that

> there are three receptor systems in the retina . . . which may be designated as *B*, *G*, and *R* to indicate their essentially qualitative uniqueness in yielding, respectively, blue, green, and red sensations when brought into action by light. Each receptor system produces only the sensation unique for it, regardless of the part of the spectrum which sets in into action, and the sensations produced by various parts of the spectrum result from the combined action of these three systems in different degrees. Certain combinations produce specific effects. Thus the combined actions of the *G* and *R* systems result in the unique sensation of yellow, and the combined actions of *B*, *G*, and *R* result in the unique sensation of white (*10*).

On the other hand, in the Hering view, taken as representative of a four-component theory, two pairs of excitatory color processes are assumed to be located in the retina and the associated neural paths.[1] These four processes when brought into action by light yield paired yellow and blue sensations, and paired red and green sensations. Yellow, in this view, arises directly from the stimulation of the specific yellow process in the retinal-neural system (*11*). It is *not* the result of the combined action of two other processes, as in the three-component view.

Hecht's experiment was designed to evaluate these two sharply contrasting views of the receptor processes. Both the nature and logic of the experiment are best summarized in Hecht's own words:

> If a red light and green light fall on a given retinal area of one eye and a yellow sensation results, it is not possible to decide whether this is the result of a stimulation of two receptors or of one receptor. But if monochromatic red light falls on the retina of one eye, and monochromatic green light falls on the corresponding portion of the retina of the other eye, and the result is a yellow sensation, then only Young's idea is tenable, because there must be two receptors involved in making the yellow sensation from red and green (*1*).

As has been widely reported, Hecht's experimental results were positive. Viewing a white surface with a No. 29 Wratten filter (red) before one eye, and a No. 58 (green) before the other eye, the observer sees yellow.

Some investigators have been reluctant to accept this demonstration as decisive, and they have tended on the whole to dismiss the findings as an artifact of Hecht's experimental technique (*12, 13*). Much of the critical emphasis seems to have centered about Hecht's choice of red and green filters that had relatively wide and slightly overlapping spectral transmissions. More recently, however, Prentice (*14*) has been able to demonstrate that a binocular yellow can still be evoked using narrow band Farrand interference filters, which have no appreciable overlap in spectral transmissions. The result was obtained even for short exposure times and relatively low luminances. The phenomenon of binocular yellow is accordingly interpreted as a valid result and not simply as an artifact of a particular experimental technique.

We have no difficulty whatever in confirming these experimental results. Whether the two filters used for the monocular stimuli are relatively nonselective, such as those Hecht used, or highly selective,[2] such as those used by Prentice, the binocular fusion of yellow is the unmistakable result.

If the analysis is pursued no further, Hecht's formulation of the problem seems to have been given a direct and decisive answer. When monochromatic red light falls on the retina of one eye and monochromatic green light falls on the retina of the other eye, the result is a yellow sensation. Following directly from this positive experimental result, yellow must be a phenomenon that arises in the brain out of impulses coming from two kinds of fibers or processes in the retina, and no special substance or process would appear to be required in the retina for its reception. As a corollary conclusion, then, only Young's idea is tenable.

Upon closer scrutiny, however, the problem is considerably less simple and straightforward than it has appeared up to now. The logic underlying the crucial nature of this experiment is valid only on the assumption that a so-called monochromatic red stimulus evokes a red sensation and nothing but a red sensation, and that a so-called monochromatic green stimulus evokes a green sensation and nothing but a green sensation. Then, and only then, could the binocular yellow sensation that results from two such monocular stimuli be attributed without question to the central fusion of the two independent monocular processes. This is clear from Hecht's formulation of the Young-Helmholtz

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[1] A third pair of processes mediates the black-white sensations.

[2] The interference filters were used with collimated light to assure maximal purity.

TABLE 1

Spectral Loci of Pure Hues

	Blue locus (in mμ)	Green locus (in mμ)	Yellow locus (in mμ)
Hess (*15*, 21)*	475 – 477	497 – 500	577
Westphal (*16*, 202, 204)†	480.0 ± 1.7	507.9 ± 1.7	576.4 ± 1.7
Dreher (*17*, 48, 54)‡	477.4	509.4	575
Schubert (*18*, 88)§	465 ± 2.5	497 ± 2.0	573 ± 0.5
Purdy (*19*, 554)‖	476 ± 2.4	504 ± 3.0	576 ± 3.3
Kohlrausch and Van Meerendonk (*20*, 59)¶	478 ± 2.0	518 ± 3.7	574 ± 1.7
Dimmick and Hubbard (*21*, 252)**	475.1	515.5	582.5

* One observer. Partially dark-adapted neutral state.

† Averages for three observers (M, S, and B). These three observers alone observed at each of the three luminance levels used in the experiment. Bright-adapted state. Variability measure is the average M.V. for the three observers at all luminance levels.

‡ One observer. Bright-adapted state.

§ One observer (H). Partially dark-adapted neutral state. Variability measure is stated only as "variability."

‖ One observer. Values are averages for three luminance levels. State of adaptation not specified, probably partially dark-adapted. Variability measure is average deviation for all three luminances.

¶ Averages for three observers. Partially dark-adapted neutral state. Variability measure is specified only as "reproducibility."

** Averages for ten observers. Bright-adapted state. Values are means of regions delimiting pure hues. Mean variations available only for average limits of each region.

view quoted above. Unfortunately, however, even pure physical stimuli do not necessarily evoke pure hue sensations. The psychophysical relation between hue and wavelength is a complex one, and only a clear understanding of this relation can clarify the real meaning of the experimental results under discussion.

If we excite the retina by projecting upon it a physical spectrum that consists of a series of substantially homogeneous or pure wavelengths, under normal conditions the hues range from a slightly yellowish-red at one end of the spectrum, through reddish-yellow, yellow, yellow-green, green, blue-green, and blue, to reddish-blue at the other end. Such a division of the spectrum is not dictated by whimsical or semantic considerations. It is based on the precise experimental location of the psychologically unique or pure hues within the color spectrum. Pure red is absent from the spectrum, but the wavelengths that excite pure yellow, pure green, and pure blue are readily located. Locations of these pure or unique hues as determined experimentally by a number of investigators over a period of fifty years and for a variety of experimental conditions are shown in Table 1.

For any given observer the spectral extents corresponding to the pure blue, pure green, and pure yellow hues are extremely limited. For a neutral condition of adaptation[3] they are also independent of intensity. We have made determinations of these pure hues for two observers, at three luminance levels, 1.2, 12, and 120 mL, for a neutral condition of adaptation (10 minutes of preliminary dark-adaptation). The determinations were made with a Farrand monochromator for a narrow rectangular field, 1° 12′ in width and 32° in height, at the observer's eyes. A detailed description of this apparatus and of the experimental controls (i.e., viewing times, etc.) is contained in a report of related experiments (*22*). To determine the locus of a pure hue, the observer used a bracketing technique to adjust the wavelength to the pure hue transition point. For example, to locate a pure yellow, the wavelength is varied continuously between the limits where the hue becomes just noticeably reddish-yellow in one direction and just noticeably greenish-yellow in the other. A pure yellow point is selected between these two limits.

Table 2 shows the wavelengths in millimicrons of the three pure hues for the two observers at the three luminance levels. Five measurements of each locus were obtained in a single experimental session, and five such experiments constitute a complete series. Each individual entry therefore is an average of 25 measurements, and the average result for all luminances (grand average) is based on 75 measurements for each observer. The average root-mean-square deviations (*s*) are less than 3 mμ in all cases. For a given observer, the pure point loci are independent of luminance, but, as the magnitude of the variability measures indicates, the differences in the wavelengths corresponding to the pure hues for the two observers are very real. In an experimental test neither observer will accept the settings of the other. These results are in good agreement with those reported by earlier investigators, and they confirm the narrow extents of the pure hues in the spectrum.

The average wavelengths of the pure hues for the two observers are shown graphically in Fig. 1. The locations of these hues are represented by the three vertical bars along the wavelength scale. All other

TABLE 2

Spectral Loci of Pure Hues

Observer	Luminance (in mL)	Blue locus (in mμ)	*s* (in mμ)	Green locus (in mμ)	*s* (in mμ)	Yellow locus (in mμ)	*s* (in mμ)
DAJ	1.2	476.3	2.4	501.4	1.5	579.8	1.8
	12.0	476.1	1.6	495.3	1.9	578.7	1.3
	120.0	473.9	2.8	497.7	1.5	579.9	1.2
	Grand average	475.4		498.1		579.5	
LMH	1.2	469.5	2.0	489.4	1.7	589.3	2.9
	12.0	466.7	2.4	488.2	1.1	589.0	1.9
	120.0	467.9	2.6	491.7	2.1	588.3	2.1
	Grand average	468.0		489.4		588.9	

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[3] The loci of the pure hues are very sensitive to changes in chromatic adaptation of the visual system (*11*).

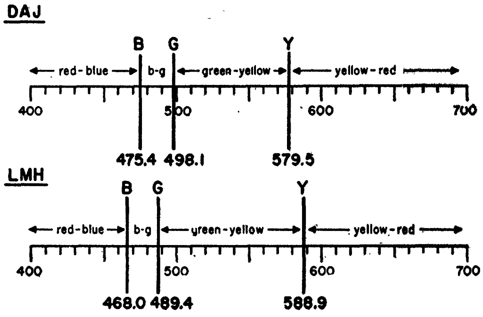

FIG. 1. Average locations of pure hues in the spectrum.

wavelengths in the spectrum elicit sensations that are mixed in hue. Starting from the short wavelength end, any homogeneous wavelength elicits a sensation that has both a red and blue hue component, with the blue becoming proportionately greater until the pure blue transition point is reached. Beyond the pure blue position any homogeneous wavelength elicits a sensation which has both a blue and green component, the green component becoming increasingly stronger until the pure green transition position is reached. Beyond the pure green any homogeneous wavelength elicits a sensation that has both a green and a yellow component, the yellow becoming increasingly more prominent until the pure yellow transition position is reached. Beyond this point all homogeneous wavelengths produce yellow-red sensations. In short, most physically pure spectral or so-called monochromatic stimuli evoke sensations that are mixed in hue.

It should be emphasized that this analysis is not contingent upon the specific hue names employed, nor is it conditioned by personal or cultural associations. The sensory discrimination of the unique or pure hues is made with relative ease and independently of any specific hue names used to characterize the perceptually discriminable differences in quality. The discrimination is ultimately dependent on the peculiar kind of discontinuity or change in *mode of variation* in hue which occurs at the transition points in question (*23*). These transition points might be referred to as points where a differential discontinuity occurs.

With this relation between homogeneous spectral stimuli and hue in mind, we may now return to the binocular mixture experiments which employ so-called red and green monocular stimuli. Fig. 2*a* shows the spectral transmission curves of Hecht's red and green Wratten filters, No. 29 on the right and No. 58 on the left. The vertical bars represent the locations of the pure hues for observer DAJ. It is clear from the positions of the maximal transmissions in relation to the pure point loci that the light transmitted by the "green" filter will evoke a predominantly yellow-green sensation in the one eye, and the light transmitted by the "red" filter a predominantly yellow-red sensation in the other eye. Quite apart from any fusion or cancellation of the monocular red and green hues, the hue component common to both monocular sensations is a yellow, and it would indeed be surprising if the binocular fusion product failed to exhibit a yellow hue.

The situation is not altered in any appreciable manner by using narrow band filters. Fig. 2*b* represents the spectral transmissions of the two Farrand interference filters used in the Prentice experiment. Considered in relation to the locations of the spectral stimuli which evoke pure hues, the light transmitted by these "red" and "green" filters similarly evokes predominantly yellow-red and yellow-green monocular sensations.

Furthermore, even with monochromatic homogeneous spectral stimuli selected from these same two spectral regions, the results are exactly the same. Trendelenburg (*24*) has reported binocular mixture results which include the wavelength pairs 671 mμ and 567 mμ, 617 mμ and 535 mμ, and 671 mμ and 535 mμ. In each instance the binocular mixture was equated to 589 mμ seen monocularly. The stimulus pair 671 mμ and 535 mμ (ordinarily used in the Rayleigh equation) is represented in Fig. 2*c*. Binocular yellow is reported in all instances. We have no difficulty in confirming these results in our laboratory.

The validity of the binocular fusion of yellow in

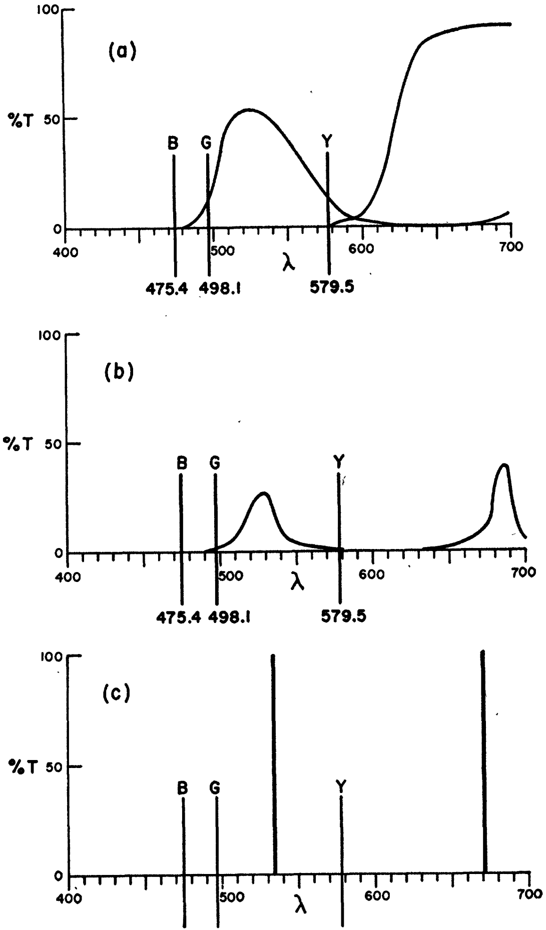

FIG. 2. Spectral characteristics of stimuli used for binocular yellow mixtures in relation to the loci of the pure hues in the spectrum.

experiments that employ stimuli each of which excites yellow monocularly, yellow-red in one eye and yellow-green in the other, is unquestioned. On the other hand, it is obvious that such experiments cannot be used to demonstrate that yellow arises in the brain as a fusion of two independent peripheral processes, a red process in one eye and a green process in the other These results can be accounted for either in terms of a three-component theory with no independent peripheral yellow process, or in terms of a four-component theory which postulates such an independent peripheral process.

The next experimental step is an obvious one. What happens when we fuse a psychologically pure green presented to one eye with a psychologically pure red presented to the other eye? Pure red is, of course, extraspectral, but it can be obtained by mixing homogeneous stimuli from the long and short wavelength regions of the spectrum (*11, 23, 25–27*). A zero dispersion double monochromator, with a double slit and two variable neutral gelatin wedges in the vertical plane of the primary spectrum, was used to provide a monocular pure red stimulus. With the two slits fixed at the wavelengths 671 mμ and 440 mμ, each observer determined the intensity ratio of the two spectral components necessary to evoke a unique red sensation in the left eye—i.e., a sensation that is neither bluish-red nor yellowish-red. The average ($N = 25$) amounts of each component (in millilamberts) for each of two observers for a neutral state of adaptation (10-minute preliminary dark-adaptation) are:

DAJ: 12.8 (671 mμ) + 2.5 (440 mμ)
LMH: 12.8 (671 mμ) + 3.0 (440 mμ)

This unique red for the given observer was then presented to the left eye, and the spectral stimulus for pure green (provided by the Farrand monochromator) was presented to the right eye. The stimuli were viewed through two matched short-focus monocular telescopes, one in front of each eye. In order to facilitate binocular fusion, a 4.7° circular field was used. The ratio of the two monocular stimuli intensities was adjusted by means of a continuously variable neutral gelatin wedge in the optical path of the homogeneous green stimulus. As this ratio was varied, the binocular fusion product was predominantly reddish, predominantly greenish, or, at a critical mixture ratio, a neutral, hueless sensation. The binocular fusion of pure red and pure green is definitely not a yellow sensation. The average ($N = 5$) amounts (in millilamberts) for the critical mixture ratio for each of the two observers for a neutral condition of adaptation (10-minute preliminary dark-adaptation) are:

DAJ: 15.3 (671 mμ + 440 mμ) + 0.55 (498.1 mμ)
LMH: 15.8 (671 mμ + 440 mμ) + 0.36 (489.4 mμ)

Although this result is in direct conflict with the ordinary assumptions of a three-component theory, it is quite possible that further modifications in such a theory will enable it to account for the emergence of a white sensation from a mixture of pure red and pure green. This result is, of course, predicted by traditional four-component theories, where red and green are assumed to be opponent or complementary colors (*11*). Since any adequate color theory must, in the last analysis, integrate and account for a prodigious amount of experimental data, we should like to emphasize that it is not our intention to make a decisive evaluation of three- vs. four-component color theories on the basis of any single experiment. The fact that does clearly emerge from these results is that, unless there is a yellow sensation and corresponding to it some form of yellow excitatory process (whether a single or dual event) in each monocular system (and by that phrase we understand the combined receptor-neural processes), there is no mysterious, synthetic central emergence of the quality yellow.[4]

Finally, one experimental fact common to all these results should claim our attention. When yellow-red and yellow-green stimuli are mixed, the resulting sensation is a yellow. Neither the green nor the red aspect of either monocular stimulus appears in the final product. When pure red and pure green stimuli are mixed, the resulting sensation is a neutral at an appropriate mixture ratio. Here, too, neither green nor red appears in the final product. The nature of the mechanism whereby this central "cancellation" occurs constitutes a real problem.

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[4] Murray's original critique of Hecht's demonstration included the point that yellow was present in both monocular sensations (*12*). Although she recognized that this was true even for homogeneous physical stimuli, this aspect of her criticism seems to have received little attention.