matter increases as particle size decreases, and the smaller particles presumably offer more sites for vapor condensation.

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7 October 1965

Spectral Sensitivity of Color Mechanisms: Derivation from Fluctuations of Color Appearance near Threshold

Abstract. *A method for determining the spectral sensitivity of the different color mechanisms of the human eye uses the pattern of color names applied to small, brief, dim, monochromatic flashes. Such responses are often due to the activation of single neural units. Preliminary spectral sensitivity curves for two color mechanisms have been obtained.*

Data from electrophysiologic and microspectrophotometric studies indicate that discrete units subserving color vision in primates can be isolated and their spectral sensitivities measured (*1, 2*). Under suitable experimental conditions single neural units can be activated in the intact living eye. Since the optics of the eye impose an uncertainty as to the exact retinal position of an incident photon, the same neural unit cannot be activated repeatedly; hence fluctuations in color perceptions at the threshold of vision appear (*3*). Preliminary measurements of the spectral sensitivities of two classes of neural units, based on analysis of these fluctuations, are presented in this report.

In a preliminary experiment an observer was asked to match the hues of small, brief, dim, flashes of monochromatic light at a wavelength of 580 mμ by adjusting the wavelength of a larger steady field of light generated by a monochromator. The results are shown in Fig. 1. The matches were clearly bimodal, with no overlap. The stimuli were verbally described as "orange-red" or "red" for the long wavelength and "blue-green" for the short wavelength. No "yellow" matches were made. Sometimes the flashes could not be matched because they were not seen or because they appeared "white." This experiment indicates that under suitable conditions members of only one class of neural unit may be activated.

To develop a quantitative account of these results, consider the visual system as composed of N independent neural units organized in such a way that activation of any unit is sufficient to generate a perception. By simple binomial theory the probability of activation of k neural units is

$$\frac{N!}{k!(N-k)!}\; P^k(1-P)^{N-k}$$

where P is the probability of activation of a single unit. The probability of nonactivation of neural units (that is, the probability of not seeing) is obtained by setting $k = 0$. The fraction of perceptions based on the activation of one, two, or either one or two neural units as a function of probability of seeing is plotted in Fig. 2. These are limiting values reached as N approaches infinity. The fraction of single neural unit activations is greater than that shown if the probability of activation of single neural units is not uniform, as would occur if two or more classes of neural units existed.

This analysis can be extended to the case where several classes of neural units (that is, red, green, blue) are to be considered. Denoting the classes by subscripts, the probability of activation of neural units of class x only is:

$$\sum_{k=1}^{\infty} \frac{N_x!}{k!(N-k)!}\, P_x^k\, (1-P_x)^{N_x-k}(1-P_y)^{N_y}(1-P_z)^{N_z} \ldots$$

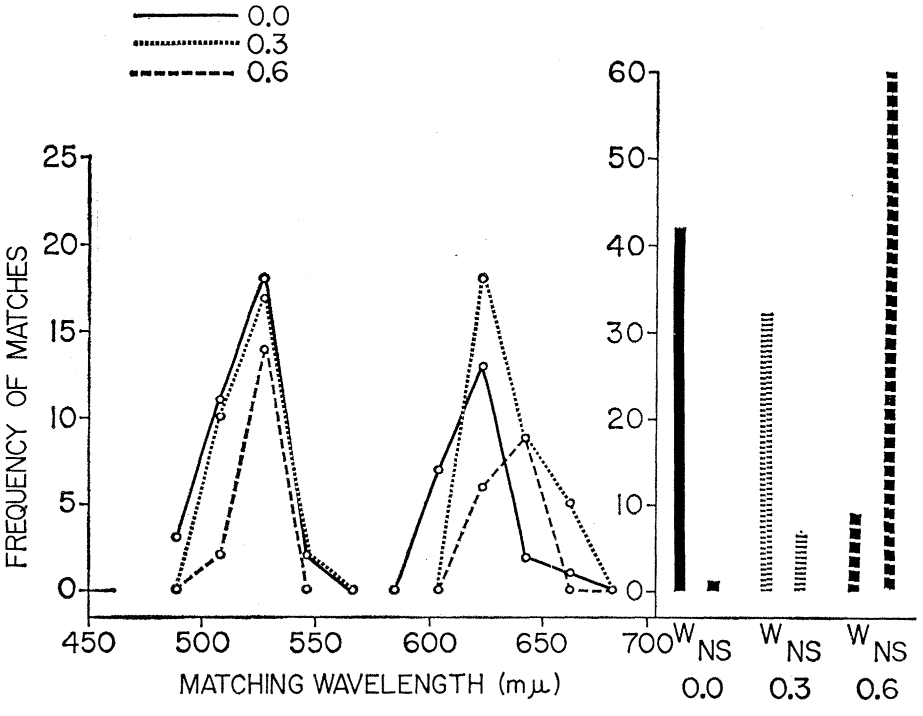

Fig. 1. Matches made to brief, small, low-energy stimuli; wavelength, 580 mμ. Ordinate, frequency of matches; abscissa, wavelength of matching light. Bar graph at right gives frequency of "white" (*W*) and "not seen" (*NS*) judgments. Data for the test stimulus at relative intensities of 0.0, 0.3, and 0.6 log units.

Spectral sensitivity is defined as the relation between wavelength and reciprocal energy (or number of quanta) required to produce a constant visual effect. To evaluate the spectral sensitivity of a particular system, the visual effect measured must depend on that system only. An index satisfying these conditions can be obtained by dividing the above expression by the probability of activating no neural units. Designating this index as F_x:

$$F_x = \sum_{k=1}^{\infty} \frac{N_x!}{k!(N-k)!} P_x^k (1-P_x)^{-k}$$

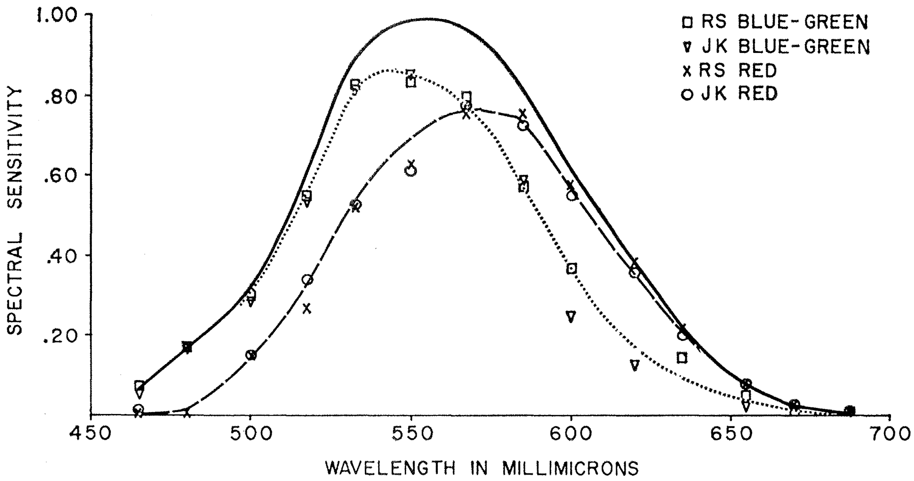

Fig. 4. Spectral sensitivities for two color mechanisms. Data for two observers. The solid curve is the C.I.E. photopic luminosity function.

It is possible to calculate the spectral sensitivity if the parameters of the ratio F_x can be measured. These are, first, the probability of activation of no neural units, which is the frequency of not seeing, and, second, the probability that only members of a single class of neural units are activated, which is the frequency of the unique report determined by this event (*4*).

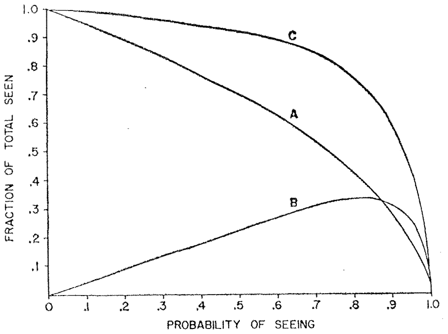

Fig. 2. Fraction of reports of seeing arising from activations of (*A*) a single neural unit, (*B*) two neural units, and (*C*) one or two neural units as a function of probability of seeing. Theoretical curves for large total number of neural units.

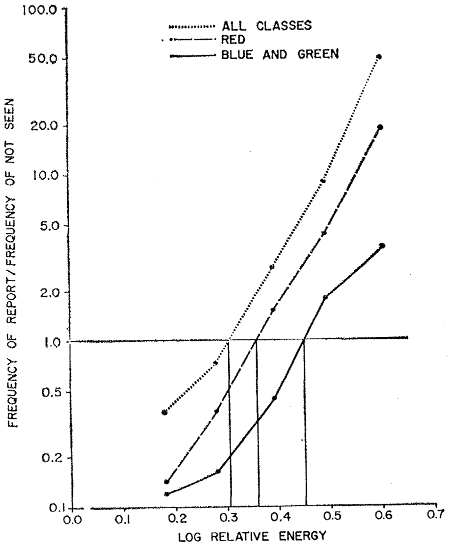

Fig. 3. Sample data curve for frequency of reports of "red" (green) (all classes of positive report) divided by frequency of reports of "not seen" as a function of stimulus energy. Stimulus wavelength, 550 mμ.

To measure the parameters of the ratio an apparatus was constructed which presented a circular target 1.3 minutes in diameter for a duration of 0.7 msec to a dark-adapted subject on his own command. The target was delineated by a precisely drilled hole located in the grating image plane of a Bausch and Lomb monochromator and was attached to the back of a photodetector. All of the light in the grating image fell on the photodetector except that which passed through a small hole in its center and then through the target hole. The signal from the photodetector was used in a feedback circuit to control the current supplied to the source lamp by a well-filtered d-c supply. Fine control of intensity was accomplished with a series of neutral density filters. Wavelength and intensity were controlled automatically by a tape programmer so as to produce a random order of stimuli for which these parameters varied independently. Fourteen different wavelengths were used, seven in each of two series. Series 1 consisted of wavelengths from 464 to 670 mμ in steps of approximately 35 mμ, and series 2 consisted of wavelengths from 483 to 688 mμ in steps of approximately 35 mμ. An experimental session contained 25 trials at each of five intensities for each wavelength in the series. In addition there were 125 trials on which no stimulus was presented; hence there were 1000 trials per session. A thin, dim annulus 20 minutes in diameter was used to control fixation. The stimuli appeared in the center of the annulus and thus fell on the central fovea. A session lasted 1 hour, and 20 sessions were run for each observer (250 trials for each wavelength and intensity condition).

Nine reporting categories were chosen: "not seen," "red," "green," "blue," "white," "desaturated red," "desaturated green," "desaturated blue," and "flash seen but color uncertain." While the number of color names used is admittedly arbitrary, it is clear from consideration of Fig. 2 that only those categories of judgments which resulted from activation of single neural units should decrease in relative frequency monotonically with increasing frequency of seeing. "Red," "green," and "blue" responses behaved this way, but "white" and "color desaturated" responses increased in frequency with increasing frequency of seeing and therefore can be eliminated as single neural unit responses. The numbers of "blue" and "green" judgments appeared to remain in fixed ratio as a function of wavelength, and hence were judgments applied to activation of neural units with identical spectral sensitivities.

The indices *F*(green-blue) and *F*(red) were calculated for each observer as a function of wavelength. A typical curve is shown in Fig. 3. A criterion value of log $F_x = 1$ was selected, and the energy required to produce this value was found by interpolation except for a few extreme wavelengths. The spectral sensitivities for the two color mechanisms determined for two observers are shown in Fig. 4. These curves were computed by assuming that each observer's overall spectral sensitivity was that of a standard observer as defined by the Commission International de l'Éclairage (C.I.E.). This procedure produces better agreement between the observers than computation based on energy calibration of the stimuli because it cancels out the effects of individual differences in absorption by the ocular media.

The curves are in reasonable agreement with the absorption difference spectra found for human parafoveal cones by Marks and MacNichol and Brown and Wald, and with the retinal densitometry measurements of Rushton (*2, 5*). However, it should be emphasized that this is a preliminary study on only two trained observers and that detailed comparisons are premature.

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31 August 1965

Differential Classical Conditioning: Verbalization of Stimulus Contingencies

Abstract. *The verbal activity of female subjects undergoing differential classical conditioning was investigated through their verbal reports between conditioning trials and interviews with them after conditioning. Conditional differentiation in galvanic skin responses occurred only in the group of subjects who accurately verbalized the stimulus contingencies.*

The cognitive activity of human subjects undergoing classical conditioning has been investigated in numerous experiments concerned with subjects' knowledge of stimulus contingencies and procedural shifts (*1*). Most frequently, the approach has been to instruct subjects about the stimulus contingencies prior to acquisition or extinction trials, with the result that acquisition or extinction is markedly facilitated (*2*). It is not clear, however, how applicable these results are to interpreting findings of more conventional classical conditioning experiments in which preparatory instructions are omitted.

Without preparatory instructions, subjects may develop recognition of stimulus contingencies during conditioning. This process has been studied by obtaining subjects' verbal reports either between conditioning trials or during an interview after conditioning. Results based upon interviews following conditioning have been inconsistent (*3*), perhaps because of some instances in which interviews were conducted and analyzed unsystematically. The three available studies (*4*) using intertrial verbal reports also used conditional responses potentially under voluntary control. The early, exploratory studies by Hamel and by Schilder were followed by a more systematic study by Hilgard, Campbell, and Sears, in which intertrial verbal reports were elicited during differential eyeblink conditioning. Hilgard *et al.* noted a slight indication that subjects showing the most marked eyeblink differentiation also were most accurate in describing the stimulus contingencies. Though Grant (*5*) suggested that "a systematic study of verbalization and resulting behavior during conditioning should do much to clear up the problem of controlling verbal processes with human subjects," no further studies using intertrial verbal reports in classical conditioning have been reported.

We probed cognitive activity during differential conditioning of the galvanic skin response (GSR) both by intertrial reports and by an interview after conditioning. Systematically analyzed verbal data were used to specify the subject's degree of accuracy in verbalizing the differential stimulus contingencies. We compared rates of differential conditioning of the GSR in subjects who differed in accuracy of verbalization. We assessed synchrony between conditional GSR differentiation and the first accurate report of the stimulus contingencies.

The subjects were 26 women of ages 20 to 55. The GSR was recorded monopolarly from the palmar surface of the second phalange of the right index finger. Basal resistance was measured in ohms, and GSR was measured in microohms.

The unconditional stimulus consisted of an electric shock (0.25 second long, 100 pulses per second) applied to the left forefinger and adjusted to the subject's tolerance. The two conditional stimuli were 8-second tones of 700 and 3500 cy/sec. The tone intensities were above threshold for all subjects; subjective intensities had been equated earlier in another group of subjects by psychophysical procedures.

The initial instructions were that, when the experimenter said "report," the subject was to state aloud what she had observed, thought, or felt about events occurring in the experiment since her last report. No references were made to the tones or to the stimulus contingencies. There were 36 trials in three phases: 8 for adaptation, 20 for acquisition, and 8 for extinction. In each phase an equal number of the two tones was presented in unsystematic order, with the same tone never presented more than twice successively. During acquisition, half the subjects had the 3500-cy/sec tone paired with shock, and half the 700-cy/sec tone. The tone duration was 8 seconds and shock presentation was coincident with tone offset. The signal to report followed the offset of each tone by 10 to 15 seconds. The mean interval between tone onset in one trial and tone onset in the next was 49.8 seconds (standard deviation = 16.5 sec).

After the 36 trials, an experimenter who had not been present during conditioning interviewed the subjects, using a standard series of increasingly informative questions. The first question was, "What did you think about it all?", and one of the last was, "Did you have the idea that one type of tone signaled that a shock was coming?"

Three raters, working individually, analyzed separately the content of intertrial verbal reports and of interviews. The content-analyses of both focused upon the subject's communication of information relevant to the experiment and placed it on a continuum ranging from "no reference to relevant stimuli" to "accurate conceptualization of stimulus relationships." On the basis of the content-analyses, each subject was placed in an "Accurate" or an "Inaccurate" group. The Accurate group consisted of subjects