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Spectral efficiency of blackness induction

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The spectral efficiency of blackness induction was measured in three normal trichromatic observers and in one deuteranomalous observer. The psychophysical task was to adjust the radiance of a monochromatic 60–120′ annulus until a 45′ central broadband field just turned black and its contour became indiscriminable from a dark surrounding gap that separated it from the annulus. The reciprocal of the radiance required to induce blackness with annulus wavelengths between 420 and 680 nm was used to define a spectral-efficiency function for the blackness component of the achromatic process. For each observer, the shape of this blackness-sensitivity function agreed with the spectral-efficiency function based on heterochromatic flicker photometry when measured with the same 60–120′ annulus. Both of these functions matched the Commission Internationale de l'Eclairage V_λ function except at short wavelengths. Ancillary measurements showed that the latter difference in sensitivity can be ascribed to nonuniformities of preretinal absorption, since the annular field excluded the central 60′ of the fovea. Thus our evidence indicates that, at least to a good first approximation, induced blackness is inversely related to the spectral-luminosity function. These findings are consistent with a model that separates the achromatic and the chromatic pathways.

Hering[1–5] and Mach[6] regarded blackness as an active sensory experience and not, as proposed by Helmholtz,[7] as merely the lack of stimulation by light. That blackness is not merely the absence of light stimulation can easily be appreciated, as the complete lack of visual stimulation produces the perceptual experience of an equilibrium gray rather than of black.

Hering's[8] proposal that blackness is neurally coded by a black–white opponent process has been incorporated into the quantitative formulations of the achromatic process of Jameson and Hurvich.[9,10] This achromatic process along with the two opponent-chromatic processes is assumed to account for all aspects of color experience. Spectral-response functions for the opponent-chromatic processes have been measured in several different investigations,[9,11,12] but the achromatic process has been less completely studied, at least in terms of Hering's original concepts. For instance, the spectral sensitivity of the blackness component of the achromatic process has not been measured. The white component of the achromatic process has also not been spectrally isolated using a perceptual criterion, although its isolation has been inferred indirectly through measurements of spectral sensitivity and saturation.[9,13]

Hering[8] pointed out that the black–white process differs from chromatic processes in fundamental ways. First, black arises only by virtue of spatial or temporal contrast induction. Second, the opponent nature of blackness and whiteness is different from that of the chromatic processes. That is, although one cannot simultaneously experience opponent hues at the same retinal locus, the sensations of blackness and whiteness can be experienced simultaneously; they mix to form a blackish-white, or gray, sensation.

As was pointed out by Heggelund,[14] Hering was not completely consistent in his theorizing about the black–white process. He sometimes assumed that this process mediated sensations that are independent of chromatic activity and at other times considered that the black, white, and brightness components of colors were intrinsically related to their chromatic components. The latter view was favored by Hillebrand,[15] Hering's student, but most modern formulations of Hering's theory, particularly those of Jameson and Hurvich,[9,10] are based on separation of the chromatic and the achromatic components of a color.

Although the spectral efficiency of blackness induction has not been measured, it is assumed in modern opponent-color theories that the spectral-response function for blackness is merely the inverse of the whiteness-sensitivity function.[10] Since a directly measured spectral-response function for whiteness is also not available, both functions have been represented by a photopic spectral-sensitivity function. The spectral-sensitivity function for various aspects of achromatic sensitivity (e.g., flicker, minimally distinct border, brightness) are not identical,[16] nor are the effects of chromatic annuli the

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same for brightness and flicker sensitivity.[17] Thus it is not clear which spectral-sensitivity function should be assumed to represent the black–white process. If chromatic and achromatic signals are processed in parallel,[18–21] a function based on flicker photometry might be reasonable to assume; however, if achromatic activity is not independent of chromatic activity, a function similar to that obtained for brightness might be more appropriate to describe the spectral efficiency of blackness.

In their original formulation, Jameson and Hurvich[9] represented the achromatic channel with the photopic spectral-luminosity function of the Commission Internationale de l'Eclairage (CIE) standard observer, V_λ. We are not aware of any experimental determinations of a spectral function for true blackness induction, although previous results do show that threshold darkening of a test stimulus can be predicted from inducing field luminance, independent of its wavelength.[22,23]

This study was designed to isolate psychophysically and to describe quantitatively the blackness component of the achromatic process. Our method is based on spatial induction and uses a perceptual criterion: the appearance of blackness. On the assumption that we have isolated the blackness-inducing mechanism, we conclude that blackness is inversely related to the spectral-luminosity function.

METHODS

Observers

Two female and two male observers, all of whom are between 20 and 40 years of age, served as subjects. Three of the observers were color-normal according to the Farnsworth–Munsell 100-hue test and several sets of pseudoisochromatic plates. The fourth observer (JW) was deuteranomalous by these criteria and by Rayleigh matches. These matches indicated a significant deviation in the direction of deuteranomaly but with a narrow range of match acceptance. Two of the observers had minimal experience as psychophysical observers, and two had previous experience. All observers knew the purpose of this research, but they were not aware of their results while they were being tested.

Stimulus and Apparatus

Figure 1 illustrates the stimulus that was used. The stimulus was presented in a Maxwellian-view optical system and consisted of a broadband (5500-K), central, 45′ spot that was surrounded by a monochromatic annulus having a 120′ outer diameter. The central spot and the annulus were separated by a 7.5′ dark gap. The entire stimulus was foveally presented as 0.5-sec flashes (3.0 sec between flashes).

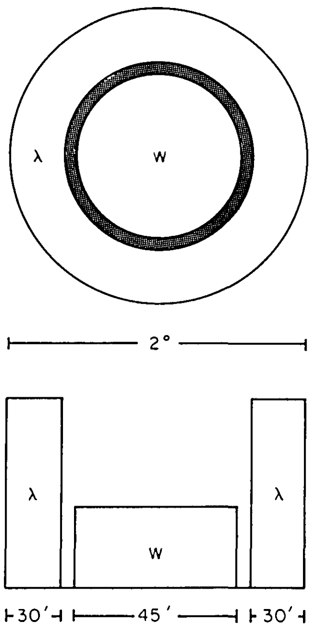

Fig. 1. Spatial configuration and luminance profile of the stimulus.

The stimulus shown in Fig. 1 was produced by two channels of an optical system having a common source, a 1000-W xenon arc lamp. This source was regulated at 980 W by a dc power supply. The light in each channel was collimated and passed through a water filter to reduce infrared energy. One channel was focused onto the entrance slit of a grating monochromator (Instruments S-A; 12-nm half-bandpass). This monochromatic beam was then collimated, passed through neutral-density filters, focused onto a neutral-density wedge, and recollimated. The position of the neutral-density wedge was monitored with a potentiometer and a digital voltmeter. The second channel was essentially identical with the first, except that the light was not passed through a monochromator, and hence it provided a broadband stimulus. The two beams were united by a beam splitter at a focal point. This beam splitter could also be removed and replaced by a rotating sectored mirror to produce counterphase flicker. The common beam was recollimated and focused to a 0.5- × 0.8-mm image in the plane of the observer's pupil. All lenses were achromatic, and all mirrors were front surfaced.

The observers were aligned by using a dental-impression bite bar that was mounted to a milling table. Movement of the table allowed for accurate positioning. The subject fixated straight ahead without a fixation point. In most sessions, however, observer CC used a bank of four barely visible (grain-of-wheat) lights, which were equally spaced from the central axis of the optical system, to assist in the control of fixation. The results were not affected by the presence of these fixation lights.

Calibration

Radiometric measurements and neutral-filter calibrations were made with a silicon photodiode (P-I-N-10) and a linear readout system, both of which were calibrated against a standard from the National Bureau of Standards. Calibrations with average wedge positions at each wavelength were made following each experimental session.

The dial of the monochromator was calibrated so that the maximal emission of a He–Ne laser (Spectra-Physics; 632.8 nm) occurred at 633 nm. Blocking filters were not used with the monochromator because sensitivity under these conditions was unaffected by placing narrow-band interference filters in a collimated portion of the beam.

Retinal illuminance was determined using an SEI photometer and the method outlined by Westheimer.[24]

Procedure

Each experimental session began with 15 min of dark adaptation. The observer's task was to adjust the radiance of the monochromatic annulus until the central broadband field just turned black, its contour disappeared, and the central field became indistinguishable from the dark surrounding gap that separated it from the annulus. In pilot experiments we found that the gap was not necessary, but it did make the task easier by providing a clearer criterion point.

Wavelengths between 420 and 680 nm (10-nm steps) were used for observers RK and DDR, whereas observers CC and JW were tested from 440 to 660 nm (20-nm steps).

The phenomenal experience during these adjustments was similar to that described by Hess and Pretori[25] and by others[26,27] for achromatic centers and achromatic surrounds. If the radiance of the surround is low, the central spot appears gray, and as the annulus radiance increases, the central spot turns darker gray and then black. Once this point is reached, further increases in the annulus radiance do not make the central spot blacker. Thus it is necessary to find the point of perceived blackness by approaching the criterion point from only one direction (increasing radiance of the annulus).

The assumption underlying this method is that the radiance of the monochromatic light required to induce blackness is inversely proportional to the sensitivity of the theoretical black lobe of the achromatic process.

A second task involved standard (15-Hz) heterochromatic flicker photometry (HFP) using the annular portion of the stimulus. In addition, for two observers, HFP was also measured with the central spot. The wavelengths used for HFP were identical with those used in the blackness-induction task.

RESULTS AND DISCUSSION

Blackness Induction

Figures 2–5 show log quantal sensitivity of blackness induction (filled circles) plotted separately for each observer. Each data point was based on six to eight observations. The standard errors of the mean ranged from 0.04 to 0.06 across observers. The specific illuminances of the central spot and the annuli that rendered them black are presented in Table 1. Note that, where two different curves were measured with the same observer, the ratio of the center-to-annulus illuminance required to induce blackness was approximately constant. In Figs. 2 and 3, the data for the higher illuminance level of the central test spot were arbitrarily displaced by 2.0 log units below the data for the lower illuminance level. The shape of the blackness-induction curves closely resembles Judd's modification of the CIE spectral-luminosity curve,[28,29] except at short wavelengths. To compare these two curves, each blackness-induction curve was fitted to the 2° CIE V_λ curve. The optimal fit was determined by using a least-squares cri-

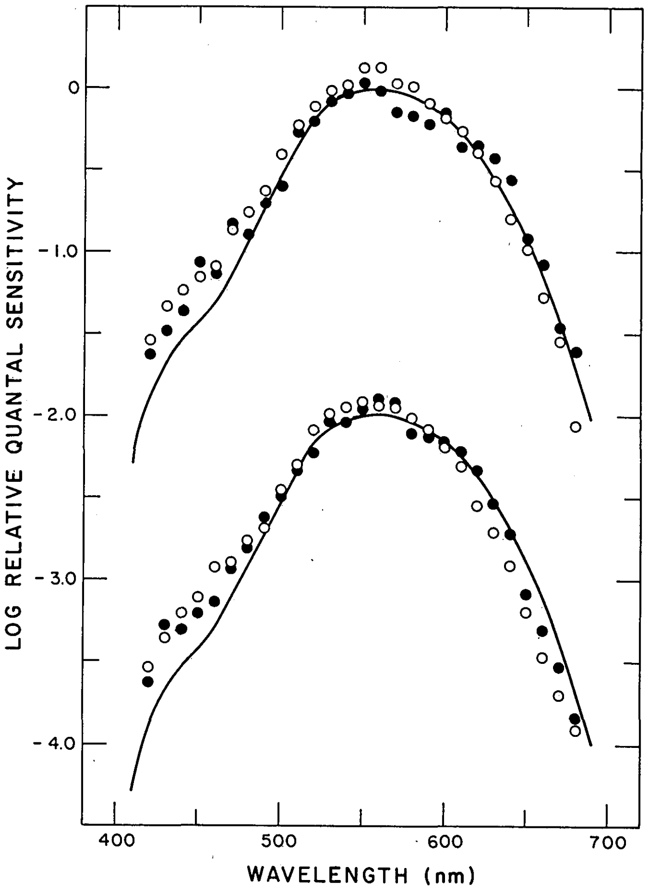

Fig. 2. Log quantal sensitivity plotted as a function of wavelength for observer RK. Filled circles denote quantal efficiency of blackness induction; open circles denote data obtained from heterochromatic flicker photometry using the annulus. The upper sets of data represent measurements made with the lower-illuminance central test; the lower sets of data, measured with the higher-illuminance central test, have been vertically shifted by 2.0 log units. The smooth function is Judd's modified CIE V_λ function.

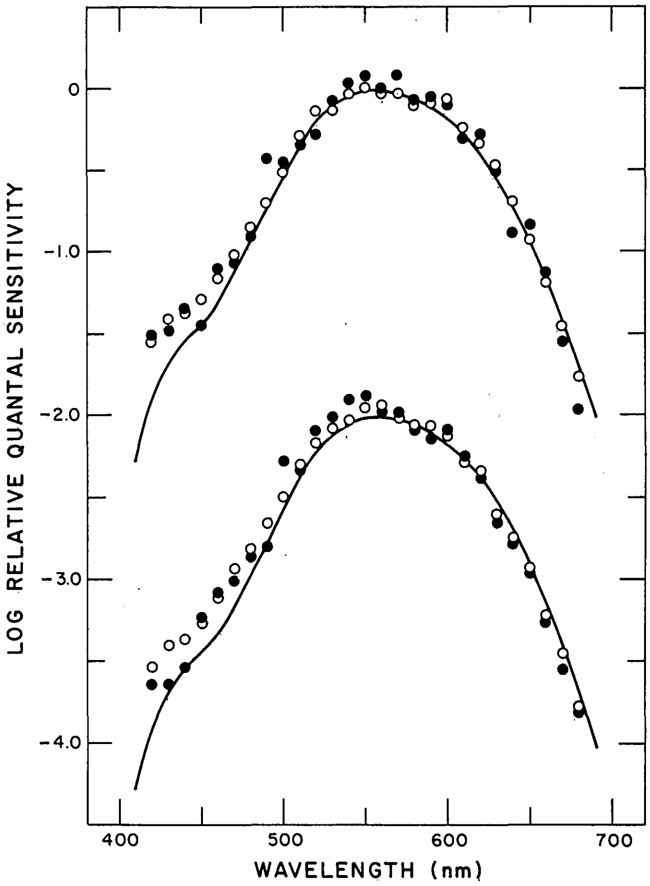

Fig. 3. Log quantal sensitivity plotted as a function of wavelength for observer DDR. Filled circles denote quantal efficiency of blackness induction; open circles denote data obtained from heterochromatic flicker photometry using the annulus. The upper sets of data represent measurements made with the lower-illuminance central test; the lower sets of data, measured with the higher-illuminance central test, have been vertically shifted by 2.0 log units. The smooth function is Judd's modified CIE V_λ function.

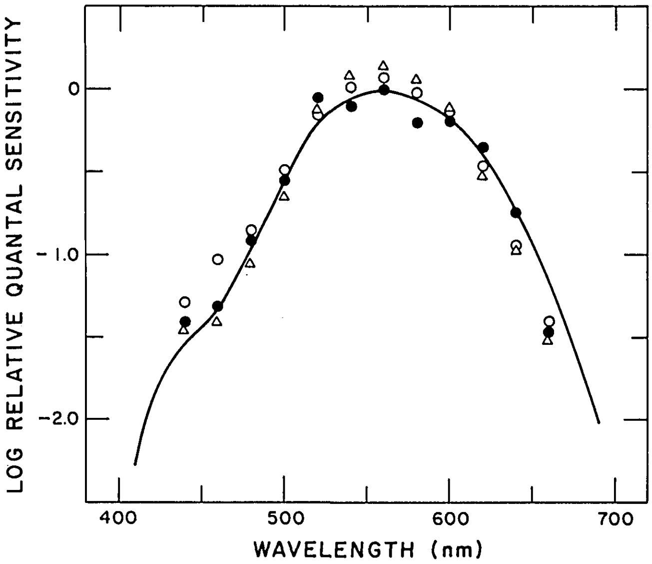

Fig. 4. Log quantal sensitivity plotted as a function of wavelength for observer CC. Filled circles denote quantal efficiency of blackness induction; open circles and triangles denote data obtained from heterochromatic flicker photometry using the annulus and the central 45′ spot, respectively. The smooth function is Judd's modified CIE V_λ function.

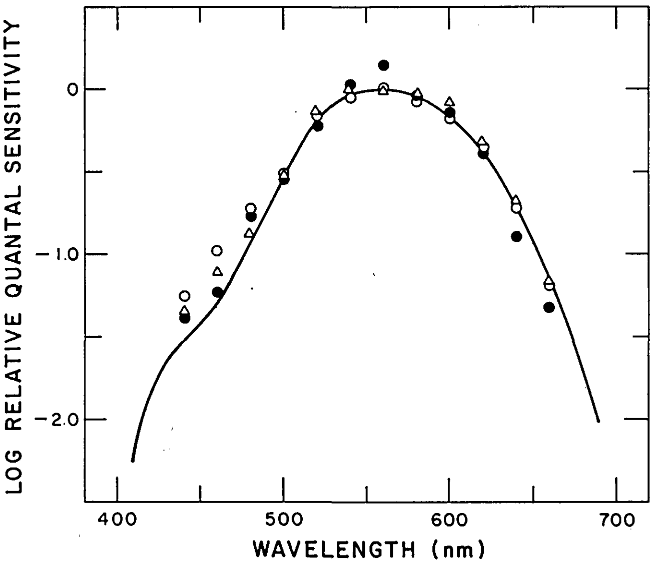

Fig. 5. Log quantal sensitivity plotted as a function of wavelength for observer JW. Filled circles denote quantal efficiency of blackness induction; open circles and triangles denote data obtained from heterochromatic flicker photometry using the annulus and the central 45′ spot, respectively. The smooth function is Judd's modified CIE V_λ function.

Table 1. Annular Illuminances as a Function of Central Spot Illuminances[a]

	Central Spot		
Observer	1	7	11
RK	135		1175
DDR	55		617
CC		407	
JW			759

[a] Illuminances are specified in trolands.

terion, with each point weighted inversely with its variance. Only wavelengths above 500 nm were used to determine these fits. As can be seen, the blackness-induction data are well fitted to the CIE curve, except at short wavelengths.

The elevation in shortwave sensitivity of blackness induction might be an artifact associated with greater light scatter at short wavelengths. Indeed, the shortwave scatter was noticeable and added to the difficulty of the task. However, several other possibilities for the difference between our blackness-induction data and the CIE curve seem equally likely even if they are both mediated by the same mechanism. For example, it seems possible that the differences could be due to our use of an annular field that excludes the central 60′ of the fovea.

To determine more directly whether blackness induction has the inverse spectral efficiency of the spectral-luminosity curve, we obtained HFP curves for each observer using only the annular portion of the stimulus configuration. Thus a broadband light (the same correlated color temperature as used for blackness induction) was presented with each monochromatic light in counterphase to obtain individual flicker curves. The illuminance of the broadband standard was adjusted for each observer so that the radiance (at 550 or 560 nm) required to eliminate flicker was identical with that required for blackness induction. The results of these determinations are presented as open circles in Figs. 2–5. Each data point was based on six observations. The standard errors of the mean ranged from 0.01 to 0.02 across observers. The data were normalized for comparison with the CIE curve by using the same procedures as those used for blackness induction. The average absolute difference between the normalized blackness-induction curves and the normalized flicker curves was 0.10 log unit (subject range, 0.07–0.12). Thus, when comparable regions of the retina are stimulated, the spectral-efficiency curves of blackness induction and of HFP have the same shape.

The elevation of shortwave sensitivity in the blackness-induction curves is probably not the result of a stray-light artifact, since this elevation was present when sensitivity was based on a criterion that only involved the annulus, i.e., the stray light was still present with HFP, but it was irrelevant to the criterion response.

It seems likely that the elevation of shortwave sensitivity compared with that of the CIE curve could simply be due to our use of an annular field that stimlulates different retinal regions and that is filtered differently from the foveal center by macular pigment. This idea is supported by additional HFP measurements for observers CC and JW using only the 45′ central spot. These data are presented in Figs. 4 and 5. The data are based on six observations per point with the same standard errors of the mean (0.01–0.02) as those obtained with HFP using the annulus. For observer CC, HFP data are now in better agreement with the CIE curve than when the annulus was used. A change in the same direction was obtained with observer JW.

Intrinsic Darkness of Colors

The above results suggest that the activity of the achromatic process is, at least with this paradigm, separate from chromatic activity, even though our stimuli were large and the flash duration was long—conditions that are generally thought to favor contributions from chromatic process.[19] This is consistent with some of Hering's[8] writings and with most modern formulations of the mechanisms of color appearance. This is not, however, consistent with all Hering's speculations or with the research of Hillebrand[15] and of Müller[30] on the intrinsic lightness and darkness of colors. According to the latter view, chromatic and achromatic processes are not separate. Thus Hering[8] wrote (p. 62) "I have for some time ascribed an *intrinsic brightness* [*Eigenhell*] to the yellow and red and an *intrinsic darkness* [*Eigendunkel*] to the blue and green. Brightness is thus a property that is intrinsic to the three primary visual qualities white, yellow, and red, and darkness a property that is intrinsic to the three primary qualities black, blue, and green." In contrast, our results suggest that the blackness (darkness) of a color is inversely related to its luminance. Thus bluish lights appear dark and yellowish lights appear light by virtue of their different contributions to a separate achromatic process. If this is correct, we should be able to predict the illuminance of the annulus that is required to induce blackness for any combination of colors simply from the HFP curve. This was, in fact, established with one observer (RK) by substituting the central broadband spot with his unique blue and inducing blackness with a unique blue (463-nm) or a unique yellow (573-nm) annulus. The illuminance required to induce blackness was predictable simply from the flicker curve for observer RK. It therefore seems that the darkness of blue and the lightness of yellow are not intrinsic to the hues but are related to the sensitivity of a separate achromatic process. We did not pursue this line of investigation exhaustively, and the strength of this conclusion must be qualified accordingly. However, more-extensive results from the two observers of Mount and Thomas[23] support our observations. Mount and Thomas determined the spectral efficiency for just-perceptible darkening of a test disk by an inducing annulus. Thirteen different wavelengths of the annulus were used with four different wavelengths of the central spot: 452, 518, 580, or 650 nm. All radiances required to induce darkening were predictable from luminance and did not depend on the wavelength combinations of the spot and annulus. Thus the induction of blackness in our results and the induction of just-perceived darkness in the results of Mount and Thomas do not appear to be affected by the hues of the stimuli.

CONCLUSIONS

The data indicate that induced blackness is, at least to a good first approximation, inversely related to the spectral-luminosity function. This relation holds for four observers over retinal illuminances from approximately 50 to 1200 Td. The only systematic deviations from the CIE V_λ curve were at short wavelengths, and this is probably due to our use of an inducing stimulus that excludes the center of the fovea.

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