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Perception of blackness

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We sought to measure the mechanisms underlying the perception of blackness in the following way. A central spot (45′) of fixed luminance was surrounded by a dark ring (7.5′), and surrounding all was an annular zone (30′) of light. This stimulus was presented in Maxwellian view for 0.5 sec every 3 sec. The radiance of the annulus required to make the central area (spot and ring) appear uniformly black was measured for different wavelengths (440–660 nm) of the annulus. These measurements were made for test spots that were either broadband or of wavelength 480, 500, 580, or 660 nm. In all conditions the measured spectral efficiency of induced blackness matched the inverse of the V_λ function. Using the same stimulus, we have also measured increment-threshold functions. For a fixed luminance of the spot, the radiance of the surrounding annulus required to bring the central spot to threshold was measured. These increment-threshold functions do not match the V_λ or blackness functions. Our results show that induced blackness is inversely related to the luminous efficiency function and that the spectral efficiency of induced blackness is distinct from the increment-threshold function measured under these conditions. Furthermore, blackness appears to be independent of the wavelengths of the inducing annulus as well as of the central spot. Thus these results link induced blackness to the luminance pathway and argue against the involvement of the chromatic pathways in the perception of blackness.

INTRODUCTION

Although blackness is acknowledged to be a bona fide perception, little attention has been given to its understanding. Hering[1] pointed out that the achromatic pathway mediating the perception of blackness differs from the chromatic pathways in fundamental ways. First, black arises only by virture of spatial or temporal induction of contrast. Second, the opponent nature of the achromatic pathway is different from that of the chromatic pathways. That is, whereas one cannot simultaneously experience both red and green or both yellow and blue at the same retinal locus, achromatic sensations differ only in degree and form a continuum of perceptions from white through grays to black.

In order to quantify perceived blackness we used a method based on spatial induction. In brief, the stimulus consisted of a central spot of fixed illuminance and an annular zone whose radiance could be varied so as to make the central spot appear black. We recently reported that when these measurements were made with a central spot that is a broadband stimulus (and appears nearly white), the spectral efficiency of induced blackness matched each subject's heterochromatic flicker photometric function.[2] These results supported the conclusion that induced blackness is inversely related to the spectral-luminosity function, that is, V_λ.

We now report results that further serve to link induced blackness to the luminance pathway and argue against the involvement of the chromatic pathways in the perception of blackness. Our new results show first that when the central spot is no longer a broadband stimulus but is instead monochromatic, the measured spectral efficiency of induced blackness still matches the flicker function. Second, using the same stimulus configuration, we have also measured increment-threshold functions. These increment-threshold functions match neither the flicker function nor the induced-blackness function. Thus we are assured that what we measure as induced blackness is distinct from increment thresholds. Preliminary results of this study were previously reported elsewhere.[3]

METHODS

Observers

Three female observers served as subjects. The observers were color normal according to the FM-100 hue test and several sets of pseudoisochromatic plates. Two of the observers had minimal experience as psychophysical observers and one had extensive 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

The stimulus was presented in a Maxwellian-view optical system and consisted of a 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). The central spot was of wavelength 480, 500, 580, or 660 nm or broadband with a correlated color temperature of 5550 K. The luminance of the central spot was fixed at 7 Td. Wavelengths of 440–660 nm (20-nm steps) were used in the annulus.

Details of the optical apparatus and calibrations can be found in a previous paper.[2]

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Procedures

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 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 research we found that the gap was not necessary, but it did make the task easier by providing a clearer criterion point. 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 was that the radiance of the monochromatic light required to induce blackness was inversely proportional to the sensitivity of the theoretical black lobe of the achromatic channel.

A second task involved standard (15-Hz) heterochromatic flicker photometry (HFP) using either the annular portion or the central portion of the stimulus. The wavelengths used for HFP were identical to those used in the blackness-induction task.

RESULTS AND DISCUSSION

Figure 1 shows results that are preliminary to our main experimental findings. Because our task is a novel one, we wanted to be sure that our results were not dependent on the particular psychophysical procedure used. Although we used the method of adjustment for two of our three subjects, we verified for one subject that a more stringent psychophysical procedure would produce the same results. Here

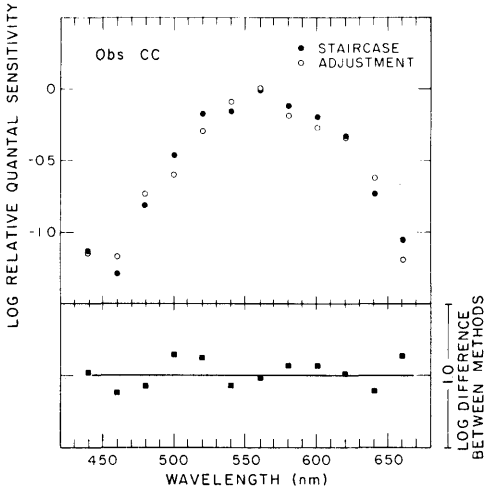

Fig. 1. Measurements of induced blackness made using the method of adjustment (open circles) or a modified staircase procedure (filled circles) are shown not to differ. The data points represent the inverse of the radiance of the annulus required to induce blackness in the central area. The results were normalized by vertical translation, and log relative quantal sensitivity (ordinate) is plotted as a function of wavelength of the annulus (abscissa). Plotted at the bottom of the figure are the differences (filled squares) between the measurements made using these two methods. The straight line marks zero difference.

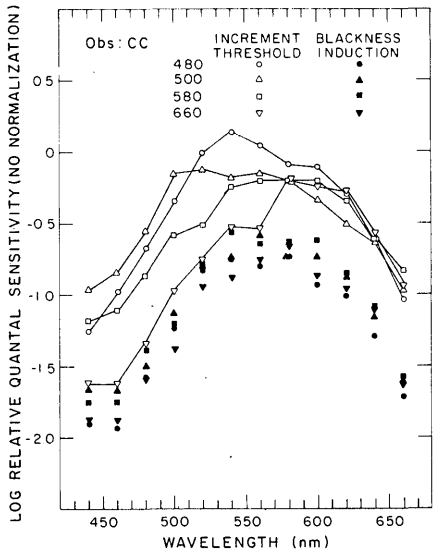

Fig. 2. Shown here are results of blackness induction (filled symbols) and increment threshold (open symbols) measured using identical stimulus configurations. In each condition the luminance of the central spot was fixed at 7 Td and the wavelength was set at 480 (circles), 500 (triangles), 580 (squares), or 660 nm (inverted triangles). The data have not been normalized. Our measurements of blackness induction are shown to be distinct from measurements of increment threshold in shape as well as absolute level.

we show, for one set of experimental conditions, that the blackness-induction function obtained using the method of adjustment (open symbols) does not differ significantly from that obtained with a staircase procedure (filled symbols). The filled squares at the bottom represent the log differences between the measurements made with the two methods at each wavelength. These differences are seen to hover about the straight line marking zero differences.

Is what we measure nothing more or less than an increment threshold with our annulus providing background stimulation? This is unlikely, for our blackness-induction functions match the CIE V_λ function, whereas one might expect that increment-threshold functions would be much broader, reflecting the activity of different cone types depending on the particular combination of the wavelength of the central spot and the wavelength of the annulus.[4] Furthermore, if induced blackness involves the luminance pathway exclusively, one should be able to predict the blackness function from the test *luminance*, regardless of wavelength. On the other hand, increment thresholds should depend on the particular combination of test wavelength and annulus wavelength. Shown in Fig. 2 are results of experiments designed to test these points. The results for two subjects were similar, so here we show only the results for subject CC. Blackness induction and increment threshold were measured using indentical stimulus configurations. For each condition shown here, the central test spot varied only in wavelength (which was set at 480, 500, 580, or 660 nm). Test luminance was held constant at 7 Td. For a fixed central spot, as annular wavelength was varied between 440 and 660 nm, the subject determined the illuminance of the annulus required to reduce the central spot to threshold for detection or, in the case of blackness, used the procedure just outlined. The open symbols are for increment threshold and the filled symbols for blackness induction. Note that the data points

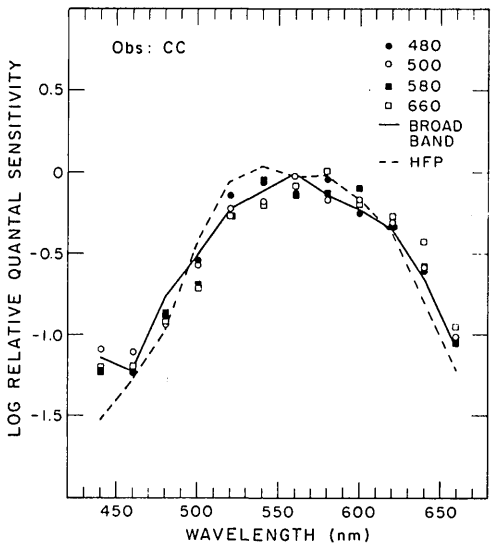

Fig. 3. Our four main experimental conditions involved using central spots of fixed luminance and wavelengths 480 (filled circles), 500 (open circles), 580 (filled squares), or 660 (open squares) nm. The results are plotted as described for Fig. 2. The solid lines connect the measurements of induced blackness made when the central spot was broadband. The dashed lines connect the measurements of HFP made with a central spot at a temporal alternation rate of 15 Hz. Both dashed and solid functions have been normalized to zero at 560 nm. A method of least squares was used to obtain a best fit of each data set measured with a monochromatic center to the broadband results. There is no systematic difference between the results when the central spot is broadband as compared with when it is monochromatic. The match to the flicker-photometric function is also shown to be close to the blackness-induction functions.

have not been normalized. As would be expected, increment thresholds are lower than the thresholds measured for induced blackness, but this is not the essential difference.

There are two points to be made here. First, since for each condition the central spot varied in wavelength but *not* in luminance, any measurements that were determined by the luminance pathway should not differ as a function of test-spot wavelength. The blackness-induction functions are tightly clustered, indicating that induced blackness is dependent on luminance, not wavelength, of the central spot. Increment-threshold functions, however, vary widely, dependent on central-spot wavelength. Second, in general, the increment-threshold functions are broader than the blackness-induction functions. Thus we can be fairly well assured that the blackness-induction functions are distinct from increment-threshold functions measured under identical conditions.

Figure 3 shows the normalized spectral efficiency of induced blackness when measured with various monochromatic test spots. Log quantal sensitivity for blackness induction is plotted as a function of the annular wavelength. The solid lines mark the blackness-induction function when measured with a broadband central test spot. There is no systematic difference between the results when the test spot to be rendered black by the surrounding annulus is broadband or monochromatic. The dashed line connects the data points obtained for HFP measured with the central spot at a temporal alternation rate of 15 Hz. Both dashed and solid functions have been normalized to zero at 560 nm. Then each data set measured with a monochromatic center was vertically shifted to obtain a best fit to the broadband function by a modified method of least squares, which applied a weighting to each data point that was inversely related to its variability.[5] Now, if blackness induction involves chromatic pathways, one would expect the blackness-induction functions (data points and solid line) to vary significantly from the flicker function (dashed line). Instead, as shown here, the fit is quite good, and blackness induction is shown to be inversely related to the flicker-photometric function. Thus these measurements indicate that perceived blackness is inversely related to luminosity.

Figure 4 shows a plot of the log differences between blackness induction measured with a broadband center as compared with measurements made with each monochromatic center. Each panel plots results for a different central-spot wavelength. The error bars mark the standard errors of the mean. In these results for subject CC there appear to be no systematic differences among the blackness functions. The results for the two other subjects were substantially similar. Table 1 presents, for each observer, the average absolute

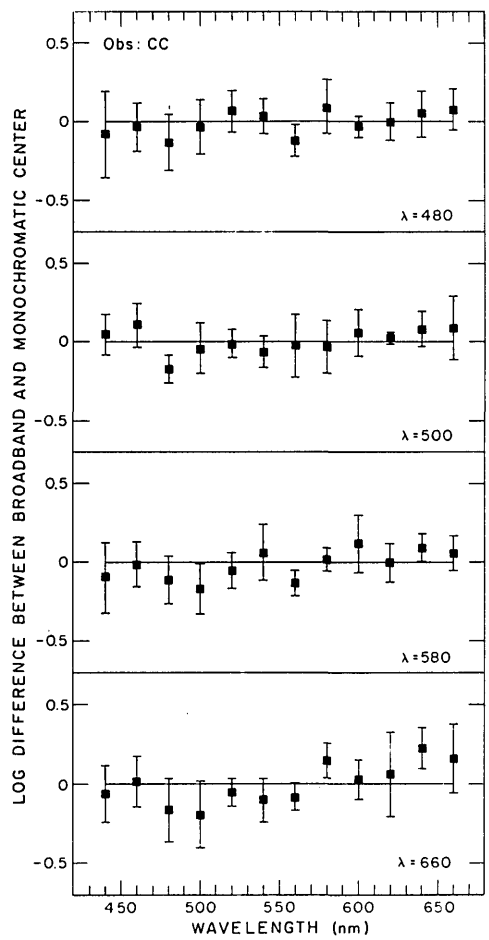

Fig. 4. Plots of the log differences between blackness induction measured with a broadband center are compared with measurements made with each monochromatic center. Separate panels show results for a different central-spot wavelength, as noted at the right. The error bars mark the standard errors of the mean for the monochromatic measurements. In these results for subject CC, there appear to be no systematic differences among the blackness functions.

Table 1. Blackness Induction: Comparison between Measurements Made with Each Monochromatic Center and the Broadband Center

Center Wavelength (nm)	Mean Absolute Deviation (log quanta)			Coefficient of Determination		
	CC	VV	SD	CC	VV	SD
480	0.06	0.13	0.11	0.97	0.92	0.93
500	0.06	0.12	0.05	0.98	0.96	0.98
580	0.08	0.07	0.06	0.96	0.98	0.98
660	0.11	0.15	0.09	0.91	0.88	0.94

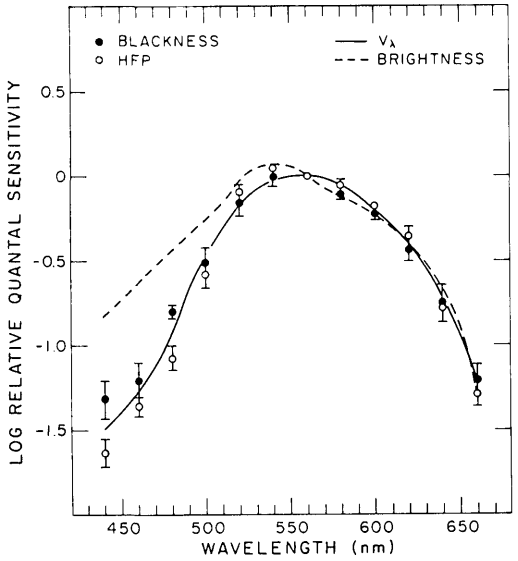

Fig. 5. The filled symbols plot the average blackness-induction function for three observers measured with a broadband center. The open symbols plot the average heterochromatic flicker function measured with 15-Hz flicker. The error bars mark the standard error of the mean. The smooth curve is Judd's modified V_λ function, and the dashed curve is Wagner's and Boynton's brightness function. All data sets have been normalized to zero at 560 nm.

deviations between the blackness-induction function measured with a broadband center and those measured with each monochromatic center. Also shown is the coefficient of determination (proportion of variance accounted for) in each case.

To emphasize that induced blackness is well described as being inversely related to the spectral luminosity function, we show in Fig. 5 the average (over our three subjects) blackness-induction function plotted against two standard functions from the literature, Judd's modified CIE V_λ function[6] and Wagner's and Boynton's brightness curve from their step-by-step brightness experiments.[7] Also shown is the average HFP function. All data sets and each function have been pinned to zero at 560 nm. No attempt has been made to shift the curves along the ordinate so as to obtain a best fit. The overall shape of the blackness-induction function, which follows closely the CIE V_λ function and the average HFP function, is clearly too narrow to be described adequately by the brightness function.

GENERAL DISCUSSION

Our results support the conclusion that induced blackness is inversely related to the spectral-luminosity function. This conclusion is based on three experimental results, as follows: (1) Induced blackness is distinct from the increment-threshold functions measured under our experimental conditions. (2) It is luminance, not wavelength, of the central spot that determines the luminance of the annulus required to render the central spot black. (3) It is luminance, not wavelength, of the annulus that determines its effectiveness in the induction of blackness. That is, the spectral efficiency of induced blackness matches the inverse of the spectral-luminosity function. Under the conditions of our experiment, induced blackness is dependent on luminance and not on wavelength; thus our results argue against the involvement of chromatic pathways in the perception of blackness.

There have been a number of studies investigating spatial induction of brightness changes using stimuli similar to ours. These studies assessed the effects of a colored surround on the perceived brightness of a central test of equal or near-equal luminance by measuring a just-perceptible dimming[8,9] or by measuring the effect of a colored surround on the flicker-photometric function.[10,11] According to the logic on which our own experiments are based, none of these studies is capable of directly measuring the sensitivity of the theoretical black lobe of the achromatic channel. This is because the changes induced in the test spot by the surrounding light were small, causing only just-detectable to moderate levels of dimming. To our knowledge, no study previous to ours used the method of requiring that the central test spot be brought to perceived blackness by the inducing surround.

Results from several laboratories have now provided evidence for the parallel processing of chromatic and luminance signals.[12-15] One simple model that is consistent with these results and also with our data would identify the opponent "achromatic channel" as signaling luminance changes and induced blackness, with a spectral efficiency that matches the luminosity function or its inverse, respectively. Indeed, Jameson's and Hurvich's[16] theoretical formulation used the CIE V_λ function to represent the positive lobe of the achromatic response function.

Perhaps it should be noted that we do not wish to imply that blackness does not play a role in hue perception. The fact that induced blackness plays a major role in our perception of different hues is clear.[17] More recently, there have been a number of striking demonstrations that showed that luminance and chromatic information can be photographically separated and then recombined to restore a complete picture of the original scene.[18,19] In these demonstrations, when one views the photograph of a scene with luminance information removed, colors appear remarkably different from those in the original scene. That this is not due simply to the removal of luminance in particular colored area can easily be appreciated by projecting the photograph upon a uniformly gray surface.[19] This serves only to dim the overall picture and does not restore the colors to their original appearance. What appears to be critical for the restoration of the scene is not only a reduction of luminance in the dark areas but also the induction of blackness into areas near those of high luminance. Demonstrations such as these serve to emphasize the importance of induced blackness in color perception. Our results show that the neural pathway that carries information about blackness must function in parallel to chromatic pathways. This separation earlier in

the visual pathway does not prevent hue perception from being ultimately influenced by the signals in this achromatic pathway.

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