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Reprinted from Journal of the Optical Society of America A

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Received March 16, 1994; accepted April 27, 1994

The influence of the illuminance and spectral composition of monochromatic surround fields on spatially induced blackness was investigated. The amount of induced blackness in a white 50′ central field was measured as a function of the illuminance of monochromatic 64′–120′ surround fields with a color-naming method. The function relating induced blackness to log surround illuminance was described by either the logistic function or the Weibull function. Action spectra for blackness were determined from those functions and were also measured directly with the method of adjustment. These action spectra indicated that blackness induction was determined only by the illuminance of the surround, regardless of the blackness level at the criteria and the wavelength of the surround. It was concluded that there is no chromatic contribution from the chromatic surround to blackness induction.

INTRODUCTION

Blackness is one of the elemental colors[1–3] and has an important role in the perception of objects.[4–6] Spatially induced blackness is observed experimentally when a central test spot is surrounded by an annulus of higher luminance. Hering[7] proposed a white–black opponent-achromatic channel as well as yellow–blue and red–green opponent-chromatic channels in his color vision model. In the opponent-achromatic process the perception of whiteness and blackness are not mutually exclusive as are the paired chromatic sensations. Many contemporary models of color vision adopt Hering's concept of opponent-color channels to account for the perception of hue.[8–10] In these modern models, however, the achromatic process, particularly blackness induction, was paid little attention. As described in previous studies,[11–13] it has been assumed that the spectral response function for blackness is merely the inverse of the whiteness-sensitivity function as represented by a spectral luminosity function,[8] although neither the function for blackness nor the function for whiteness had been directly measured. This assumption implicitly states that our perceptions of whiteness and blackness should be independent of stimulus wavelength because there is no chromatic contribution to the luminosity function.[10]

The first issue addressed by this investigation is whether there is a chromatic contribution to spatially induced blackness. In other words, is the luminance of chromatic lights in the annulus that is required for induction of a criterion amount of blackness influenced by the hue of the stimulus? Werner *et al.*[11] and Cicerone *et al.*[12] measured action spectra for spatially induced blackness with a completely black criterion, at which observers could not discriminate a center test light from a dark gap that separated the center from an annulus. They reported that induced blackness of a white center, induced by monochromatic annuli, depended only on the luminance ratio of the center and the surround and not on the wavelength of the annuli. Their reports were supported by tests of additivity in the luminance of the surround for this criterion.[14] Evans[15] and Mount and Thomas[16] also reported that the luminance of a series of monochromatic surrounds that was needed for induction of just-detectable blackness for a white center was constant.

On the other hand, with different criteria, some studies have shown that the hue of a stimulus can influence the spectral efficiency of spatially induced blackness. Action spectra measured by Fuld *et al.*[13] and by Evans and Swenholt[17,18] resembled brightness and purity discrimination functions, respectively. These results suggest that chromatic pathways might contribute to an achromatic process. The reason for the different results in the literature evaluating a possible chromatic contribution is not clear. Kulp and Fuld[19] had assumed that action spectra obtained with the completely black criterion[11,12,14] had to be similar to a luminosity function obtained with the minimally distinct border method, because contour disappearance was used as the criterion in both experiments. Their results, however, indicated that the criterion of contour disappearance was not significantly different from the criterion of blackness scaling.

Two hypotheses may explain the difference between these results. First, it could be that different criterion levels of the amount of blackness were used. The level of blackness was 100% at the completely black criterion,[11,12,14,19] but it was 50% or less at the other criteria.[13,15–18] Fuld *et al.*[13] and Volbrecht *et al.*[14] suggested the possibility that at the level of complete blackness, induced blackness was determined only by the output of a single achromatic system because only a blackness process can contribute to it at this level. At the level of equal whiteness and blackness, however, the interaction of parallel blackness and whiteness processes may have altered the action spectrum. It may be the case that measurements made with different blackness criteria may reflect differences in the contributions of chromatic and achromatic processes to our perception of blackness. Thus it is important to measure action

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spectra for blackness induction not only at the level of 100% blackness but also at the level of 50% blackness and 50% whiteness. Another possibility is that a difference in duration time produced different results.[11,13] All results obtained with experiments of 500-ms duration[11,12,14] showed that blackness induction depended strictly on the luminance of stimuli. However, results obtained in durations of 2 s or longer[13,17,18] showed that action spectra depended on the wavelength of stimuli, except for experiments by Evans[15] and by Mount and Thomas.[16] The response times of chromatic processes are longer than the response time of a luminance process, and chromatic contribution to brightness becomes maximal at 1-s duration[20]; however, 500 ms is adequate for the contribution of the chromatic processes to be manifest.

The second issue addressed by this study concerns the relation between induced blackness and the luminance of the surround. The perception of blackness increases with increasing luminance of the surround. If perception of blackness plotted as a function of surround luminance were affected by chromatic contributions from the annulus, the functions would be shifted horizontally on the luminance axis or would vary in shape because the luminance of the surround that induced the same amount of blackness would be different for different wavelengths. The influence of hue would not necessarily be the same for different wavelengths. Heggelund[21] measured achromatic quality and chromatic strength but only in a white center surrounded by a white annulus. Fuld and Otto[22] measured the appearance of spectral colors for a central spot with brighter surround fields, using a color-naming method. Their results showed that estimated points of blackness as a function of surround luminance were not the same for different wavelengths. However, the influences of the hue of the surround on spatial blackness-induction functions have not been measured yet.

In this study spatial blackness induction was measured as a function of surround illuminance by a color-naming method. The stimulus consisted of a white central test spot of fixed retinal illuminance surrounded by a series of monochromatic or achromatic annuli. Action spectra for blackness induction (at 50% criterion) were also measured by an adjustment method. A preliminary form of a part of these data has been presented elsewhere.[23]

METHODS

Stimulus

The stimulus consisted of a white ($x = 0.31$, $y = 0.35$), 50′ circular test light of fixed retinal illuminance [50 trolands (Td)] surrounded by white ($x = 0.30$, $y = 0.40$) or a series of monochromatic (449, 478, 510, 550, 579, 597, 635, and 665 nm), 64′–120′ annuli. The stimulus was presented to the fovea. The retinal illuminance of the annuli was increased in 0.25-log-unit steps, changing the level of perceived blackness from 0 to 100%. The maximum retinal illuminance was set at 4.45 log Td because the glare of higher levels was uncomfortable for the observers. The maximal illuminance for 480- and 665-nm lights was 3.45 and 4.20 log Td, respectively, because of limitations of the apparatus. A relatively high retinal illuminance (50 Td) was used at the white center to produce 100% whiteness of the center without the surround. Stimulus duration was 2 s. Four dim red light-emitting diodes were used to assist in the control of fixation of the eye. The fixation points were equally spaced at 2 deg from the central axis of the optical system.

Apparatus

We used a three-channel Maxwellian-view optical system with a 1-kW xenon arc lamp. A series of monochromatic lights in one channel was created by interference filters with half-bandwidths of 10 nm. Broadband lights in the other channels were corrected by color-compensating filters so that they appeared more whitish. Light intensity was controlled with neutral-density wedges and filters. Stimulus duration was controlled by electromagnetic shutters. The shapes of the center and surround fields were made by insertion of metal and glass apertures. The computer automatically controlled the choice of the interference filters, the opening and closing of the electromagnetic shutters, and the density of the wedges as well as recording the observers' responses.

The observer's head was held steady with a bite bar. To avoid excessive dark adaptation, a white plate illuminated by a white light at luminance of 0.07 cd/m^2 was presented during the latter half of dark adaptation and during the interval between stimuli.

Procedure

The observer's task was to describe the appearance of the center of the stimulus by assigning percentages to the terms blackness, whiteness, and hue. The sum of these percentages had to equal 100. Before sessions the observer dark adapted for 10 min. A series of stimuli was presented in random order when the observer pressed a button. To show the standard of 100% whiteness, the white center of 50 Td without the surround was presented 1 s before the presentation of the center–annulus configuration. With a 1-s interval after the preceding white center, the stimulus was then presented for 2-s duration. It was confirmed in a control experiment that no temporal blackness induction was caused by the preceding white standard. The observer could view the stimulus as many times as he wanted. After the observer's response, the white plate was presented while the wavelength and intensity of the annulus were changed.

The spectral luminosity function for each observer was measured by heterochromatic flicker photometry (HFP) with use of a 2-deg circular monochromatic field, flickering at 8.6 Hz with a 50-Td standard white. The equal-brightness function was measured by heterochromatic brightness matching with use of 2-deg bipartite fields, which had the same outer diameter as the chromatic surround, with a 50-Td reference white. Additionally, the retinal illuminance of the monochromatic surround was measured for each wavelength when the white center of 50 Td became equally white and black with the adjustment method. The observer changed retinal illuminance during the interval between presentations.

In all experiments, stimuli for each condition were presented either once or twice per session. At least four settings were done for each test condition. Observers (including the first author) were not informed about the results until all sessions were completed.

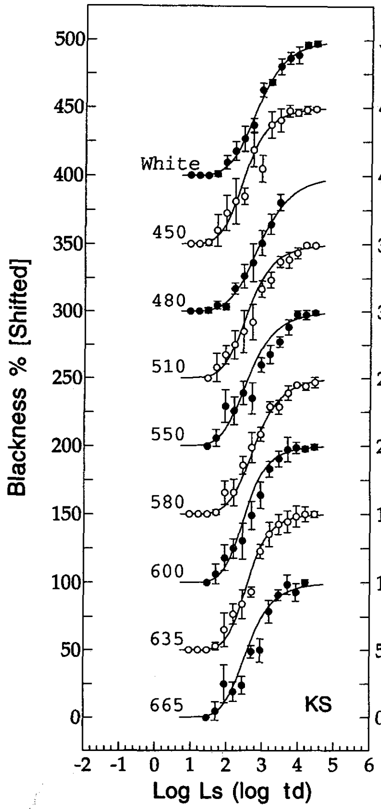

Fig. 1. Perceived blackness plotted as a function of log retinal illuminance of the monochromatic or achromatic surround (Ls) for observer KS. Blackness percentages were calculated by Eq. (1). The wavelengths of the surrounds are shown at the left of the data curves. The curves are the logistic functions fitted to each set of data (see text for details). The blackness percentages and the fitting functions were vertically displaced by the values in multiples of 50. Error bars denote ±SD.

Observers

Three observers ranging in age from 26 to 28 years were used in these experiments. All observers were color normal and had some experience as psychophysical observers. Except for the first author (KS), the remaining two observers were naïve as to the purpose of the experiments. All observers were optically corrected for the test distance.

RESULTS AND DISCUSSION

The observers often reported the appearance of hue even in the central test field. This effect might be caused by color induction or scattered light from the surround.[24] When retinal illuminance of the surround (Ls) was as low as that of the center, a complementary color of the surround was perceived in the center for some surround wavelengths. The amount of hue in this case was reported as several percent. As Ls increased toward maximum, the same color as the surround was perceived in the center, especially at short or long wavelengths. It can be assumed that the intensity of the scattering lights was ~1% of the surround intensity, regardless of the wavelength.[25–27] The means across observers in the maximum hue response for all Ls were 24.5% (at 450 nm), 17.5% (at 480 nm), 11.9% (at 510 nm), 11.7% (at 550 nm), 9.1% (at 580 nm), 14.7% (at 600 nm), 28.0% (at 630 nm), and 30.3% (at 660 nm). The reason that the hue responses were systematically higher at short and

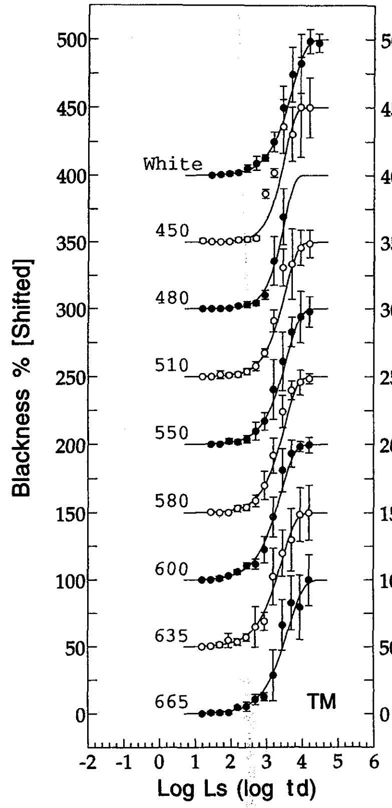

Fig. 2. Same as Fig. 1 except for observer TM and curves fitted with Weibull functions.

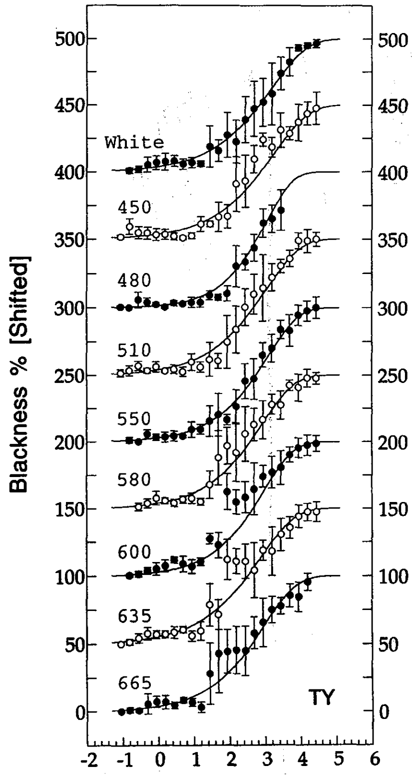

Fig. 3. Same as Fig. 1 except for observer TY and curves fitted with Weibull functions.

long wavelengths might be that the effect of the scattering light increased at these wavelengths, causing an increment in the responses of the chromatic processes, as was the case for the brightness function. The results of a control experiment with use of monochromatic annuli without the white center indicated that this increment in hue responses was caused by the scattered light from the surround. The data also showed that the scattered light increased only the hue, not the whiteness. Thus, to eliminate the influence of these effects from the observer's response, we calculated the amount of blackness from original percentages with the following equation:

$$\text{blackness } \% = (\text{blackness } \%)/(\text{blackness } \% + \text{whiteness } \%) \times 100(\%)\,. \quad (1)$$

In this experiment red fixation points were used. Under some conditions they alter the appearance of the test center by chromatic induction,[28] but the illuminance of the surround field was usually so high that the effect could be ignored.

Figures 1–3 show the amount of blackness calculated by Eq. (1) for each observer, plotted as a function of log retinal illuminance of the monochromatic surround (Ls). These results for all observers showed that the relationship between the intensity of the stimulus (log Ls in this case) and the psychophysical response (blackness %) could be described by an s-shaped psychometric function. The logistic function, the Weibull function, and the Gaussian integral function are commonly fitted to s-shaped psychometric functions.[29] It was found that the logistic function provided the best fits for observer KS's data and that the Weibull function was the best for the data of observers TM and TY. These functions are shown below[29]:

$$\text{Logistic function:}\quad \text{blackness } \%(\log \text{Ls}) = 1/\{1 + [(\log \text{Ls})/\alpha]^{-\beta}\}\,, \quad (2)$$

$$\text{Weibull function:}\quad \text{blackness } \%(\log \text{Ls}) = 1 - \exp\{-[(\log \text{Ls})/\alpha]^{\beta}\}\,. \quad (3)$$

α is the stimulus intensity (log Ls) at which the slope of the function is maximum. β is the steepness of the function. The solid curves in Figs. 1–3 show these functions with the coefficients that fit the data best according to the method of least squares. Means and standard deviations (SD's) of parameters α and β are shown in Table 1.

For observer KS (Fig. 1), blackness was ~0% at Ls of less than 1.5–1.75 log Td and increased rapidly at higher Ls. For observer TM (Fig. 2), blackness increased gradually when Ls was lower than 2.5 log Td and increased rapidly for higher Ls. For observer TY, however, blackness was perceived even at low Ls, and the points of blackness percentages were almost the same up to ~1 log Td. This tendency corresponded to the shape of the Weibull function. The range of Ls over which blackness increased from 0 to ~100% was approximately 3.5 log units for observer KS, 3.0 log units for TM, and 6.0 log units for TY. Further, the fit of the Weibull function to TY's data was not so good at long wavelengths; the discrepancy between these functions and the data became maximum in the middle range of Ls.

If it is correct that the differences among action spectra for blackness induction in previous studies were caused by the differences in the blackness criterion, Ls at ~100% blackness would have to be equal for different wavelengths, but Ls at 50% blackness would have to vary across the spectrum. In luminance terms, spectral efficiency should be constant at the completely black level[11,12,14] and not constant at the equal white–black level.[13] Thus blackness-induction functions would have various slopes for different wavelengths. On the other hand, if that difference were caused by other factors, the shapes and slopes of blackness-induction functions would be the same for different wavelengths. Despite variations in the results between observers, the expected changes of the slope of the blackness-induction functions did not exist, as shown in Figs. 1–3 and Table 1. These results indicate that induced blackness as a function of Ls was little influenced by the wavelength of the surround. Thus the action spectrum for blackness induction was independent of the wavelength of the surround in luminance terms. For confirmation, Ls's were calculated from the fitted functions at 50% blackness for each wavelength of the surround and are plotted in Fig. 4. Because the retinal illuminance on the ordinates was corrected individually by the results of HFP measurement, the equal-luminance functions for each observer are horizontal lines. In these coordinates, lower values of Ls mean higher efficiency for blackness induction, because a lower luminance was needed for induction of the same amount of blackness in the center. There was a dispersion of Ls's of ~0.4 log unit for observers KS and TY, although Ls's for observer TM were approximately equal. Perhaps this dispersion is due to the relatively large luminance steps (0.25 log unit) used.

Table 1. Numerical Values of Parameters α and β in Fitting Functions

Observer	Function	α (±SD)[a]	β (±SD)[b]
KS	Logistic	2.64 ± 0.15	7.48 ± 0.67
TM	Weibull	3.50 ± 0.12	7.8 ± 1.4
TY	Weibull	3.040 ± 0.041	3.84 ± 0.11

[a] α corresponds to Ls when the blackness percentages in the functions become 50% in the logistic function and 63% in the Weibull function.

[b] β is the steepness of the functions when Ls equals α.

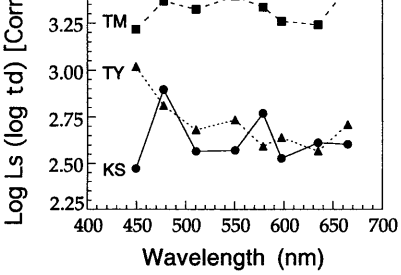

Fig. 4. Log retinal illuminance of the monochromatic surround (Ls) at 50% blackness produced by fitting functions in Figs. 1–3 as a function of the wavelength of the surround. The retinal illuminance on the ordinate axis was corrected individually by the results of HFP.

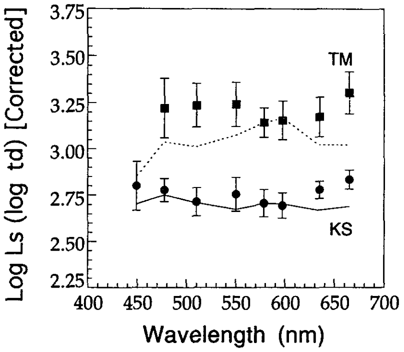

Fig. 5. Log retinal illuminance of the monochromatic surround (Ls) measured by the method of adjustment as a function of the wavelength of the surround when the center was perceived as having equal whiteness and blackness. The retinal illuminance on the ordinate axis was corrected individually by the results of HFP. Error bars denote ±2 SE. The solid and the dotted curves show equal-brightness functions measured by heterochromatic brightness matching for two observers. These equal-brightness functions were normalized to match Ls of the blackness data at 580 nm.

To measure spectral efficiency with higher accuracy, we performed an additional experiment on observers KS and TM with the method of the adjustment.[11,12,19] Ls was measured for a criterion in which the center was perceived as having equal amounts of white and black. Figure 5 shows the results of this experiment with the same coordinates as in Fig. 4. Error bars denote ±2 SD. For observer TM the measurement at 450 nm was not performed because of the influence of the highly scattered light on the appearance. Equal-brightness functions obtained by the heterochromatic brightness matching measurement were also plotted. In Fig. 5 spectral efficiency for blackness induction was almost constant, and the dispersion of the data was reduced as expected. It was not clear whether induced blackness was determined only by luminance, because the equal-brightness function for observer KS had little dependence on wavelength. For observer TM, whose equal-brightness function was strongly dependent on wavelength, the action spectrum for blackness and the equal-brightness function were clearly separated. This separation, which was larger than the error bar, showed a meaningful difference between them at the 5% significant level (4.6%, precisely).

GENERAL DISCUSSION

Three results were obtained in these experiments: first, the amount of induced blackness as a function of Ls was described by either the logistic function or the Weibull function. This result shows that the amount of blackness changes gradually with increasing surround illuminance and that there is no critical point at which the perception of blackness will be changed suddenly. Second, the blackness-induction functions for each wavelength were almost identical. Thus the action spectra must be the same even at different blackness levels. Because these action spectra must be little affected by the criterion amount of blackness, the hypothesis that the level of blackness influences whether the chromatic contribution appears was rejected in the experimental version of this paper. Third, in terms of luminance, induced blackness had no dependence on the wavelength or hue of the surround even at the level of 50% blackness. Thus it was concluded that the amount of induced blackness is determined not by brightness but only by the luminance (measured individually by HFP) of the surround. In other words, the hue of the surround does not contribute to blackness in this stimulus configuration.

The hypotheses in this paper could not explain the results from previous studies. Differences of stimulus duration do not account for the different results, because the results of these experiments obtained with 2-s duration corresponded to results in previous studies[11,12,14] with a 500-ms duration. A possible alternative hypothesis to explain the discrepancies in the literature might concern the stimulus configuration, whether the center is achromatic or chromatic. In previous studies the amount of blackness was determined by luminance when blackness was induced for a white center by a chromatic surround.[11,12,14–16] By contrast, the hue of a chromatic center affected the amount of blackness induced in the center by a white surround.[13,17,18] It is possible that if the central field is chromatic the amount of blackness perceived in the center might be influenced by hue (or wavelength), even if the luminance contrast from the center to the surround is the same. This hypothesis should be investigated by future experiments.

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