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Journal
Journal of the Optical Society of America A, 7(1)

ISSN
1084-7529

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Publication Date
1990

DOI
10.1364/josaa.7.000106

Additivity of spatially induced blackness

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Received March 13, 1989; accepted August 21, 1989

Tests of additivity of the postreceptoral pathways that mediate the perception of blackness were conducted under conditions of spatial contrast. Observers increased the radiance of a surrounding annulus until a broadband (white) test center appeared completely black. Additivity tests with heterochromatic flicker photometry (HFP) and direct brightness matching were also conducted for each observer. The results indicated that the luminance level of the annulus required to induce blackness did not change with variations in spectral composition. Results consistent with additivity were also obtained for HFP, but the results from brightness matching were not consistent with additivity. The data support the view that the perception of blackness is mediated by neural mechanisms that additively combine the input of middle- and long-wave photoreceptors.

The spectral efficiency of induced blackness has been investigated under conditions of spatial contrast to enable us to gain a better understanding of the processes mediating our perception of achromatic colors.[1–4] In one set of studies,[2,3] using a response criterion of complete blackness, the spectral efficiency was found to resemble the overall shape of the photopic luminosity function of the standard observer and individual observers' heterochromatic flicker photometry (HFP) functions. This relation was maintained whether blackness was induced in a broadband field[2] or in a range of monochromatic fields.[3] These findings were, however, challenged by the work of Fuld and colleagues,[4] who, using a response criterion of equal blackness and whiteness, reported a spectral efficiency function similar to that obtained by brightness matching. Of course, since the response criteria were not the same in the above studies, it is quite possible that the discrepancies in the results reflect mediation by different neural processes.[4,5]

In the studies on spatially induced blackness,[2,3] comparisons were made between each observer's blackness-induction function and his or her own HFP function and the average brightness-matching function of Wagner and Boynton.[6] In contrast, Fuld *et al.*[4] compared their observers' equal black–white functions with their respective brightness-matching functions but did not measure their observers' HFP functions. Thus it is difficult to conclude strongly from these studies whether the perception of blackness is mediated by neural processes more similar to those underlying HFP or to those underlying brightness.

Recently Kulp and Fuld[7] repeated the spatial induction studies with a criterion of pure blackness and measured all three response functions—blackness induction, HFP, and brightness matching—for each observer. They found that for some observers the blackness-induction functions more closely resembled their HFP functions and for others the blackness-induction functions more closely resembled their brightness-matching functions. Volbrecht and Werner[8] have also taken this approach in their study of temporally induced blackness. They reported that the blackness-induction functions were more similar to the observers' HFP functions than to their brightness-matching functions but conceded that the differences among the three functions were small.

Although the differences among the measurements of blackness induction, HFP, and brightness matching appear to be quantitatively small, they are theoretically significant. The HFP function is thought to represent the additive input of middle- and long-wavelength cones,[9–12] whereas the brightness-matching function reveals input from opponent-chromatic processes as indicated by an inflection (Sloan's notch[13]) at approximately 580 nm.[14–16] Thus it is expected that additivity of blackness induction should occur if blackness induction is mediated by the same neural processes as HFP but that additivity should fail if blackness induction is mediated by processes similar to those underlying brightness. Additivity has also been investigated with temporally induced blackness,[8] and the results indicate that blackness induction, like HFP, shows no failures of additivity. Since the spectral efficiency functions of spatially and temporally induced blackness are similar in shape,[8] it is anticipated that spatially induced blackness will also show mediation by a mechanism with additive cone input.

METHODS

Observers

Two females (25 and 30 years of age) participated in this experiment. Both observers had normal color vision as assessed by the F-2 tritan plate, Dvorine, and American Optical pseudoisochromatic plates and the Farnsworth-Munsell 100-hue test; neither observer reported a family of color vision deficiencies. Observer VV was aware of the purpose of the experiments but did not receive feedback on her data during the test sessions. Observer LA was not aware of the purpose of the experiments and did not receive feedback until all experimental sessions were completed.

Stimuli

All stimuli were generated by a conventional Maxwellian-view optical system and foveally presented to the observer's

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right eye. The stimulus configuration used for the spatial induction of blackness consisted of a 0.75-deg broadband test center surrounded by a 0.94–2.44-deg annulus. A 0.19-deg dark gap separated the center from the surround. The annular inducing field was composed of one of seven variable wavelengths (430 to 670 nm, in 40-nm steps), one of two addends (510 and 630 nm), or a combination of a variable and an addend wavelength. The test center was a metameric match to a 2-Td, broadband (5500-K) standard, except for the intensity series (see the Procedure subsection) of observer LA, for whom the test center was a 4-Td, broadband (5500-K) stimulus. The metameric match to the standard was achieved by a 580- and 487.5-nm mixture. Both the center and the annulus were presented for 500 msec, with a 3-sec interstimulus interval.

HFP was measured by presenting a 2.44-deg circular field composed of a variable wavelength (430 to 670 nm, in 40-nm steps), an addend wavelength (510 or 630 nm), or a mixture of a variable and an addend wavelength in square-wave counterphase (14 Hz) with a 2.44-deg, broadband (5500-K) circular field. A 2.44 deg, vertically divided bipartite field was used for brightness matching. The two half-fields were separated by a dark hairline gap to prevent melting of the borders.[17] One of the half-fields consisted of a variable wavelength (430 to 670 nm, in 40-nm steps), an addend wavelength (510 or 630 nm), or a mixture of a variable and an addend wavelength. The other half-field was composed of a broadband (5500-K) standard. The flickering field for HFP and the bipartite field for brightness matching were presented for 500 msec, followed by a 3-sec interstimulus interval, the same temporal parameters used to measure induced blackness.

For all experimental conditions, except the 4-Td intensity series of LA, the illuminances of the broadband standards in HFP and brightness matching were equated to the mean illuminance required to induce blackness at 550 nm with a 2-Td test center. Since the standards in HFP and brightness matching were equated at 550 nm, near the peak sensitivities of all three psychophysical functions, any differences among the three functions could not be ascribed to differences in adaptation level for the three tasks. The illuminance values were 37 Td for LA and 102 Td for VV. Since only one pair of wavelengths (510 and 630 nm) was examined in the intensity series (see the Procedure subsection), the illuminance value for the 4-Td test center of LA was equated to the mean illuminance required to induce blackness at 510 nm. This value was 123 Td.

Apparatus
Different subsets of a five-channel, Maxwellian-view optical system were utilized in each of the three psychophysical tasks. The essential features of the apparatus have been described elsewhere.[5,8]

Calibrations
Radiometric measurements were made after each session for each individual wedge setting of each monochromatic light. All measurements were made with a silicon photodiode (PIN-10) and a linear readout system (United Detector Technology), both calibrated relative to standards traceable to the National Institute of Standards and Technology.

Photometric calibration and calibration of monochromators, shutters, and timing devices were specified in a previous paper.[5]

Procedure
All sessions commenced after 10 min of dark adaptation and after a series of practice trials on the task of interest.

The procedures for testing additivity were conceptually identical for all three psychophysical tasks. The only fundamental difference among the tasks was the response criterion. For blackness induction the observer increased the radiance of an annular surround until the test center appeared completely black. With HFP the observer adjusted the radiance of the field flickered in counterphase with the broadband standard until a bracketed range of minimal flicker or no flicker was found. The direct-comparison method was used in brightness matching. In this task the observer adjusted the radiance of one half-field until it matched the brightness of the reference field.

At the beginning of each test session the optical channel of the variable stimulus was blocked so that blackness induction, HFP, or brightness measures could be made with the addend alone. Two response settings were obtained at this wavelength to determine the mean radiance required for the criterion response. This mean radiance level was reduced by 70%, and the channel that generated the variable stimulus was opened. For one setting the variable stimulus was presented by itself and the addend channel was blocked. For the other setting at this wavelength the variable field was superposed on the addend. With both settings the observer only manipulated the radiance of the variable wavelength to set the response criterion.

Response settings were always obtained in pairs at a particular variable wavelength, one with the addend and one without the addend. The presentation order of the seven variable wavelengths was pseudorandom, as was the order of the addend and no-addend settings at each wavelength. Four settings were obtained for each variable wavelength, two with the addend and two without the addend. A pair of response settings was obtained for all seven variable wavelengths before the wavelengths were presented again. At the end of the session the channel with the variable stimulus was again blocked, and two response settings were acquired with the addend alone. These settings provided a check to see whether the observer's response criterion had shifted from the beginning to the end of the experimental session. [Across addends, tasks, and observers, the mean change from the beginning to the end of session was 0.04 log quantum (range, 0.01 to 0.11 log quantum).] Only one addend, either 510 or 630 nm, was used during a test session. Both observers were tested in three sessions with each addend, yielding a total of six responses per datum.

Intensity series. A second series of additivity tests was conducted for blackness induction, HFP, and brightness matching, but instead of one radiance ratio with several wavelength pairs, a single pair of wavelengths (510 and 630 nm) was examined for five different radiance ratios. After 10 min of dark adaptation and a series of practice trials, observers adjusted the radiance of the 510-nm field to induce blackness, minimize flicker, or match brightness, de-

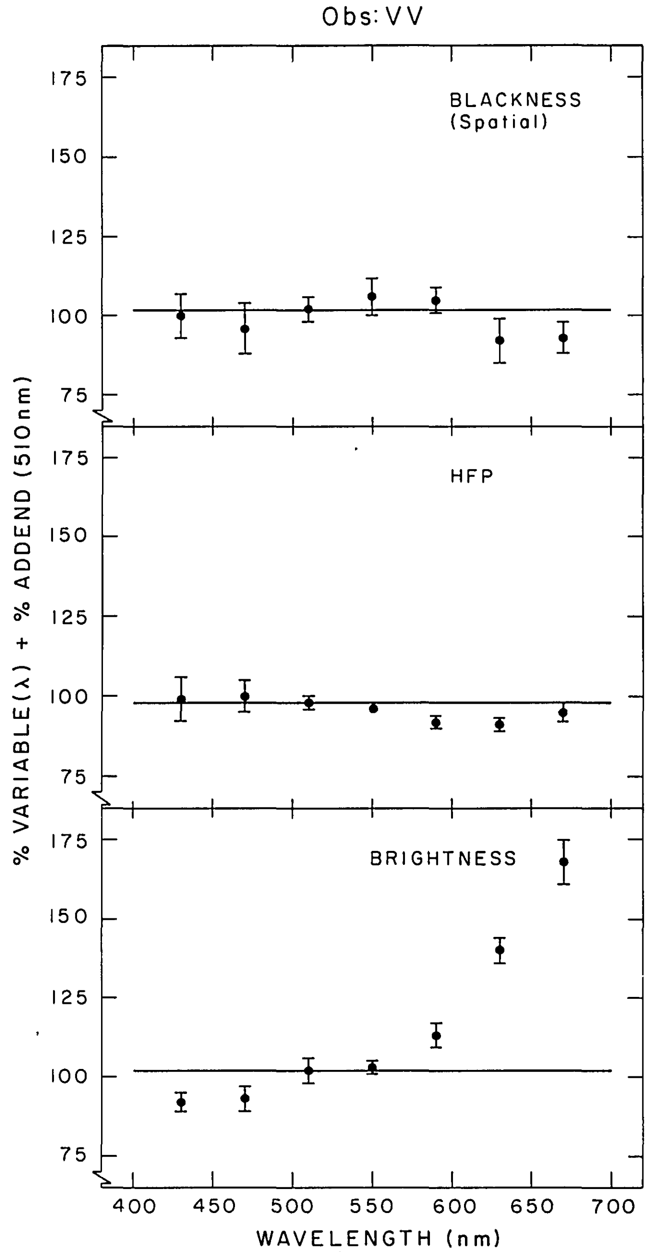

Fig. 1. Mean percentage of light in a mixed field with a 510-nm addend plotted as a function of variable wavelength for observer VV. Separate panels show additivity results for blackness induction (top panel), HFP (middle panel), and brightness matching (bottom panel). Error bars denote ±1 SEM. The horizontal line is drawn through the percentage value where the variable wavelength and the addend wavelength are both 510 nm.

pending on the psychophysical task. The mean of two settings at this wavelength was used to define the unit amount required for a particular response criterion. The 630-nm field was then presented either alone or in combination with various proportions of the 510-nm field, which were set to 25%, 50%, or 75% of the unit amount required when the 510-nm field was presented alone. The response criterion was obtained by adjusting only the radiance of the 630-nm field when presented alone or in combination with the 510-nm field. After one response setting was made with 630 nm alone, and with each 510-nm combination, two response settings were again made to redetermine the unit amount required for the criterion response with the 510-nm field. This process continued until a total of four response settings was obtained for each 510–630-nm combination and the 630-nm field alone. There were 3 test sessions for each task, generating 12 responses per data point for the 630-nm field alone and when combined with the 510-nm field and 24 responses per data point for the 510-nm field alone.

RESULTS AND DISCUSSION

If blackness induction is mediated by a process that additively combines cone signals,[18,19] then the radiance required of each member in a mixture of two wavelengths should be predictable from the amount of light needed when each wavelength is presented alone in the stimulus field. Accord-

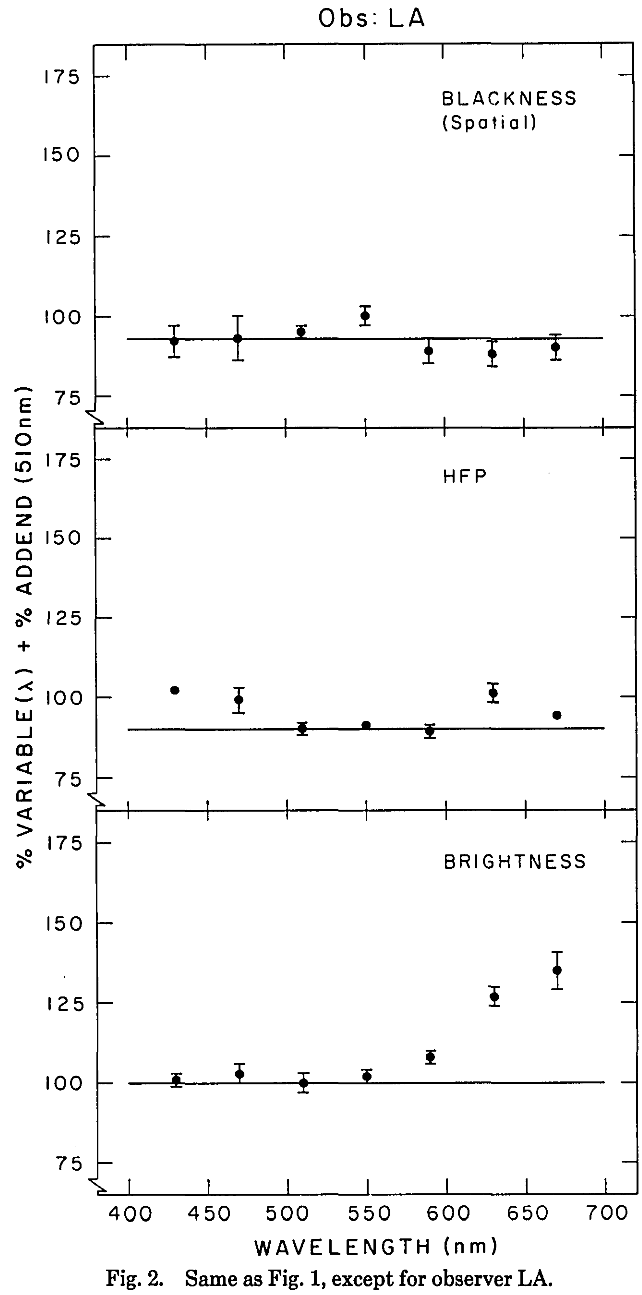

Fig. 2. Same as Fig. 1, except for observer LA.

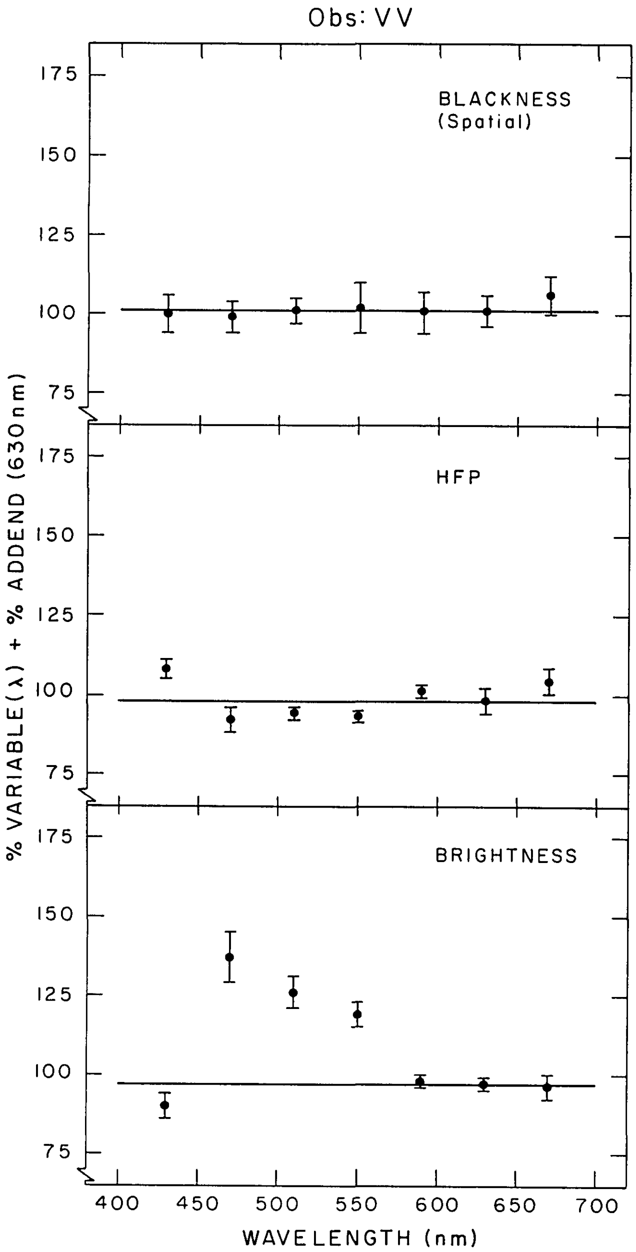

Fig. 3. Mean percentage of light in a mixed field with a 630-nm addend plotted as a function of variable wavelength for observer VV. Separate panels show additivity results for blackness induction (top panel), HFP (middle panel), and brightness matching (bottom panel). Error bars denote ±1 SEM. The horizontal line is drawn through the percentage value where the variable wavelength and the addend wavelength are both 630 nm.

ingly, if the addend is set at 30% of the radiance level required when it is presented alone, and the radiance level of the variable wavelength in the mixed field is measured to be 70% of that required when it is presented by itself, then the unit amount of light needed for a particular response criterion has been restored and additivity is upheld. If the amount of light for a particular response criterion yields a percentage value more or less than 100, then the hypothesis that the cone signals are additively combined can be rejected.

The total percentage of light in the mixed field with respect to each field alone is plotted as a function of variable wavelength in Figs. 1–4. Figures 1 and 2 show results from the two observers with the 510-nm addend, and Figs. 3 and 4 show results for the same two observers with the 630-nm addend. The error bars represent ±1 standard error of the mean (SEM) and have been specified when larger than the data point. The horizontal line in each panel is drawn through the percentage value where the variable wavelength is the same as the addend. This should, of course, yield a percentage value of 100; deviations from 100% indicate measurement and/or observer variability. The percentages, when the addend and variable wavelengths were the same, varied from 90% to 102% across observers and tasks.

The results from spatially induced blackness (top panels in Figs. 1–4) show few, if any, deviations from additivity, and in most instances the error bars overlap each other and the

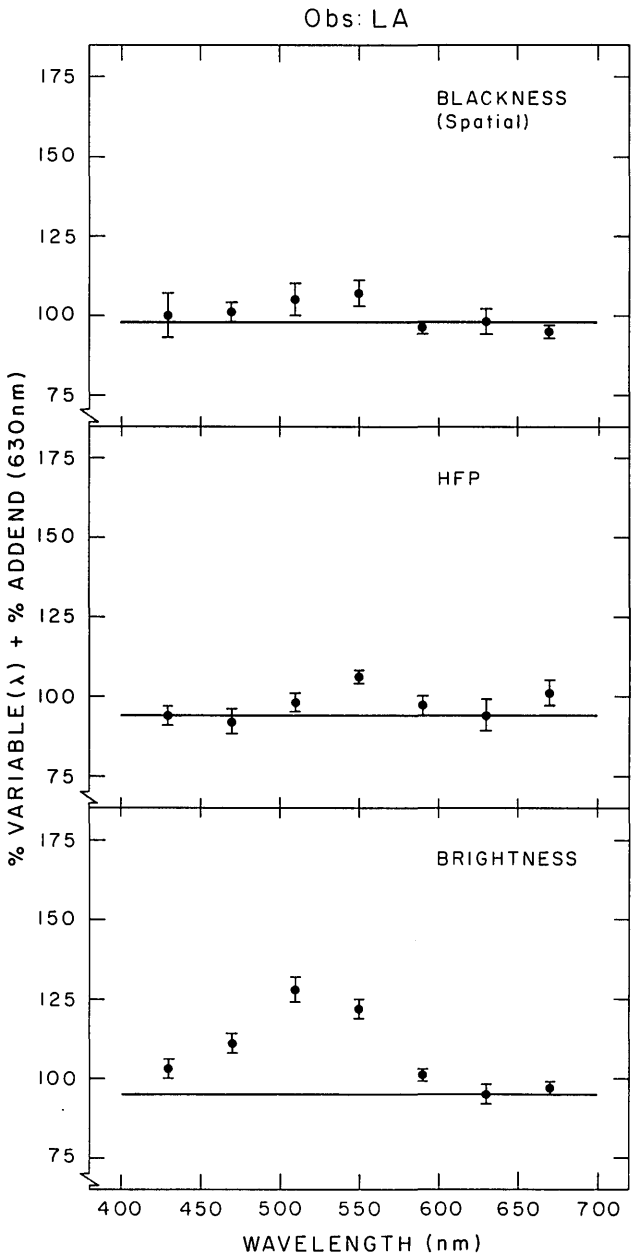

Fig. 4. Same as Fig. 3, except for observer LA.

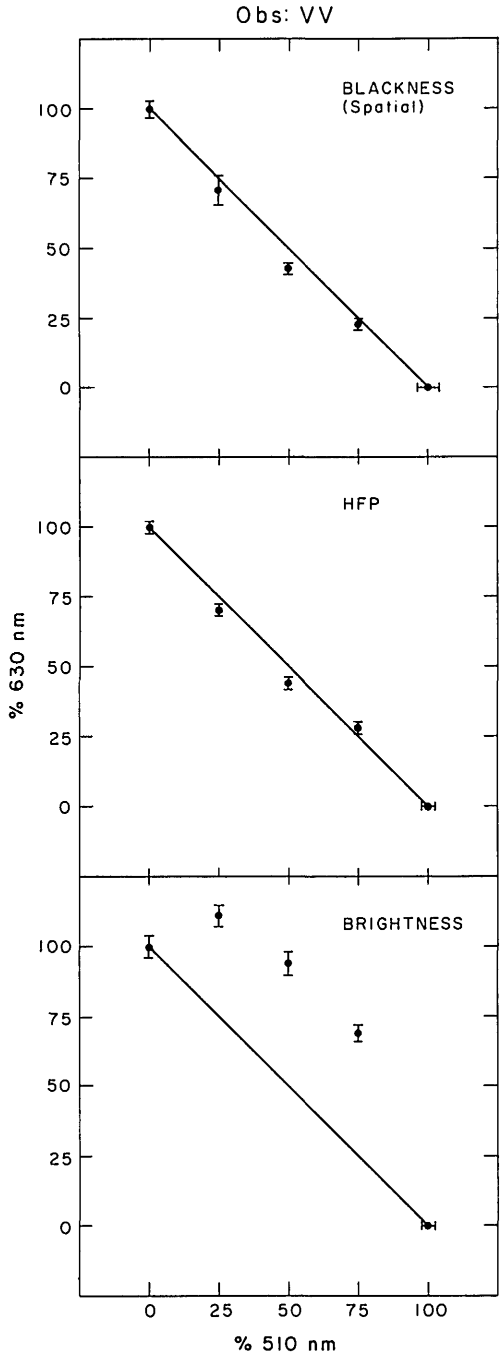

Fig. 5. Mean percentage of 630 nm in the wavelength mixture plotted as a function of the mean percentage of 510 nm (25%, 50%, or 75%) in the mixture; blackness induction (top panel), HFP (middle panel), and brightness matching (bottom panel) for observer VV. Error bars denote ±1 SEM. The diagonal lines represent complete additivity.

reference line. These results are similar to those shown for HFP (middle panels). Although the data points from blackness induction and HFP do not fall perfectly on the reference line, the deviations appear to be unaffected when the addend is changed from 510 to 630 nm. With a change in the addend, a change in the pattern of the deviations between the data points and reference line would be expected if there were violations in additivity, either of the cancellation type or of the enhancement type.

As others have demonstrated,[15,16] the mean percentage values from brightness matching (bottom panels) show strong departures from additivity. The nature of the deviations from additivity is wavelength dependent and similar for the two observers. For both observers, the 630- and 670-nm variable wavelengths are subadditive with the 510-nm addend, and the 460-, 510-, and 550-nm variable wavelengths are subadditive with the 630-nm addend; that is, both observers require more light for mixtures of these wavelength combinations than predicted from the amount required when each wavelength is presented alone (cancellation). Also, for VV there is a suggestion of superadditivity at shorter wavelengths with the 510-nm addend; that is, less

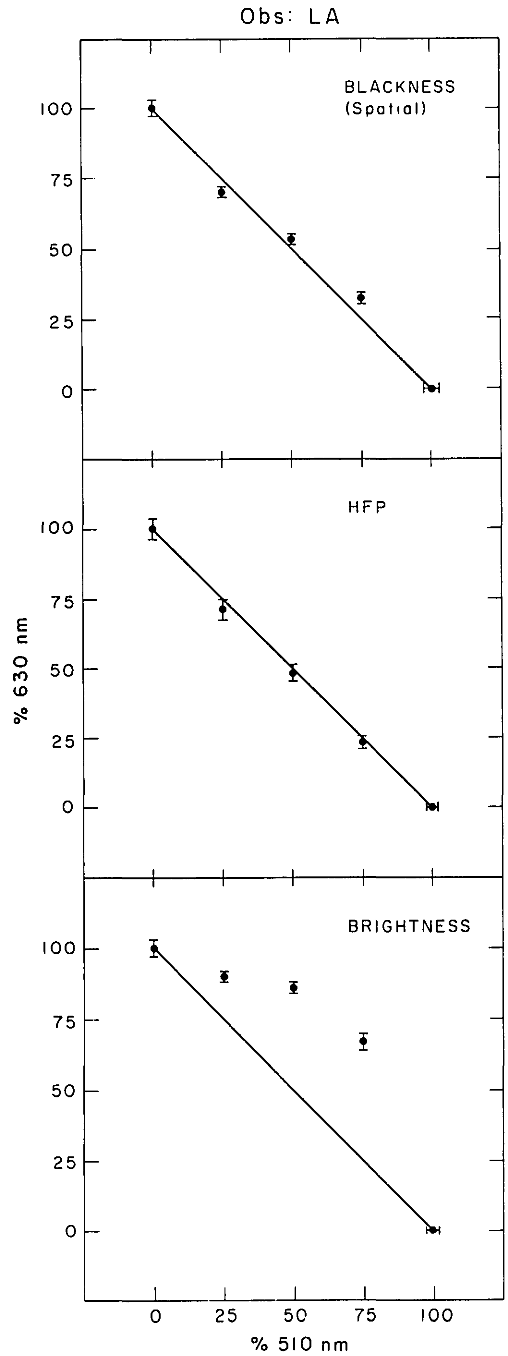

Fig. 6. Same as Fig. 5, except for observer LA.

light is required in a field mixture to match brightness than when either wavelength is presented alone (enhancement). Overall, these patterns of additivity failure are consistent with the view that opponent-chromatic pathways contribute to brightness but not to HFP or to blackness induction.

Intensity Series. The additivity tests presented in Figs. 1–4 were conducted with one ratio of the variable and addend wavelengths. Figures 5 and 6 present data that cover a wider range of proportions, using one pair of wavelengths, 510 and 630 nm. The figures show the mean percentage of 630 nm in the wavelength mixture plotted as a function of the mean percentage of 510 nm (25%, 50%, or 75%) in the mixture for the three different psychophysical tasks, blackness induction (top panels), HFP (middle panels), and brightness matching (bottom panels). The error bars represent ±1 SEM and have been specified when they are larger than the data points. The 100% values for both wavelengths denote response measures made with that wavelength alone. The diagonal line with a slope of −1.0 designates the predicted outcome for complete additivity.

The top and middle panels show that additivity is obeyed for blackness induction and HFP; the percentage values follow the predicted line of additivity. The results in the bottom panels for brightness matching display a different pattern from those in the two upper panels. As indicated by comparison with the diagonal line, the 630-nm percentage values are greater than those expected for an additive process. The largest deviations occur when the 630-nm wavelength is combined with the 50% and 75% addends. All failures are of the subadditive type, consistent with the cancellation of cone signals at a chromatic-opponent site.

CONCLUSION

Results from previous experiments that compared the spectral efficiency of spatially induced blackness with HFP and brightness matching[2,3,7] were inconsistent in that some indicated a link between spatially induced blackness and HFP[2,3,7] and others suggested a resemblance between spatially induced blackness and brightness matching.[7] A close similarity to HFP implies that blackness induction is mediated by additive input from middle- and long-wave cones, whereas a greater similarity to brightness suggests that blackness induction is influenced by postreceptoral, chromatic processes that are known to be nonadditive.

The additivity tests described in this paper were performed to differentiate between these two physiological models of blackness induction. If the perception of blackness is mediated by additive cone signals, then changing the chromatic composition of the visual stimuli should not affect the luminance required for induction. However, if spatially induced blackness is dominated by postreceptoral, opponent mechanisms, then there should be violations of additivity for certain wavelength combinations. The results of these additivity experiments demonstrate that the spectral composition of the inducing stimulus has no effect on the blackness-induction response. The luminance of the stimulus, not its chromatic content, is the crucial factor. Consequently, the additive combination of signals from the middle- and long-wavelength-sensitive photoreceptors appears to mediate the spatial induction of blackness. These findings are consistent with results obtained when blackness induction was induced over time[8] rather than space, as in the present study.

These data help to clarify the nature of the cone signals to the achromatic process when the criterion response is complete blackness. These results were expected from studies by Werner *et al.*[2] and Cicerone *et al.*,[3] who showed that the spectral efficiency of spatially induced blackness closely resembled that of HFP. However, Fuld and Kulp[7] and Volbrecht and Werner[8] showed that differences in the spectral efficiency of induced blackness, HFP, and brightness matching are sometimes too subtle to permit either of the functions to be rejected as a match to the other. In addition, Fuld *et al.*[4] concluded that when the criterion response is one of equal blackness and whiteness, the results are probably fitted better to the spectral efficiency of brightness than to HFP. It is possible that the result of Fuld *et al.* is due to the criterion of equal blackness and whiteness, which may be dependent on different processes than when the criterion is pure black. A criterion of equal blackness and whiteness may, for example, represent the interaction of parallel blackness and whiteness processes rather than the output of a single achromatic system.[5] The present results, of course, do not address this hypothesis, but they do clearly establish that cone signals are additively combined by the achromatic process mediating the perception of blackness.

ACKNOWLEDGMENT

This research was supported by National Institutes of Health grant AG04058 to J. S. Werner.

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