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16. Abstract

Retroreflective markings can be used effectively to enhance nighttime recognition of pedestrians. Past experimental work concentrated on factors such as retroreflective power, area, and positioning of retroreflective markings. However, the effect of color received less attention, mainly because the use of color reduces the retroreflective power of the material.

A nighttime field experiment was performed to address the effects of color. Subjects, seated in a car with low beam headlights on, had to rate the brightness of different colors of retroreflective materials. Independent variables included color (blue, green, yellow, orange, red, and white), ambient illumination, age, and sex.

Results showed that chromatic stimuli were perceived as brighter than photometrically matched achromatic stimuli. The brightness ratings for the chromatic stimuli followed a U-shaped function of dominant wavelength, with the highest brightness ratings at both extremes of the visual range. Efficiency factors for each color relative to a white retroreflective material were calculated.

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# CONTENTS

# INTRODUCTION

Retroreflective markings are effective in enhancing the nighttime recognition of pedestrians. (For an overview of both laboratory and field studies see Luoma, Schumann, and Traube, 1996.) The major variables that contribute to the efficiency of retroreflective markings for pedestrians have been identified as the retroreflective power of the material, the area of the material, and the positioning of the material on the pedestrian (Nordic Research Cooperation for Night Traffic, 1982). On the other hand, the effect of the color of the retroreflective material has received less attention, mainly because the use of color reduces the retroreflective power of the material. In the following, some theoretical and practical issues that are of importance for the perception of colored retroreflective material during night driving will be summarized.

## Basic color research

Evidence from basic color research indicates that photometric measures of luminance do not correlate well with perceived brightness when visual stimuli of different chromaticities are compared. Generally, chromatic stimuli will appear brighter than achromatic stimuli. This effect is often referred to as the Helmholtz-Kohlrausch effect (Wyszecki and Stiles, 1982). The effect increases as excitation purity (saturation) increases. The Helmholtz-Kohlrausch effect usually results in a U-shaped function of dominant wavelength (see Figure 1), with the minimum brightness around the dominant wavelength for yellow (Chapanis and Halsey, 1955). The size of the Helmholtz-Kohlrausch effect varies across subjects, and increases with illuminance level and source size (Stalmeier and de Weert, 1994).

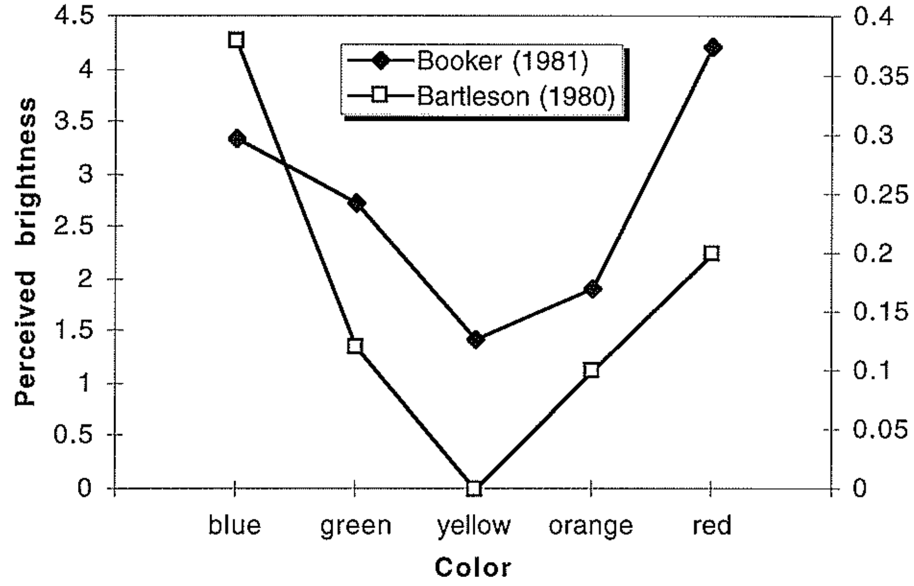

Figure 1. Two sets of data showing the Helmholtz-Kohlrausch effect. The ordinate shows perceived brightness (arbitrary units) of highly saturated colors with dominant wavelengths corresponding to blue, green, yellow, orange, and red. The data points were extracted from Booker (1981; Figure 2) and Bartleson (1980; Figure 6).

## Ambient illumination during night driving

While driving with low beam headlights, a driver will be adapted to a luminance level of about 1 cd/m$^2$ (Olson, 1993). For field luminances between about 0.001 and 3 cd/m$^2$ an intermediate state of vision exists, called mesopic vision. During mesopic vision both rods and cones operate, and therefore both affect the perception of colors (Boyce, 1981). As conditions brighten from mesopic to photopic conditions, the spectral response of the eye changes due to the decreasing role of the rods with increasing luminances. At the lower (mesopic) light level, the eye is more sensitive to shorter wavelengths. At higher light levels, the peak sensitivity of the eye shifts toward longer wavelengths; this shift in sensitivity is called the Purkinje shift (Wyszecki and Stiles, 1982).

The Purkinje shift might influence nighttime driving especially on dark roads where the only illumination is that provided by headlamps. Although a driver on a dark road might be more sensitive to low luminance blue and green light sources, this increased sensitivity to blue and green should be less pronounced when significant illumination is provided by fixed road lighting.

### Colored retroreflective pedestrian markings

Zwahlen and Yu (1991) conducted a series of experiments to determine the distances at which the color of retroreflective targets could be identified at night under low beam headlamp illumination. In one experiment the recognition distances of retroreflective samples with equal retroreflective efficiency were significantly longer for red and orange, compared with blue, green, yellow, and white. However, these results could not be fully replicated in another experiment. Because subjects had to name (i.e., recognize) the specific color, these experiments do not necessarily provide information about the distances at which different colors can be detected.

Venable and Hale (1996) performed a field experiment based on night conspicuity judgments of chromatic vs. achromatic markings and calculated from the subjects' responses a color correction factor $F_C$ as the ratio of the luminance of an achromatic marking ($L_a$) to the luminance of an equally conspicuous chromatic marking ($L_c$) (see Equation 1).

$$F_C = \frac{L_a}{L_c} \tag{1}$$

Their results followed a U-shaped function expected from the Helmholtz-Kohlrausch effect, with higher conspicuity values (i.e., higher color correction factors $F_C$) for red and blue, and the lowest value for yellow.

In a second step, they mathematically derived $F_C$ values for each color using two approaches:

(1) calculating $F_C$ as the color difference from black in a uniform color space (UCS),

(2) calculating $F_C$ as recommended in the specification ASTM E 1501 (1992).

The two approaches resulted in nearly identical $F_C$ values ($R^2$ =.99) for the different colors. A comparison of the calculated $F_C$ values using the recommendation from ASTM E 1501 (1992) with their experimentally obtained $F_C$ values showed a relatively good fit ($R^2$ = .62).

## Research questions

The present study was designed to investigate the effect of different colors of retroreflective material on perceived brightness. Research questions were as follows:

(1) Does color have an effect on the perception of brightness as could be expected from the Helmholtz-Kohlrausch effect?

(2) Is brightness of retroreflective color affected by both the ambient illumination level and the retroreflective power of the material?

# METHOD

## Subjects

Twenty-four paid subjects, all licensed drivers, participated in the study. There were two age groups, each consisting of twelve subjects balanced by sex. Subjects were paid for their participation in the experiment, and they were recruited from lists of potentially interested subjects maintained at UMTRI. The ages of subjects in the younger group ranged from 19 to 39 years (mean = 26.8; standard deviation = 5.2), and in the older group from 61 to 75 years (mean = 68.7; standard deviation = 4.3).

Subjects wore the same eyewear, if any, that they would normally wear when driving at night. All subjects were color normal, as determined using the Standard Pseudoisochromatic Plates (Ichikawa, Hukami, Tanabe, and Kawakami, 1978).

## Psychophysical task

The psychophysical method was magnitude estimation without an anchor (e.g., Marks, 1974). Subjects were told to assign for each retroreflective stimulus a number that stood for the degree of apparent brightness. The exact wording of the instruction was as follows:

> During the study, I am going to present a number of retroreflective stimuli to you. Your task is to judge how "bright" each stimulus looks to you by assigning numbers to stand for the degree of brightness. To the first stimulus, assign whatever number seems most appropriate to represent the degree of brightness. Then, for succeeding stimuli, assign other numbers in proportion to brightness. If one stimulus seems three times as bright as another, assign a number three times as great; if it feels one-fifth as bright, assign a number one-fifth as great. Any type of positive number, whole number, decimal, or fraction, may be used. Do not use zero or negative numbers.

These instructions were repeated three times, at the beginning of the instruction period, at the beginning of the first trial, and during a break between experimental blocks.

## Equipment and setup

Schematic diagrams of the experimental setup and subject's view are shown in Figures 2 and 3.

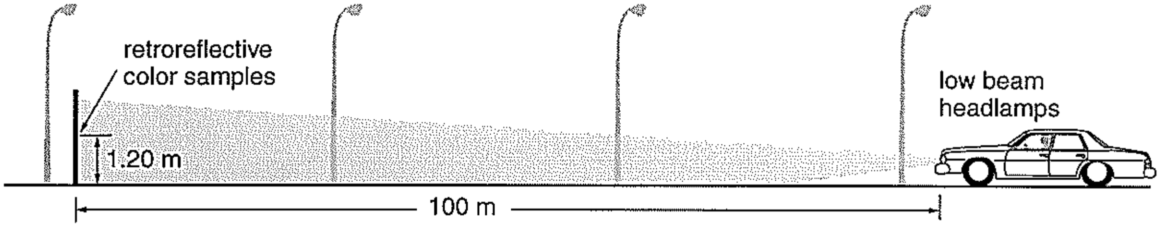

Figure 2. A schematic diagram of the experimental setup with parking-lot lights (metal halide lamps).

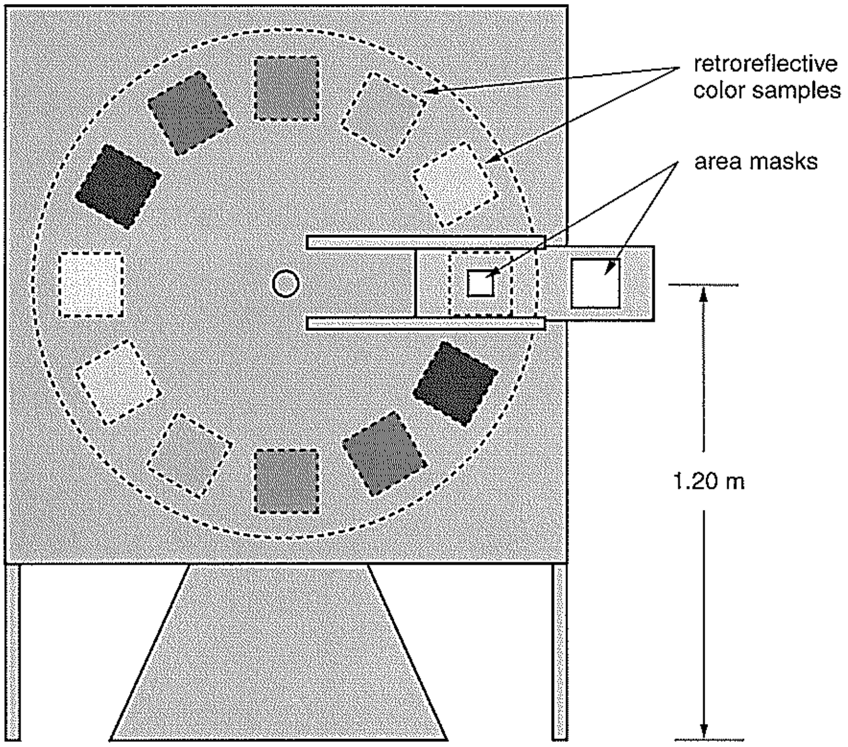

Figure 3. A schematic diagram of the setup for the retroreflective colors. The 12 color samples (6 colors by 2 levels of retroreflective power) were placed on a revolving disk. On any given trial, the subject could see only one color through one specific area mask (6 cm x 6 cm or 12 cm x 12 cm).

The study was performed on a straight and flat road adjoining the UMTRI parking lot. Subjects were seated in a 1993 Nissan Altima, which was parked at a distance of 100 m from the retroreflective materials. The low beam headlights of the car, which were properly aimed, were on during the entire experiment. The headlights were connected to an external power source in order to keep the voltage constant during the entire experiment. Car jacks were placed under the front and the back of the car to keep the vertical aim of the headlights constant across all subjects.

The retroreflective color samples were placed on a revolving disk (see Figure 3). This disk was hidden by a large board, which was covered with a black, matte cloth. On each experimental trial, only one color sample was visible to the subject through a mask with two square openings, either of which could be slid into position in front of the sample. The mask was positioned at a height of 1.2 m to simulate a retroreflective marking on a pedestrian. The center of the retroreflective sample was at 1.3° from straight ahead of the driver, and 0.9° from straight ahead for the passenger.

Two experimenters ran the experiment. One experimenter, seated in the back seat, supervised the sequence of trials. The second experimenter stood behind the setup of the retroreflective colors (not visible to the subject) and changed the retroreflective samples by turning the disk and sliding the area mask, as needed.

The experiment was conducted on dry pavement. There were no other light sources or retroreflectors within the field of view of the subjects. The parking-lot lights (see Figure 2) were turned off for one block of the experiment, and turned on for the other block. The illuminance at the retroreflective samples with and without the parking-lot lights on, and with low beam headlamps always on, was 13 lux and 0.25 lux, respectively.

## Stimulus conditions

There were 24 different retroreflective stimuli, produced by using all combinations of six retroreflective colors (blue, green, yellow, orange, red, and white), two different levels of retroreflective power in terms of SIA (i.e., specific intensity per unit area; also referred to as the coefficients of retroreflection R'), and two area masks (6 cm x 6 cm and 12 cm x 12 cm, resulting in field sizes of 2' and 4' arc of visual angle, respectively). Table 1 shows the measured actual SIA values for the six retroreflective colors, the two SIA levels, and the two area masks. The same retroreflective material (i.e., the same retroreflective optics) was used for all colors. The average luminance level—measured from the eye point—for the lower SIA-level materials was about 1 cd/m$^2$, and it was about 3 cd/m$^2$ for the higher SIA-level materials.

Table 1

Retroreflective power (SIA) for the retroreflective stimuli (measured at an entrance angle $\beta = -4°$ and an observation angle $\alpha = .2°$).

| | **SIA values** [cd/lux/m$^2$] | | | |
|---|---|---|---|---|
| | low SIA | | high SIA | |
| **Color name** | 6 cm x 6 cm | 12 cm x12 cm | 6 cm x 6 cm | 12 cm x12 cm |
| blue | 34 | 41 | 150 | 148 |
| green | 23 | 26 | 96 | 97 |
| yellow | 33 | 36 | 136 | 136 |
| orange | 33 | 36 | 118 | 124 |
| red | 36 | 41 | 102 | 111 |
| white | 31 | 35 | 123 | 125 |

Table 2 shows the x and y chromaticities of the retroreflective samples. The colors were measured using illuminant A under the same geometry as in Table 1. Figure 4 shows these chromaticity coordinates plotted using the CIE 1931 chromaticity diagram.

Table 2

CIE 1931 chromaticity coordinates (x,y) of the retroreflective stimuli.

| | low SIA | | high SIA | |
|---|---|---|---|---|
| **Color name** | x | y | x | y |
| blue | .373 | .395 | .366 | .384 |
| green | .252 | .589 | .251 | .601 |
| yellow | .578 | .423 | .512 | .421 |
| orange | .611 | .369 | .621 | .365 |
| red | .684 | .312 | .686 | .310 |
| white | .457 | .410 | .462 | .417 |

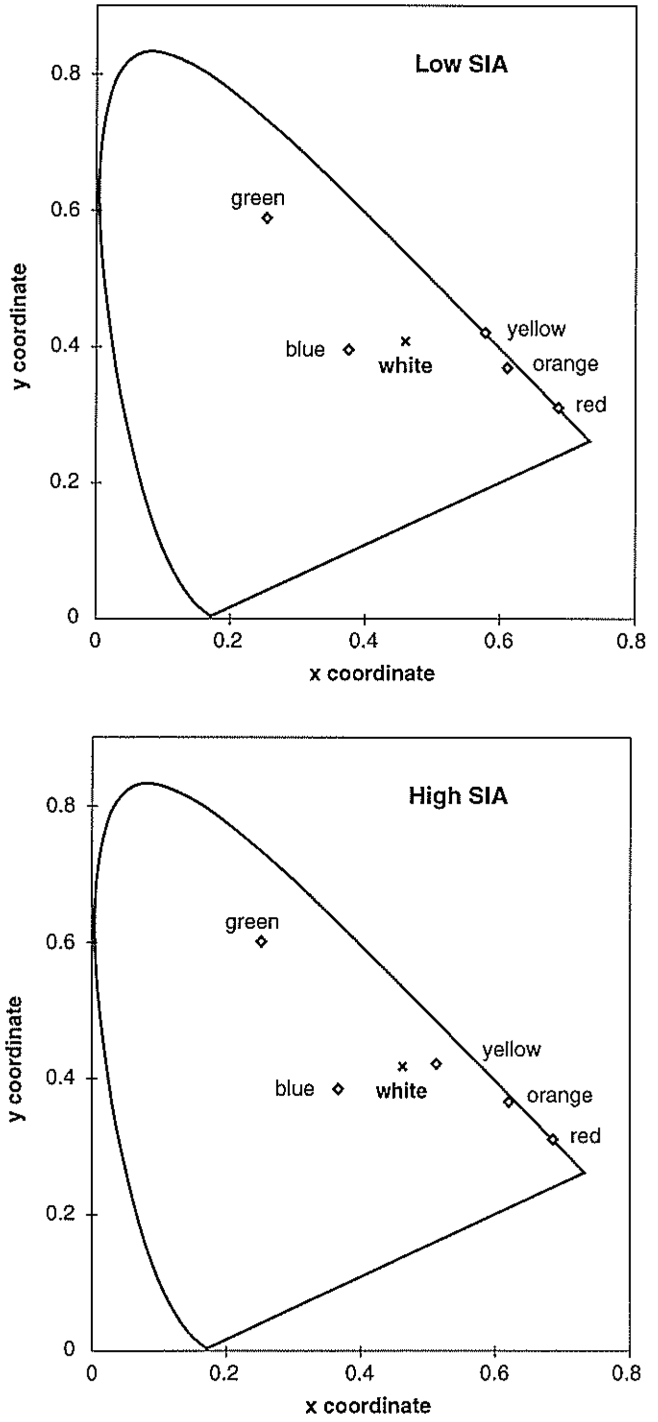

Figure 4. Chromaticity coordinates of the retroreflective samples plotted on the CIE 1931 chromaticity diagram.

## Experimental design

The following independent variables were factorially combined:

(1) age, a between-subjects variable with two levels (younger, older)

(2) sex, a between-subjects variable with two levels (female, male)

(3) ambient illumination, a within-subjects variable with two levels (parking-lot lights on, off)

(4) retroreflective color, a within-subjects variable with six levels (blue, green, yellow, orange, red, white)

(5) retroreflective power, a within-subjects variable with two levels (low SIA, high SIA)

(6) area, a within-subjects variable with two levels (6 cm x 6 cm, 12 cm x 12 cm)

The retroreflective stimuli producing 24 combinations of retroreflective colors, SIA value, and area (6 x 2 x 2) were each presented twice in a block of 48 randomized trials. One such block was presented for each of the two ambient illumination conditions. The order of the ambient illumination conditions was balanced over pair of subjects.

## Procedure

Two subjects were tested at a time. After completing a color vision test (Standard Pseudoisochromatic Plates; Ichikawa et al., 1978), they were seated in the car, one in the driver position, and one in the right-front passenger position. This seating configuration was balanced by age and sex.

Subjects were instructed to lower their heads between trials, without closing their eyes, until the experimenter in the back seat of the car said “go” to begin a trial. When the subjects heard that signal, they had to raise their heads and look forward and toward the right side of the road where the retroreflective stimulus was visible. They were instructed not to move their heads to the right or left after they spotted the retroreflective stimulus. After they decided on their brightness ratings, they had to look down again and write the rating next to the corresponding trial number on a response sheet. The subject in the passenger seat had to say “ready” after completing his or her brightness rating. As soon as the subject in the driver seat had completed his or her rating and had heard the subject on the passenger side say “ready,” he or she honked the horn to notify the second experimenter behind the stand for the retroreflective materials to change the stimulus for the next trial. A complete trial sequence took about 20 seconds to complete, which resulted in about 15 minutes for each of the two blocks of 48 trials.

There was a 20-minute break between the two blocks distinguished by ambient illumination (i.e., parking-lot lights on or off). This break was necessary because the parking-lot lights took about 18 minutes to reach their asymptotic light output. During this break, subjects stayed in or close to the experimental car in order to avoid major light-adaptation changes. The instructions to the subjects at the beginning of the experiment, which were given with the subjects in the experimental car, took about 15 minutes to administer. Thus, there was enough time before each of the ambient-illumination blocks (15 or 20 minutes) for the subjects' light adaptation to be reasonably stable (which takes about 10 minutes for color vision; see Cornsweet, 1971).

## Data analysis

Following Marks (1974), the geometric mean was used to provide central tendency information for the magnitude-estimation data. Data from magnitude estimates often exhibit a linear relationship of stimulus intensity on log-log coordinates (Marks, 1974). This relationship was used for analyzing the data.

The efficiency of retroreflective material is normally expressed in terms of SIA (i.e., specific intensity per unit area). Taking into account the visible, reflective area of the retroreflective material, the efficiency can also be expressed in terms of CIL (i.e., coefficient of luminous intensity[1]; see Equation 2):

$$C = 1000aS \tag{2}$$

where,

$C$ is CIL in mcd/lux,

$a$ is area in $m^2$,

$S$ is SIA is in cd/lux/$m^2$.

Using Equation 2, and taking into account the assumed linear relationship of the brightness ratings, a linear regression analysis was used to estimate the relationship between log CIL and log brightness rating. This was done for each combination of subject, ambient illumination, and retroreflective color. For each such combination there were four CIL values (the product of the two SIA levels and the two areas). The approach is shown in Figure 5 for one such combination.

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[1] The coefficient of luminous intensity is also called $R_I$ (see ASTM E 1501, 1992).

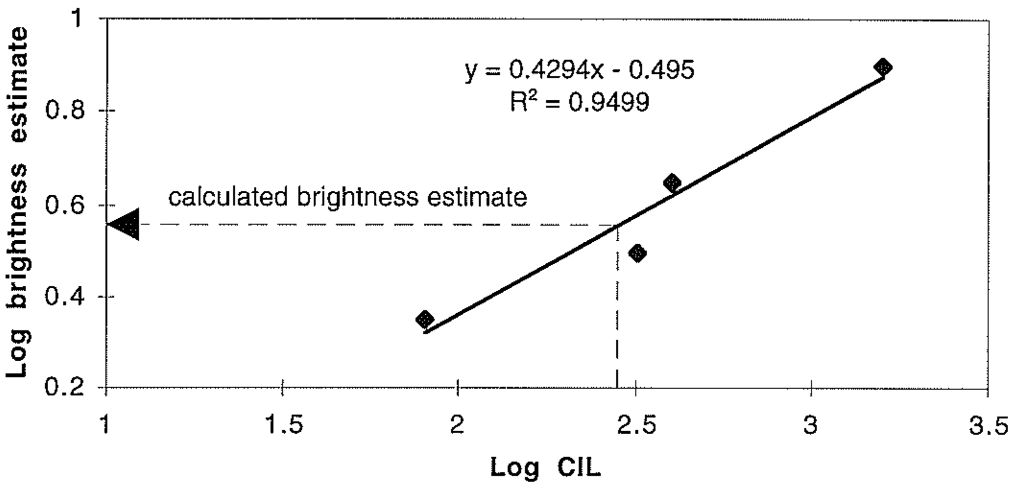

Figure 5. Data set for one combination of subject, ambient illumination, and retroreflective color. The line is the result of regressing log rating on log CIL. The calculated brightness estimate is illustrated (see text for details).

After calculating the linear models, one value of CIL was chosen to serve as a standard level for calculating predicted brightness ratings for comparison across all colors. This CIL value was set to be 300 mcd/lux, which was suggested by Rumar (1976) as a minimum for pedestrian recognition at nighttime. Rumar showed that retroreflective pedestrian markings with a CIL value of 300 mcd/lux are sufficiently bright to be detectable by a driver during nighttime at a distance of 140 m. We calculated predicted brightness ratings for CIL = 300 mcd/lux for each combination of subject, ambient illumination, and retroreflective color. We then used those values as the dependent variable in an analysis of variance to determine possible differences in rated brightness for different retroreflective colors.

# RESULTS

## Overview

The following results are based on regression models derived from subjects' brightness ratings. First, the results are presented in terms of the psychological variable (brightness rating). Then some of the results are presented in terms of a color efficiency measure based on the different values of CIL required for the colors to produce equal brightness ratings.

## Brightness rating

After calculating the regression models for each subject and each experimental condition (see Figure 5), an analysis of variance was performed on the $R^2$ values to check, for each experimental condition, whether the data fit well with the assumption of a log-log linear relationship between CIL values and rated brightness. The ANOVA incorporated two between-subjects variables (age and sex) and two within-subjects variables (ambient illumination and retroreflective color). This analysis of variance resulted in a significant main effect of retroreflective color, $F(5,100) = 23.26$, $p < .0001$. Table 3 shows the mean $R^2$ values of the linear regression models for the six different retroreflective colors. Although there are generally good fits for five of the retroreflective colors, the fits are relatively poor for the color green.

Table 3

Goodness of fit of the CIL-model for the six retroreflective colors.

| **Retroreflective color** | **$R^2$ value** |
|---|---|
| blue | .90 |
| green | .63 |
| yellow | .86 |
| orange | .86 |
| red | .88 |
| white | .86 |

Area and SIA values were chosen in such a way that the CIL value of a color sample with a large area and low SIA value would be similar to the CIL value of a color sample with a small area and high SIA value. These two similar CIL values should therefore result in similar brightness ratings. A closer look at the brightness ratings for green by each subject revealed that this was not the case. Subjects rated the large area, low SIA sample much brighter than the small area, high SIA sample, which resulted in the poor fit of the regression model for the green stimuli.

Therefore, in order to be able to compare green with the other colors, it was decided to add SIA as an independent variable in the data analysis. A new data analysis was performed, in which linear fits were obtained separately for the two SIA levels. The principle is shown in Figure 6, where the data points from Figure 5 have been separated according to their two SIA levels.

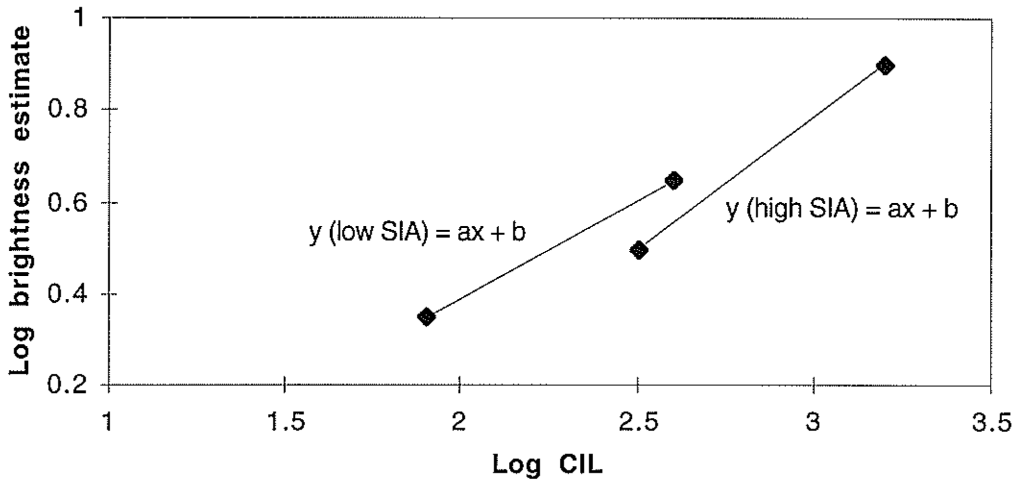

Figure 6. Data set for one subject with four brightness estimates for the four different CIL values. Data have been separated according to the two different SIA levels, and two linear regressions of log rating on log CIL have been computed independently.

As in the previous analysis, brightness estimates corresponding to a CIL value of 300 mcd/lux were computed from the regression equations, and those brightness estimates were used as the dependent variable for an analysis of variance. The analysis of variance consisted of two between-subjects variables (age and sex) and three within-subjects variables (SIA, ambient illumination, and retroreflective color). The analysis showed a significant interaction of SIA and retroreflective color, $F(5,100) = 6.98$, *p* = .0003. The high brightness rating for the green with the low SIA value is evident in Figure 7, which shows the mean brightness ratings for each color and each SIA value.

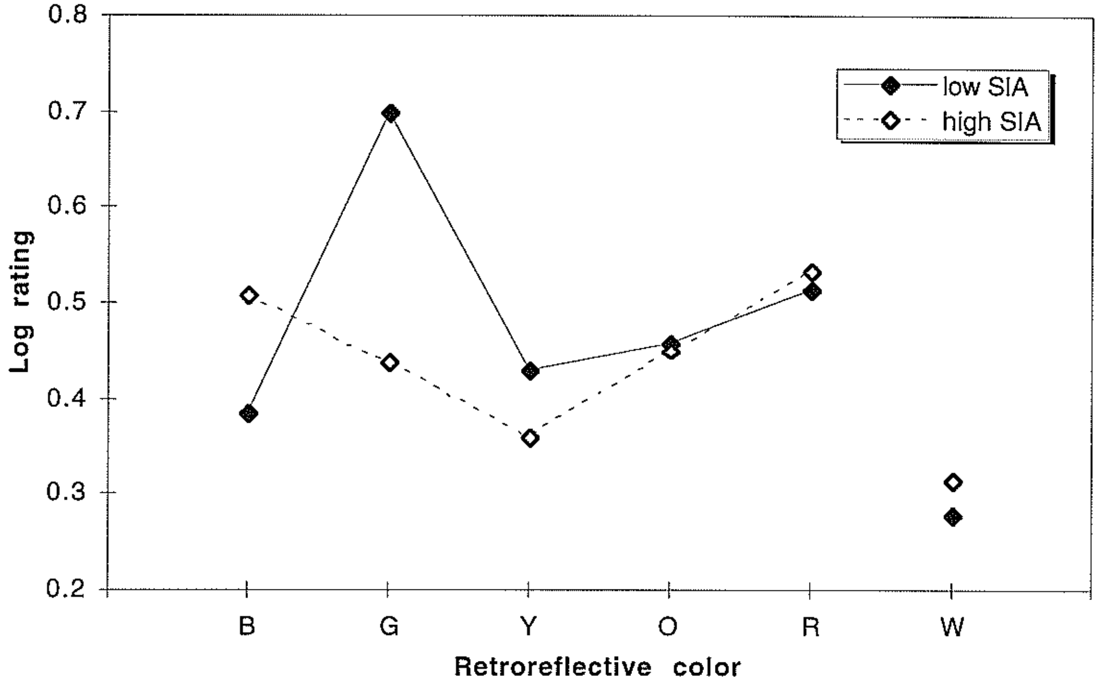

Figure 7. Calculated average log brightness rating for CIL = 300 mcd/lux, by SIA and retroreflective color (B = blue, G = green, Y = yellow, O = orange, R = red, W = white).

Since the CIL values from which the brightness ratings were calculated are the same for both SIA levels (i.e., a CIL value of 300 mcd/lux), the two calculated ratings for each color should not differ significantly. To test this assumption, a post-hoc analysis was performed on the significant interaction effect, which resulted in significant differences only for the two green SIA values, HSD (12,100) = 0.122 $\alpha = .01$.

The ANOVA also resulted in significant main effects of ambient illumination, $F(1,20) = 7.26$, $p = .014$, and retroreflective color, $F(5,100) = 11.89$, $p < .0001$. Brightness ratings were significantly lower when the parking-lot lights were on than when they were off (log ratings of 0.38 versus 0.51). The significant effect of color is shown in Figure 8.

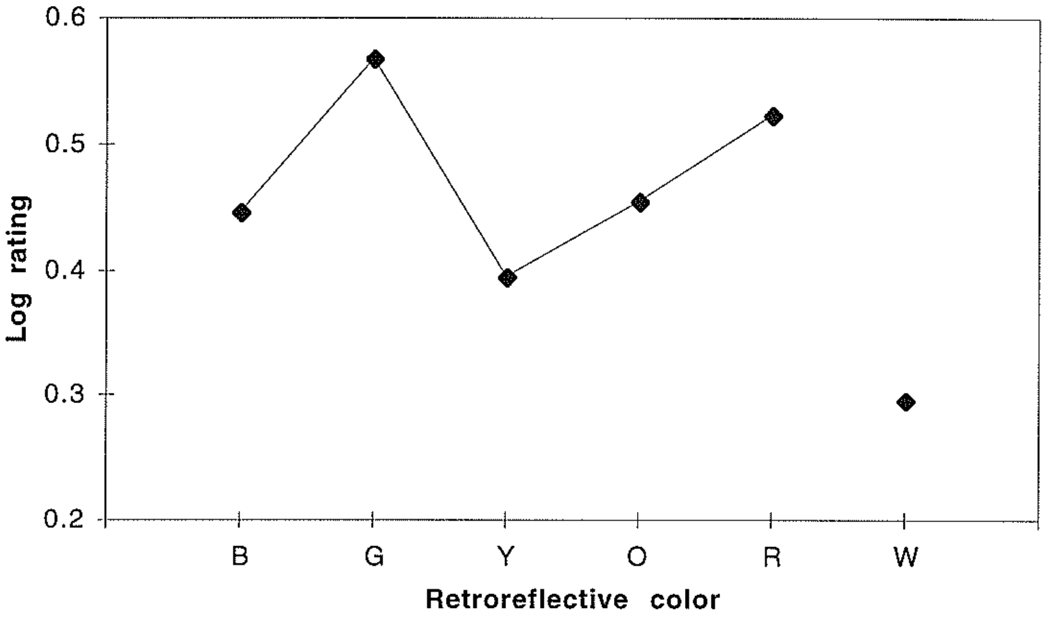

Figure 8. Calculated average brightness rating for CIL = 300 mcd/lux, by retroreflective color.

A post-hoc analysis showed that all colors were rated to be brighter than white, HSD (6,100) = 0.092 $\alpha = .01$. However, as has been shown above, the high brightness rating for green should be interpreted with caution, because its high value is based mainly on the high ratings for the low SIA level (see Figure 7).

Overall, the results demonstrated that colored retroreflective materials appeared brighter than a photometrically matched white retroreflective material. This result was independent of age group and sex, and the tendencies were similar in both ambient-illumination conditions, albeit retroreflective materials appeared brighter overall when the ambient illumination was low.

## Color efficiency

In order to discuss the results of the experiment in terms of a physical variable (CIL) instead of a psychological variable (brightness rating), it is necessary to calculate the log CIL values corresponding to a fixed brightness-rating criterion. In order to compute an index of the efficiency of the various colors relative to white, the rating corresponding to white at a CIL value of 300 mcd/lux was chosen as a reference.

The calculation of the regression equations to obtain the log CIL values for all colors was based on the average regression equations for all 24 subjects. Because of the different brightness-rating behavior when subjects were confronted with green in the low SIA-level condition, the following calculations are based only on the results from the high SIA-level condition. The brightness-rating reference value was taken from the high SIA-level, white retroreflective sample while the parking-lot lights were off. The average regression line for this condition is shown in Figure 9.

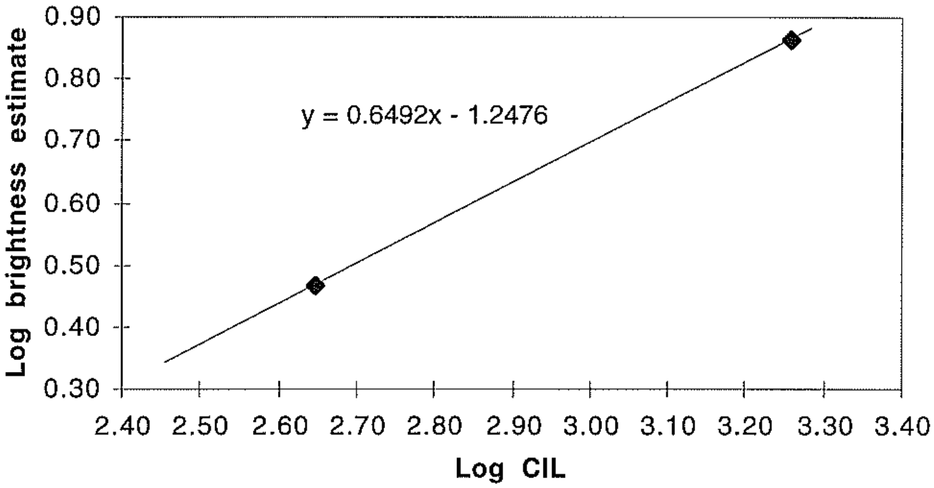

Figure 9. Average regression model (N = 24) for the high SIA, white retroreflective sample in the condition with parking-lot lights off.

The log rating value for white that corresponds to a CIL of 300 was calculated (0.36). Efficiencies for each of the nonwhite colors were then calculated as the ratio of the standard CIL value for white (300) to the CIL value for that color that corresponds to the same log rating value (0.36). This definition of a relative efficiency index, or color correction factor, is embodied in equation 3:

$$F_C = \frac{CIL_w}{CIL_c} \tag{3}$$

where,

$F_C$ is the color correction factor,

$CIL_w$ is the chosen CIL standard for white (300), and

$CIL_c$ is a CIL value for the color in question that should produce the same log rating (0.36) as a CIL value of 300 for white.

Table 4 shows the color correction factors $F_C$ for each color as obtained from the experimental data (see Equation 3) and compares them to the mathematically derived color correction factors $F_C$ using Equation 4 in ASTM E 1501 (1992). These color correction factors can be applied to the CIL values of colored materials to obtain brightness ratings equivalent to the rating for the white material (see also ASTM E 1501, 1992; Equation 1). With the exception of blue, which was very desaturated (see Figure 4), the experimentally obtained color correction factors resulted in a very good fit with the mathematically derived $F_C$ values This is shown in Figure 10, which excludes blue.

Table 4

Color correction factors $F_C$ for retroreflective materials.

| | Material chromaticity | | $F_C$ experimental results | $F_C$ calculated (ASTM E 1501, 1992) |
|---|---|---|---|---|
| **Color name** | x | y | | |
| blue | .366 | .384 | 2.35 | 1.27 |
| green | .251 | .601 | 2.17 | 1.77 |
| yellow | .512 | .421 | 1.07 | 1.19 |
| orange | .621 | .365 | 1.77 | 1.71 |
| red | .686 | .310 | 2.56 | 2.28 |

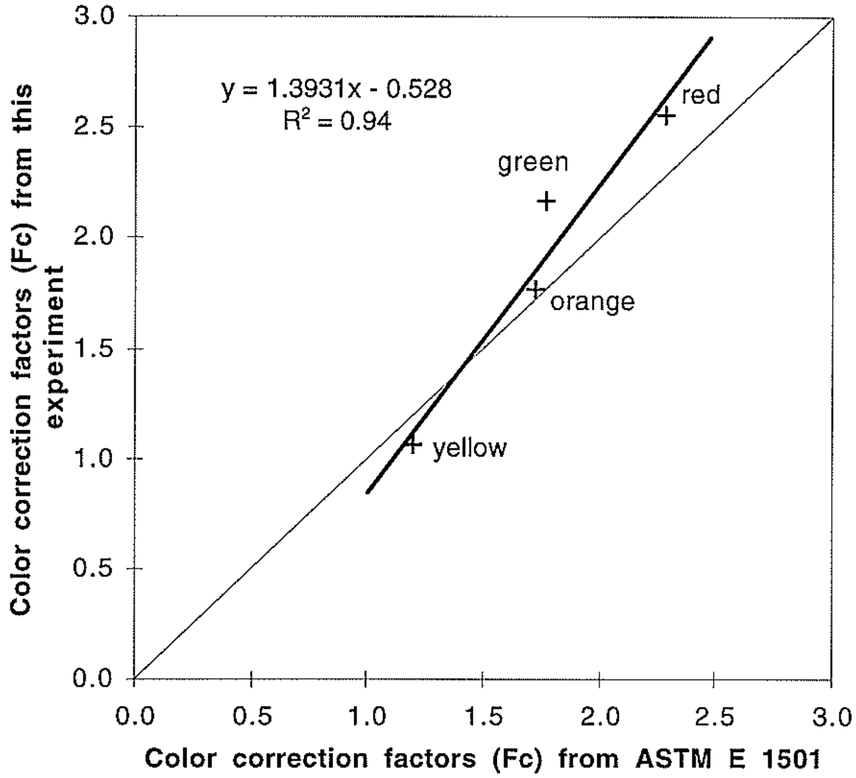

Figure 10. A comparison of color correction factors from this study with those based on ASTM E 1501.

Figure 11 summarizes experimentally obtained color correction factors from this study and from Venable and Hale (1996), and relates both of these sets of color correction factors to the predictions based on ASTM E 1501. Although the experimentally derived color correction factors were obtained with two different methods (brightness rating versus conspicuity task), they are in reasonably good agreement with each other and with the predictions based on ASTM E 1501.

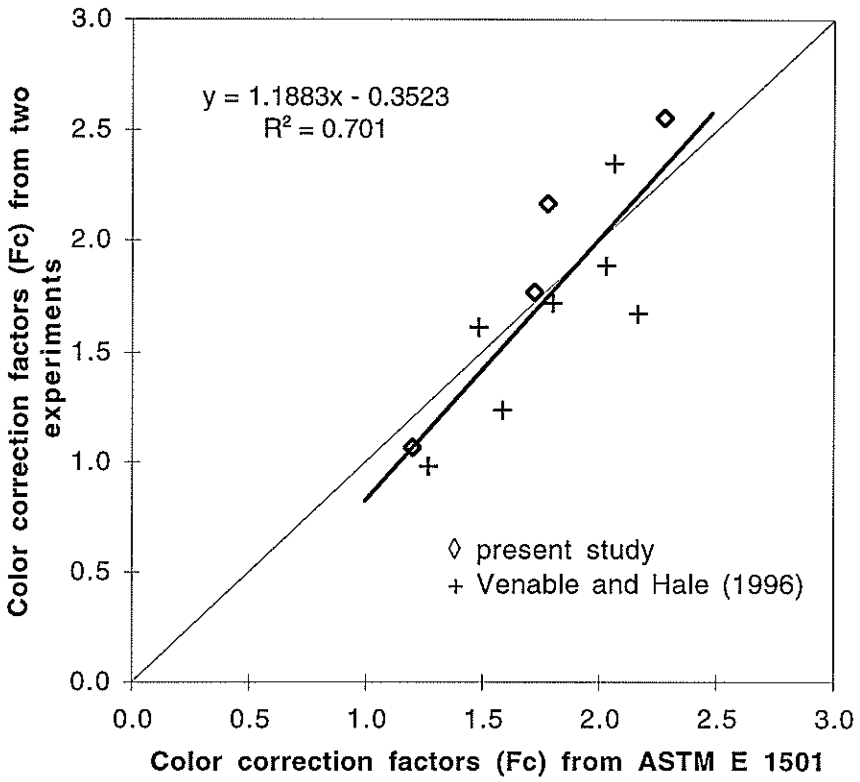

Figure 11. A comparison of color correction factors from two studies to those based on ASTM E 1501.

# DISCUSSION

The discussion is divided into two parts, corresponding to the two results sections on brightness rating and color efficiency.

An attempt to model perceived brightness of retroreflective materials as a function of the retroreflective power and the visible area of the retroreflective material resulted in a good fit for five out of six retroreflective colors. Therefore, this model can be considered to be a good approach for incorporating the effects of both the visible area and the retroreflective power to predict the efficiency of colored retroreflective markings. Previous studies have already demonstrated the validity of the CIL approach for achromatic retroreflective materials (e.g., Rumar, 1976).

However, the CIL approach did not work well for modeling the perceived brightness of green at the two levels of SIA. One possible explanation for this finding might lie in the ambient illumination conditions with low beam headlights, and the low luminance levels of the retroreflective materials used in this experiment. Ikeda, Huang, and Ashizawa (1989) demonstrated two influences on the perception of brightness in the mesopic range of vision that may be relevant. At low luminance levels, colors with short dominant wavelengths (e.g., blue and green) can appear brighter than long wavelength colors due to the Purkinje shift, and colored objects of high saturation appear brighter than those of less saturation (see also Booker, 1981). Both influences might be involved in the brightness ratings for the low-SIA material in this experiment. At the luminance levels for the low-SIA targets (about 1 cd/m$^2$), the visual system could have been more sensitive to colors with shorter dominant wavelengths. Also, the green colored material was highly saturated (see Figure 4). On the other hand, the low-SIA, blue material was considerably less saturated, which could explain the rather low rating for the low SIA blue in comparison with the green (see Figure 7). Altogether, however, the present experiment does not allow clear conclusions about the mechanisms involved in the divergent brightness ratings for the low SIA condition. This is especially the case because the sizes of the retroreflective targets were very small (2' and 4' of arc), which does not suggest a strong influence of rods.

Brightness ratings for the high-SIA retroreflective colored materials show a U-shaped form (Figure 7), which would be expected due to the Helmholtz-Kohlrausch effect. These results, therefore, are consistent with the findings by Venable and Hale (1996) that color has an influence on the brightness of retroreflective materials. Also, the present experimental-derived color correction factors for saturated colors (i.e., all tested samples except blue) are in good agreement with the predictions based on ASTM E 1501

(1992) (see Table 4). However, there was a strong deviation for the desaturated blue retroreflective material, with subjects rating the brightness of the blue much higher than expected.

The linear regression approach allowed the calculation of color correction factors for different colors with respect to white (see Table 4). In principle, the color correction factors provide a way to determine how much the retroreflective power (in terms of SIA) of chromatic materials can be reduced to obtain an efficiency that is equivalent to white materials. For example, based on the present results, an achromatic white retroreflective material with a coefficient of luminous intensity of 300 mcd/lux should be functionally equivalent to, and appear as bright as, red retroreflective material of 117 mcd/lux (300/2.56).

However, a wide generalization of the present results should be avoided due to a variety of factors which influence the perception of brightness of colored material. These factors include the saturation of the color of the retroreflective material, the luminance of the retroreflective material (i.e., the retroreflective return), and the ambient illumination conditions. Furthermore, performance-based validation of the present results is needed. Such validation should include dependent variables that are directly related to safety, such as detection or recognition distances.

Finally, the experimentally obtained correction factors for all colors, except blue, resulted in a rather good fit when compared to the color correction factors derived from ASTM F1501 (1992). More research is needed on the effects of saturation on perceived brightness of retroreflective materials.

# CONCLUSION

The main findings of this study are as follows:

(1) Chromatic retroreflective stimuli were perceived as brighter than photometrically matched achromatic stimuli.

(2) Brightness ratings followed a U-shaped function of dominant wavelength, with the highest brightness rating at both extremes of the visual range.

(3) All stimuli appeared to be brighter when street lighting was on as opposed to off.

(4) In general, log brightness ratings proved to be well described by linear functions of CIL ($R_I$)—a measure that incorporates the reflective efficiency of the material (SIA) and its visible area. However, a green, low SIA sample was rated as substantially brighter than predicted. Potential explanations of this anomaly were discussed.

(5) Color correction factors for each color tested, relative to a white material, were calculated.

(6) The derived color correction factors related well to correction factors computed from ASTM E 1501 for all saturated colors tested.

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