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16. Abstract

A nighttime field study was conducted to assess the effects of color on the detection of retroreflective pedestrian markings. Participants, seated in a stationary vehicle with its low-beam headlamps on, indicated when a moving pedestrian, who wore colored retroreflective markings on her legs, was just detectable. Independent variables included color (red, yellow, green, and white), retroreflective power (SIA), and participant age.

This experiment demonstrated that the color of a retroreflective marking does affect the distance at which a moving pedestrian can be detected. Specifically, all three chromatic stimuli examined (red, yellow, and green) were detected at significantly greater distances (ranging from 7 to 10%) than was the achromatic stimulus (white). Additional modeling determined that to be detected at the same distance as a red, yellow, or green stimulus, a white stimulus would need to be 26 to 44% higher in SIA value.

The results are consistent with previous research by Schumann et al. (1996), in which colored retroreflective stimuli were perceived by participants to be brighter than a comparable white stimulus. Furthermore, the findings are in agreement with the Helmholtz-Kohlrausch effect. In addition, a strong linear relationship was found to exist between the color correction factors determined in this experiment and those predicted by ASTM E 1501. However, the exact relationship between the experimental results and predicted ASTM color correction factors appears to be affected by the nature of the experimental task.

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**CONTENTS**

## INTRODUCTION

At night, the visibility distance of pedestrians clad in dark clothing is less than one-third the distance required to stop for a vehicle traveling 88 km/h, and approximately one-half the distance required to stop for a vehicle traveling 56 km/h (Liebowitz and Owens, 1986). The goal of increasing the detection of pedestrians at night can be achieved, in part, through the use of retroreflective markings on pedestrian garments (vests, shoes, dangle tags, etc.). Previous research to improve the visibility distance of pedestrians through the use of retroreflective markings has dealt primarily with the effects of retroreflective power, marking size, or location of the marking on the pedestrian/cyclist. See Luoma, Schumann, and Traube (1995) for a brief overview of previous research. However, other than two recent studies performed by Schumann, Sivak, Flannagan, Traube, Hashimoto, and Kojima (1996) and Venable and Hale (1996), little attention has been paid to the effect the color of these materials has on the visibility distance of pedestrians.

Recently, a study by Schumann et al. (1996) demonstrated that for photometrically matched stimuli, chromatic stimuli (red, orange, yellow, green, and blue) were perceived to be brighter than achromatic stimuli (white). Furthermore, the brightness ratings generally followed the Helmholtz-Kohlrausch U-shaped function of dominant wavelength. The Helmholtz-Kohlrausch effect was first described in early German literature as *Farbenglut* (color glow), and has also been referred to as *florence* (Wyszecki, 1986). The effect is frequently found when a chromatic test stimulus is matched photometrically with an achromatic stimulus. In general, the chromatic stimulus will appear brighter than the achromatic stimulus.

Schumann et al. (1996) and Venable and Hale (1996) both performed field experiments to evaluate the effect of color on the perception of retroreflective materials, and both experiments produced results that are consistent with the Helmholtz-Kohlrausch effect. The Venable and Hale study evaluated the effect of color on the perceived conspicuity of retroreflective materials, whereas the experiment by Schumann et al. evaluated the effect of color on perceived brightness of retroreflective materials. Despite the difference in tasks and stimuli, both studies concluded that standard photometric measurements alone did not accurately predict the perception of colored retroreflective targets.

Venable and Hale used the experimentally derived data in order to develop a dimensionless color correction factor ($F_C$) that would relate the perceived conspicuity of colored retroreflective markings to customary measurements of luminance. For each colored stimulus, the color correction factor was calculated by dividing the luminance of a chromatic marking by the luminance of an achromatic marking that was matched for conspicuity. In order to develop a dimensionless color correction factor that extended to colors other than those tested, the authors then used their experimentally derived color correction factors to investigate three commonly used color-difference equations, associated with three versions of uniform color space (UCS), to calculate a color difference from black. After evaluating the different uniform color spaces, Venable and Hale settled on the color-difference equation associated with the Hunter UCS (Equation 1), where the color difference was used as a measure of stimulus conspicuity.

$$F_c = (1+(a/L)^2+(b/L)^2)^{0.5} \qquad \text{(Equation 1)}$$

A second approach taken by Venable and Hale was to compare their experimentally derived color correction factors with those that would be mathematically derived using a color-difference equation that is recommended in the American Society for Testing and Materials (ASTM) standard E 1501 (Equation 2).

$$F_c = 1+(2/3)*((a/L)^2+(b/L)^2)^{0.5} \qquad \text{(Equation 2)}$$

Venable and Hale reported that either approach resulted in a satisfactory interpretation of the nighttime conspicuity data they obtained using colored retroreflective stimuli. They suggested that brightness may be more a function of total color difference in a UCS than luminance difference, and that equal-conspicuity judgments might be used to develop a new UCS that more closely approximates the true luminous efficiency of retroreflective stimuli.

In the field study by Schumann et al. (1996)—using five chromatic stimuli and one achromatic stimulus, two levels of retroreflective power, two levels of area, and two levels of ambient illumination—the authors employed magnitude estimation to gather subjective assessments of perceived brightness for colored retroreflective stimuli. They reported a significant effect of color on perceived brightness, with the chromatic stimuli (red, orange, yellow, green, and blue) being judged significantly brighter than the achromatic stimuli (white).

Schumann et al. investigated the linear relationship between the calculated ASTM E 1501 color correction factors and color correction factors obtained from their experimental results. They reported a very high $R^2$ (0.94) between the calculated and experimentally obtained color correction factors. Furthermore, they used the experimental correction factors from the work by Venable and Hale (1996) and arrived at similar results (i.e., there existed a reasonably good agreement between both sets of color correction factors and the mathematically derived values using ASTM E 1501).

Schumann et al. concluded that chromatic retroreflective stimuli were perceived to be brighter than photometrically matched achromatic stimuli, that the brightness ratings closely followed a U-shaped function of dominant wavelength similar to that of the Helmholtz-Kohlrausch effect, and that the calculated color correction factors were in good agreement with the mathematically derived correction factors from ASTM E 1501.

The present study investigated whether or not the color of retroreflective materials, similar to some of those used by Schumann et al., affected performance in a detection task. The results of the present study were used to calculate color correction factors. These color correction factors were then compared with the color correction factors reported by Schumann et al. and with those mathematically derived from ASTM E 1501.

# METHOD

## Participants

Sixteen paid participants, eight older (mean age = 68.9, ranging from 66 to 73) and eight younger (mean age = 21.6, ranging from 20 to 23), took part in this study. Both age groups were balanced for sex. The participants were recruited from a list of volunteers maintained at UMTRI. All participants were color normal, as determined using pseudoisochromatic plates (Ichikawa, Hukami, Tanabe, and Kawakami, 1978).

## Task

Participants were asked to detect pedestrians walking along a road, both toward and away from them (see Figure 1). The instructions were read to each participant at the beginning of the experiment and during a break between experimental blocks. The exact wording of the instructions was as follows:

> Your task is to indicate when you see a pedestrian walking along the side of the road. A person will be walking toward the car in half of the trials and away from the car in the other half of the trials. The pedestrian will always be marked with retroreflective markings on the lower extremities. Because of this, it will probably be the case that the retroreflective marking will be the first thing that you see as she walks toward the car, and the last thing that you see as she walks away from the car. Your task is to honk the car's horn when that person appears or disappears from view. For example, if the person is walking toward your vehicle, she will start at a distance far beyond your ability to see her. When you are able to see her, honk the horn. During the trials that the person is walking away from your car, honk the horn when she is no longer visible. Please respond as quickly as possible after you see the pedestrian in the trials in which she is walking toward the car and equally as quickly when she walks away from your car and disappears from view.

## Experimental site and materials

The experiment was conducted on the entrance drive to a local golf course (which was closed at night). The road was straight and relatively flat. Participants sat in the driver's seat of a 1993 midsize sedan with its low-beam headlamps on. The headlamps were properly aimed, and four jacks were placed under the car to insure that the vertical aim remained constant across participants. Neutral density filters (0.6 ND, 25% transmission) were placed over the vehicle's headlamps in order to reduce the length of road that was illuminated. This was performed to accommodate the range of stimuli to be examined, and to permit the use of a moderate length of roadway (just over 200 m). The experiment was conducted at nighttime with dry pavement. Other than the test vehicle's headlamps, there were no light sources (vehicular or fixed) present in the immediate vicinity. The illuminance at the retroreflective samples, as provided by the low-beam headlamps (with neutral density filters), was approximately as follows: 1.04 lux at 50 m, 0.35 lux at 75 m, 0.21 lux at 100 m, 0.13 lux at 125 m, and 0.11 lux at 150 m.  The vehicle's windshield and headlamps were cleaned at the beginning of each evening.

Retroreflective stimuli were mounted on the lower legs of a pedestrian at a height of approximately 25 cm from the ground.  The stimuli were located on the front of the pedestrian's right leg (for trials in which the pedestrian walked towards the test vehicle), and on the back of the left leg (for trials in which the pedestrian walked away from the test vehicle).

Figure 1.  A diagram of the experimental setup.

Three experimenters were involved in collecting the data.  One experimenter sat in the car with the participant in order to read instructions and communicate via CB radio with another experimenter acting as the "pedestrian."  The third experimenter assisted the "pedestrian" in changing the retroreflective stimuli and in recording data.

**Stimuli**

A total of eight stimuli were presented by combining four levels of color (green, yellow, red, white) with two levels of retroreflective power (low and high). The retroreflective stimuli measured 35 mm horizontally x 23 mm vertically. At a viewing distance of 100 m, the horizontal subtended visual angle of the targets was 1.2 minutes of arc. Table 1 displays the measured retroreflective power of the stimuli in terms of their specific intensity per unit area (SIA). The stimuli were measured at an entrance angle $\beta = -4^\circ$ and an observation angle $\alpha = 0.2^\circ$. Table 2 lists the chromaticity coordinates (CIE 1931) for the test stimuli.

Table 1
Retroreflective power (SIA) of test stimuli.

| *COLOR* | *LOW SIA (cd/lux/m²)* | *HIGH SIA (cd/lux/m²)* |
|---|---|---|
| Green | 30.5 | 115 |
| Yellow | 47 | 182 |
| Red | 51 | 130 |
| White | 40 | 153.5 |

Table 2
CIE 1931 chromaticity coordinates (x,y) of the test stimuli.

| *COLOR* | *LOW SIA* | | *HIGH SIA* | |
|---|---|---|---|---|
| | *x* | *y* | *x* | *y* |
| Green | .252 | .589 | .251 | .601 |
| Yellow | .578 | .423 | .512 | .421 |
| Red | .684 | .312 | .686 | .310 |
| White | .457 | .410 | .462 | .417 |

**Design**

There were sixteen trials for each participant (the combination of four levels of color, two levels of SIA, and two replications). Trials were randomized within two blocks, one block of low SIA stimuli and one of high SIA stimuli. The order of presentation of the blocks was balanced across participant age and sex. Each block lasted approximately ten minutes, with a five minute break between blocks.

## Procedure

After completing a color-vision screening, participants were driven to the test location, approximately five minutes from UMTRI. Upon arrival at the entrance to the test location, participants were seated in the stationary test vehicle. The test vehicle was parked in the right lane of the roadway. While participants were dark adapting (for approximately 10 minutes), the instructions were read to them, and questions were answered by the experimenter present in the vehicle.

Each trial began with a darkly dressed pedestrian starting at a distance that was far beyond the participant's ability to see either the pedestrian or the retroreflective stimulus, which was located on the front of her right leg. The pedestrian would begin by walking toward the participant and continue until the participant honked the car horn to indicate the pedestrian's detection. The pedestrian would immediately note her distance from the participant, to the nearest meter, using markings positioned along the edge of the roadway. The pedestrian would then walk ten meters closer to the participant, such that the retroreflective stimulus was well within view. The pedestrian then turned and began to walk away from the participant, only now with an identical stimulus visible on the back of her left leg. The pedestrian continued walking until the participant honked the car horn to indicate that neither she nor the retroreflective stimulus on the back of her left leg was visible. Again, the pedestrian noted her distance from the participant to the nearest meter. The pedestrian always walked approximately 0.3 m from the right-hand edge of the roadway, regardless of the direction of travel.

## RESULTS

Two analyses were performed on the obtained detection distances. The first analysis was performed because the SIA values of the stimuli used in the study were not perfectly matched across colors. It included modeling detection distances for the actual retroreflective markings as a function of SIA, and interpolating to find, for a single SIA value, the distances at which stimuli of different colors would be detected. The second analysis involved calculating color correction factors, and comparing them with the results from Schumann et al. (1996), as well as with mathematically derived correction factors from the ASTM E 1501 standard.

### Interpolated detection distances

For each participant, mean detection distance was computed for each combination of stimulus color and SIA. Then, individually for each participant, mean detection distance was regressed on SIA for each combination of stimulus color and SIA. An analysis of variance on the slope parameters from the regression analyses revealed no significant difference between the slopes associated with participant detection distances for stimulus color. Consequently, it was decided that one slope, across the four levels of stimulus color, could be imposed on the lines fit independently for each participant.

Linear regression of mean detection distance on SIA was used to fit lines for each color independently for each participant, with the constraint that for each participant all four colors had the same slope. The mean SIA, across all colors (93.6 cd/lux/m^2), was then calculated and used to interpolate detection distances corresponding to that single SIA value for each color. This was done independently for each participant. See Figure 2 for example data for one participant. For one participant the fitted slope was low, and therefore she was an outlier in terms of the resulting interpolated values. Her data were therefore excluded from the following analyses, although her raw detection distances were consistent with the general trend across subjects (that chromatic stimuli were detected at different distances than achromatic stimuli).

An analysis of variance was performed on the detection distances that were derived by interpolation. The analysis incorporated one within-subject variable (retroreflective color) and two between-subjects variables (age and sex).

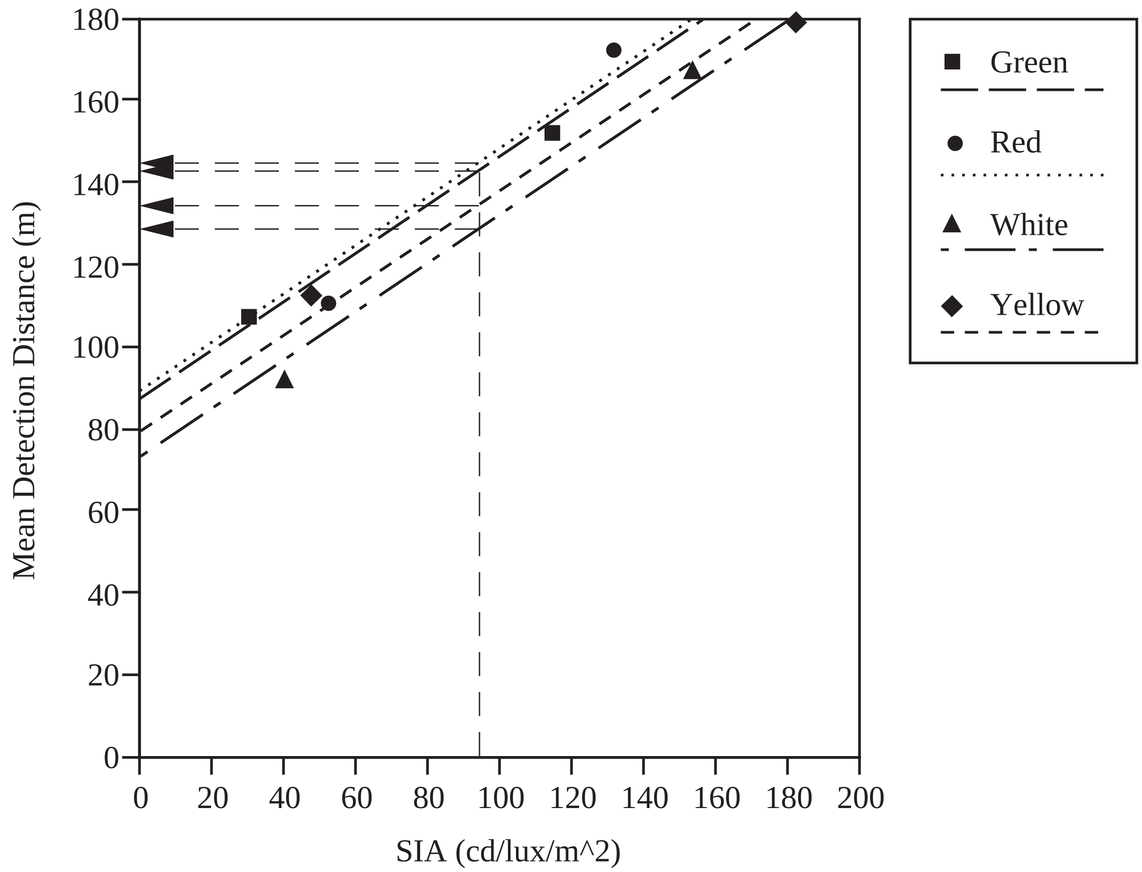


Figure 2. Example data from one arbitrarily selected participant. A linear regression of mean detection distance on SIA was used to generate lines for each color for each participant, with the constraint that for each participant all four colors had the same slope. Note that because of the equal-slopes constraint, the model lines do not exactly overlie the actual data points. The mean SIA across all levels of color (indicated by the vertical dashed line) was then calculated and used to interpolate detection distances for each level of color (indicated by the horizontal dashed lines), independently for each participant.

**Color**. There was a significant main effect of retroreflective color, $F$ (3,33) = 9.685, $p$ = 0.005. The mean interpolated detection distance for each color is plotted in Figure 3. A post hoc analysis of the mean interpolated detection distances was performed, and a Newman-Keuls test for differences between means showed that all chromatic stimuli (red, yellow, and green) were detected at significantly farther distances than the achromatic stimulus (white) ($p \leq 0.05$). The differences in detection distance between the chromatic and achromatic stimuli ranged from 7 to 10%.

**Age**. The effect of age was significant, $F$ (1,11) = 5.04, $p$ = 0.046. For all levels of color and SIA, younger participants detected the pedestrian at farther distances than did older participants. The older participants' mean interpolated detection distance was 96.5 m (standard deviation = 12.6 m) and the younger participants' mean interpolated detection distance was 115.5 m (standard deviation = 18.3 m), a difference of 16.5%.

**Sex**. The main effect of sex, and the interaction of sex and age were not significant.

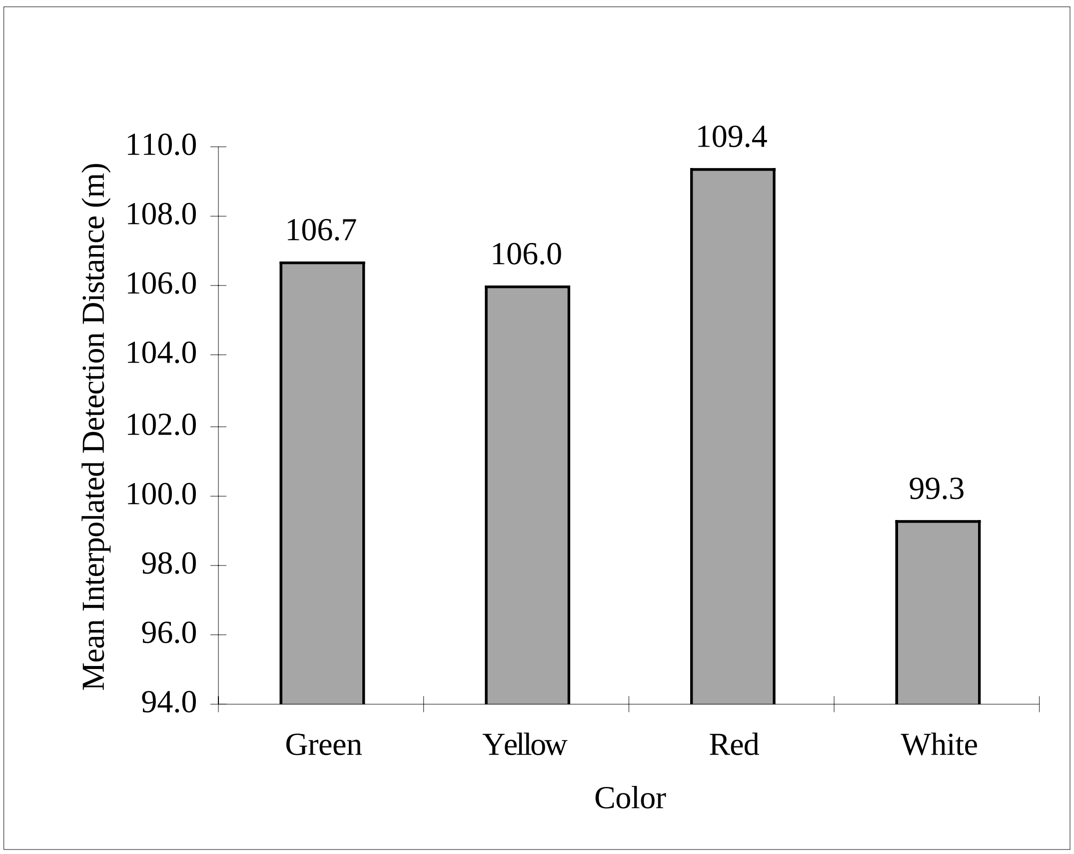


Figure 3. Interpolated detection distance by stimulus color.

**Color correction factors**

Using the same linear model discussed earlier, color correction factors were computed by selecting an SIA of 100 cd/lux/m^2 and interpolating to find the corresponding detection distance for white. An SIA of 100 cd/lux/m^2 was selected because it is near the mean SIA used (93.6 cd/lux/m^2), and it produced interpolated SIAs for the colors that were near the middle of the range of SIAs actually used in this experiment. Using the detection distance for white, SIAs for the chromatic stimuli (red, green, and yellow) were found by interpolation (see Figure 4). Finally, color correction factors were computed by calculating the ratio of the SIA of white (100 cd/lux/m^2) to the interpolated SIAs for each color. This process was applied individually for each participant, and the means of each color correction factor were calculated.

Table 3 shows the color correction factors ($F_C$) for each color as obtained from the current experiment, the results of Schumann et al. (1996), and ASTM color correction factors (ASTM E

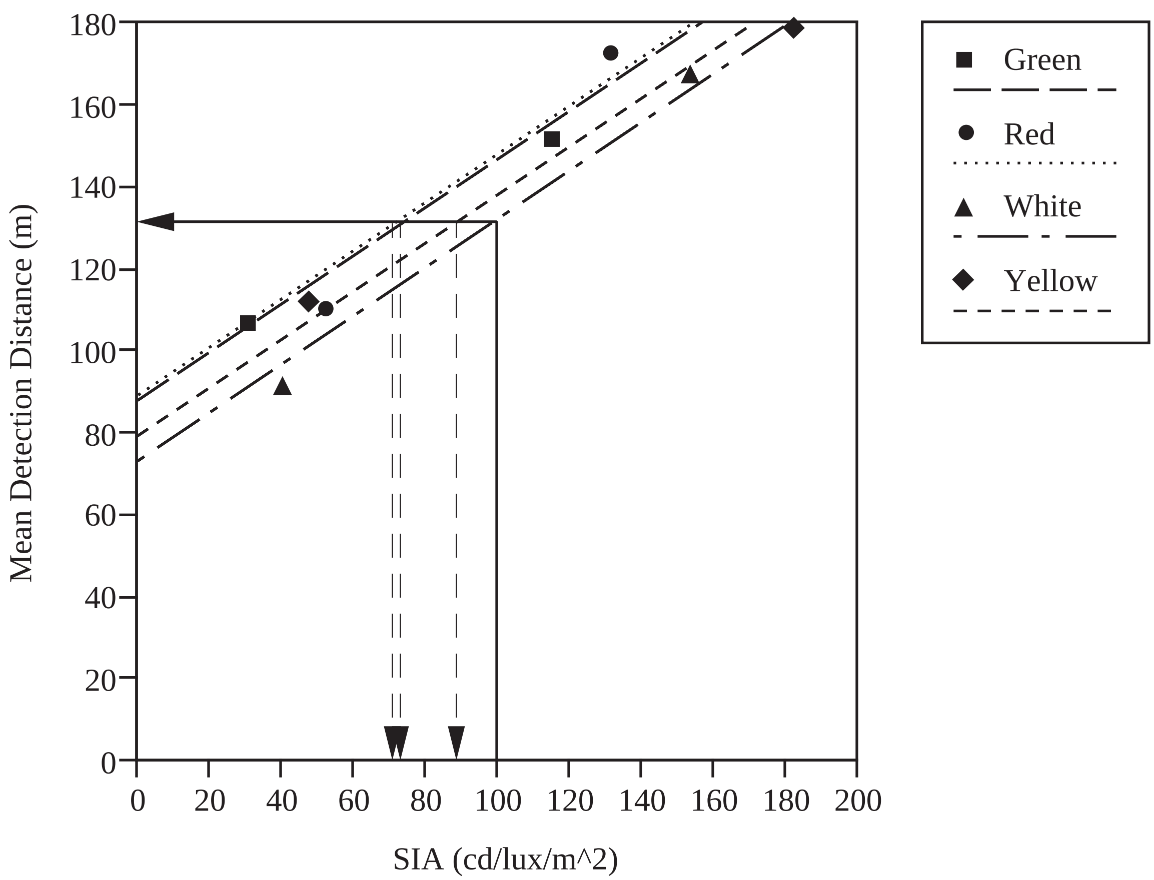


Figure 4. The same data and regression model shown in Figure 2. An SIA for white of 100 cd/lux/m^2 was used to find an interpolated detection distance. This interpolated distance for white was then used to interpolate SIAs for each color (indicated by the vertical dashed lines).

1501, 1992). Figure 5 shows the fit of the $F_C$ values from the current experiment and that of Schumann et al. with the ASTM $F_C$ values. Excellent linear relationships exist between the values of ASTM $F_C$ and those previously reported by Schumann et al. ($R^2$ = 0.95), as well as between the values of ASTM $F_C$ and this experiment ($R^2$ = 0.99), although the slopes for the two sets of experimental results differ markedly.

Table 3
Color correction factors ($F_C$) for retroreflective stimuli.

| *Color* | $F_C$ *Current Experiment* | $F_C$ *Schumann et al. (1996)* | $F_C$ *(ASTM E 1501, 1992)* |
|---|---|---|---|
| Green | 1.37 | 2.17 | 1.77 |
| Yellow | 1.26 | 1.07 | 1.19 |
| Red | 1.44 | 2.56 | 2.28 |

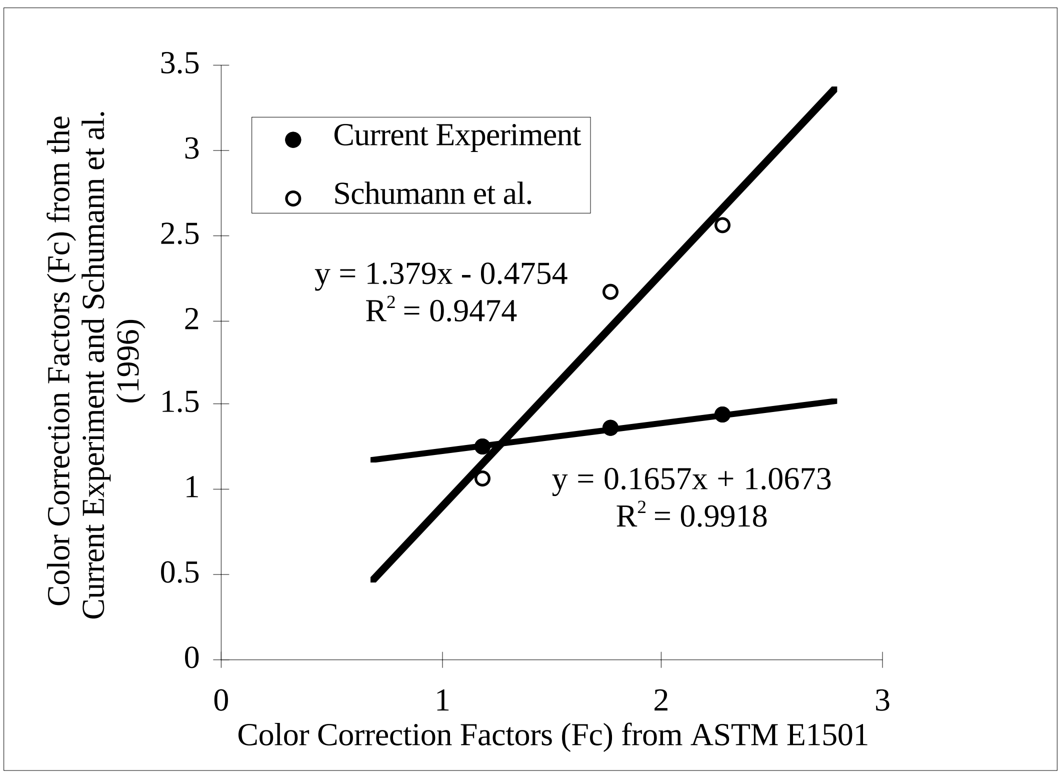


Figure 5. A comparison of color correction factors ($F_C$) from the current experiment and from Schumann et al. (1996) with those based on ASTM E 1501.

## DISCUSSION

### Color

The results of this experiment are generally consistent with those of Schumann et al. (1996), in which chromatic retroreflective stimuli were reported by participants to be brighter than photometrically matched achromatic stimuli. Specifically, in the present study chromatic stimuli were detected 7 to 10% farther away than a photometrically matched achromatic stimulus. Stated another way, to be detected at the same distance as the chromatic stimuli, the achromatic stimulus would require an SIA value 26 to 44% higher. As a result, the nighttime detection of colored retroreflectors cannot be predicted from photometric measurements alone; chromaticity must also be considered. These results are consistent with the Helmholtz-Kohlrausch effect.

### Age

The results showed that, on average, younger participants detected the retroreflective stimuli 16.5% farther away than did older participants. This finding has important implications for the design of retroreflective markings, and the distances at which they are expected to be detected. As the average age of the U.S. driving population increases, the average detection distance for retroreflective targets can be expected to decrease.

### Color correction factors

A strong linear relationship was found between the color correction values of ASTM E 1501 and the color correction factors determined in this experiment. A similar linear relationship was reported by Schumann et al. (1996). In the Schumann et al. study, the primary task was to provide a subjective rating of colored stimuli on perceived brightness. In the current experiment, the primary task involved relatively objective visual performance (detection distance). Differences in the slopes in Figure 5 could be attributable to differences in the tasks. In comparison to the almost one-to-one relationship observed for the perceived brightness task, the detection distance task of the current experiment was not as sensitive to differences in stimulus color as ASTM E 1501 calculations would have predicted. One possible reason for this may be distortion introduced by the use of linear functions to relate detection distance to SIA (as in Figures 2 and 4). Although this simple strategy is probably adequate to estimate qualitative effects of color, it could be causing some distortions in the values of $F_C$ derived from the experimental data.

## CONCLUSION

The main finding of this experiment is a confirmation that nighttime detection of colored retroreflective markings cannot be predicted from photometric measurements alone. The results of the experiment, and the associated modeling, demonstrate that chromatic stimuli are detected at significantly farther distances, 7 to 10%, when photometrically matched with an achromatic stimulus. Further analyses and modeling of the data from this experiment showed that the SIA value of an achromatic stimulus needs to be 26 to 44% higher than the SIA values for chromatic stimuli, under the conditions examined. These results are qualitatively consistent with those of Schumann et al. (1996) and Venable and Hale (1996), where chromatic stimuli were reported by participants to be brighter than a photometrically matched achromatic stimulus; and are in general agreement with the Helmholtz-Kohlrausch effect.

Natural extensions to this experiment might include examining the performance of persons with color vision abnormalities, as has been previously suggested by Venable and Hale (1996), and the inclusion of materials with wider ranges of retroreflective power or color.

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