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FACTORS AFFECTING COLOR CORRECTION OF RETROREFLECTIVE MARKINGS

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16. Abstract

A nighttime field study was conducted to assess the effects of retroreflective material area, distribution, and color on judgments of conspicuity. Participants, seated in a stationary vehicle, took part in a pairwise comparison of the stimuli. The independent variables included retroreflective power, area and distribution of the retroreflective material, color of the retroreflective material, participant age, and participant gender.

The results indicate that color (white, fluorescent yellow-green, and fluorescent red-orange) was a significant factor in the judgment of conspicuity, as might be predicted from the Helmholtz-Kohlrausch effect. In addition, color interacted with the distribution of material at the high level of retroreflective power. The area of the retroreflective material was also significant.

The present study, in agreement with a number of previous studies, indicates that color influences the conspicuity of retroreflective stimuli, but that the results are not always in agreement with color correction factors prescribed in ASTM E 1501. The discrepancy between empirically derived color correction factors seems to be attributable to an interaction of the stimulus size (subtended angle) and color, which previous studies have not extensively examined. To a lesser degree, the retroreflective power of a material also appears to influence conspicuity.

While the ASTM correction factors may be appropriate for intermediate subtended solid angles, particularly for nonsaturated colors, smaller correction factors appear appropriate for markings subtending small angles (approaching point sources), and larger factors for larger subtended angles of saturated stimuli.

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INTRODUCTION

Problem: Crashes Resulting in Nonmotorist Fatalities

Each year in the United States, pedestrians, pedalcyclists, and workers in road construction work zones are killed by motor vehicles because they were not detected in time by the driver of the striking vehicle. In 1999, 4,906 pedestrians were killed, and 85,000 injured, in traffic crashes (U.S. DOT, 2000a). In the same year, 750 pedalcyclists were killed, and 51,000 injured, due to crashes involving motor vehicles (U.S. DOT, 2000b). Of late, in any given year, between 120 to 130 roadway workers die in road construction activities, with 22.7% of these fatalities being pedestrian road workers struck by traffic traveling through a work zone, and 19.4% being pedestrian road construction workers struck by construction vehicles (Laborer's Health and Safety Fund of North America, 1998). While nonmotorist traffic fatality rates per 100,000 population have declined by 35% from 1988 to 1999, nonmotorist fatalities still account for 14% of all traffic fatalities. Much of the decline in nonmotorist fatalities has been attributed to a decline in walking trips during the same period (U.S. DOT, 2000c). Yet pedestrians remain as much as six times more vulnerable to fatality, and twice as likely to suffer an incapacitating injury, than motor vehicle occupants who are involved in crashes (U.S. DOT, 1999). Children and the elderly, in particular, are disproportionately represented in pedestrian fatalities because the former are more likely to walk and the latter are frailer.

In 1997, 90% percent of pedestrian fatalities occurred under normal weather conditions, and 66% occurred in low-light conditions (dusk, dawn, or dark) between the hours of 6 p.m. and 6 a.m. (U.S. DOT, 1999). Among pedestrians aged 21 to 44, 81% of the fatalities occurred in low-light conditions, whereas for pedalcyclists 36% of the fatalities occurred in low-light conditions (U.S. DOT, 1999). In a recent investigation by Sullivan and Flannagan (1999), extensive analyses of the Fatality Analysis Reporting System (FARS) data were performed to isolate the effect that darkness has on traffic accidents, including those resulting in pedestrian fatalities. The authors used two approaches: the first examined seasonal crash fatalities and compared those with seasonal light levels (similar to the technique developed by Owens and Sivak, 1993), and the second approach looked at crash fatalities occurring just prior to and immediately following abrupt light changes due to daylight-saving time. The results from both approaches showed that pedestrian crashes are highly sensitive to light level, more so than any other crash type. This result is consistent with that previously reported by Owens and

Sivak (1993). Sullivan and Flannagan report that pedestrians may be 3 to 6.75 times more vulnerable under dark conditions than they are under daylight conditions.

Countermeasures to Nonmotorist Fatalities at Night

It has been shown that fatalities involving nonmotorists are a significant problem, particularly at night, and a variety of countermeasures have been proposed to reduce these fatalities. Educational and informational campaigns aimed at school-aged children in particular have been credited for significantly reducing the number of child-pedestrian deaths and injuries. However, most of the proposed countermeasures are infrastructure based. (See Insurance Institute for Highway Safety, 1999 for an overview.) While some of the proposed infrastructure-based countermeasures are easily implemented at modest or moderate cost, other countermeasures require substantial restructuring of the roadway environment in order to separate vehicles and pedestrians—thereby eliminating the exposure of pedestrians to vehicular traffic. Unfortunately, many of these infrastructure-based countermeasures are either cost prohibitive or impractical, particularly for rural settings with lower levels of pedestrian traffic and limited infrastructure currently in place.

Perhaps the least expensive countermeasure would be to educate and encourage nonmotorists of all ages to wear high-visibility garments or retroreflective markings when exposed to vehicular traffic. Currently, federal regulations in the United States govern the safety apparel worn by flaggers and road construction workers exposed to public vehicular traffic. Roadway workers are expected to be provided with, and wear, safety apparel. For flaggers, these garments must be reflectorized when used at night (29 CFR 1926.201). For road construction workers, the warning garments may either be reflectorized or made of high-visibility materials (29 CFR 1926.651.) Furthermore, since 1975, the Consumer Product Safety Commission has required bicycle manufacturers to equip new bicycles with a series of retroreflectors in order to aid motorists in the detection of pedalcyclists at night. However, it is very unlikely that any state or federal authority will mandate that pedestrians wear high-visibility or reflectorized garments despite their known safety benefit.

A number of studies in recent years have shown that wearing retroreflective materials, or active light sources, significantly increases the distance at which nonmotorists are detected by drivers. At night, the visibility distance of a dark-clad pedestrian's clothing is less than one-third the distance required to stop for a vehicle traveling 55 mph (88 km/h), and approximately one-half the distance required to stop for a vehicle traveling 35 mph

(56 km/h) (Leibowitz & Owens, 1986). The goal of increasing the detection of nonmotorists at night can be achieved, in part, through use of retroreflective markings on pedestrian garments. Previous research to improve the visibility of pedestrians through use of retroreflective markings has dealt largely with the effects of retroreflective power, marking size, or location of the marking on the nonmotorist. However, several studies that are more recent have begun to concentrate on the effect that the color of these materials has on visibility distance and perceived brightness.

The Effects of Color and Area on Conspicuity

Several studies have previously demonstrated that, when photometrically matched, chromatic stimuli are perceived to be brighter than achromatic (white) stimuli. Furthermore, the brightness ratings follow a U-shaped function of dominant wavelength. This finding is referred to as the Helmholtz-Kohlrausch effect, and was first described in German literature as *Farbenglut* (color glow) and referred to as *florence* (Wyszecki, 1986). The Helmholtz-Kohlrausch effect is defined as "change in brightness of perceived colour produced by increasing the purity of a colour stimulus while keeping its luminance constant within the range of photopic vision" (CIE, 1988). This effect is thought to be the result of the contribution of a chromatic component of the stimulus to its perceived lightness where the level of contribution is different for differing hues (Nayatani, 1997, 1998).

With regard to the effect of color on conspicuity, specifically for retroreflective materials, the Helmholtz-Kohlrausch effect has also been observed in a number of recent research studies (Olson, 1988; Zwahlen & Yu, 1991; Schumann, Sivak, Flannagan, Traube, Hashimoto, & Kojima, 1996; Venable & Hale, 1996; Sayer, Mefford, Flannagan, Sivak, Traube, & Kojima, 1998; Marsh & Tyrell, 1998; Sayer, Mefford, Flannagan, & Sivak, 1999). (See Sayer, Mefford, Flannagan, & Sivak (1999) for summary descriptions of referenced studies). However, the strength of the Helmholtz-Kohlrausch effect that has been observed varies across studies. Sayer et al. (1999) suggested that the differences in the observed magnitude of the effect might be associated with the angular size of the stimulus from the observer's point of view (subtended visual angle).

Findings in the basic literature on color vision suggest that stimulus size, in terms of subtended visual angle, is a critical variable in the perceived brightness of colored stimuli. Specifically, there is evidence that the Helmholtz-Kohlrausch effect is stronger with larger stimuli. Booker (1981) measured the amount of white light required to match chromatic stimuli of various sizes and colors, and found that the amount was higher (corresponding to a stronger Helmholtz-Kohlrausch effect) for larger stimuli. For stimuli that are effectively point sources, the Helmholtz-Kohlrausch effect is considerably reduced (Guth, Donley, & Marrocco, 1969; CIE, 1978; Ikeda & Nakano, 1986). In addition, there is evidence that the Helmholtz-Kohlrausch effect diminishes when illumination is low (Ikeda & Ashizawa, 1991; Stalmeier & de Weert, 1994; Schumann et al., 1996; Sayer et al, 1998 and 1999), but that the degree of the effect seems to depend on a reduction in overall adaptation level.

The Present Study

Under static viewing conditions, the present study addresses the following questions related to the conspicuity of retroreflective materials:

- Is there an effect of stimulus color (i.e., the Helmholtz-Kohlrausch effect) on the judgment of retroreflective conspicuity?
- Is there an effect of the amount of material (area) on the judgment of retroreflective conspicuity?
- Is there an effect of the distribution of material on the judgment of retroreflective conspicuity?
- What is the effect of stimulus size in the present study on calculations of color correction relative to previous studies?

METHOD

Participants

Ten, licensed drivers participated in this study. Each participant was paid $45 for taking part in a two-hour session. Five participants were in an older age group (65-75 years, mean = 69.8 years) and five were in a younger age group (18-22 years, mean = 20.8 years). All participants were recruited from a list of potentially interested persons maintained at UMTRI. The color vision of all participants was screened using pseudoisochromatic plates (Ichikawa, Hukami, Tanabe, & Kawakami, 1978) under controlled lighting conditions (Macbeth® Examolite® D7500). All participants were determined to be color normal by that screening.

Stimuli

Forty-eight stimuli (two identical sets of twenty-four) were constructed from rigid foam covered in matte-gray cotton fabric (CIE 1931 $x = 0.43$ and $y = 0.40$ under tungsten-halogen illumination) with horizontal bands of retroreflective material. Each stimulus measured 600 mm x 550 mm. All retroreflective material was 35-mm-wide stripe of vinyl-backed, microprismatic material. The twenty-four unique stimuli consisted of the orthogonal combinations of three levels of retroreflective color (white, fluorescent yellow-green, and fluorescent red-orange), two levels of retroreflective material area (381.5 and 762.9 cm^2), two levels of retroreflective material distribution (solid or distributed), and two levels of retroreflective power (low R_I and high R_I). Figure 1 displays the configurations of the retroreflective bands corresponding to two levels each of retroreflective area and distribution. Differences in the initial retroreflective power of the materials were reduced by applying neutral density filters to approximate the same level of retroreflectivity across colors.

A Photo Research® 1980A Spectra Pritchard Photometer equipped with TF-80 Tristimulus filters was used to measure the chromaticity coordinates and luminance of the retroreflective materials. The measurements (see Table 1) were taken from the subjects' position while the materials were illuminated by the same source used in the experiment. The coefficients of luminous intensity (R_I) of these materials are also provided in Table 1. The R_I values were calculated by using measured values of R_I at entrance and observation angles of 0.2°/–4.0°, and then equating the stimuli for differences due to the application of neutral density filters. Chromaticity coordinates (CIE 1931) of the fluorescent (Fl) materials are shown in Figure 2.

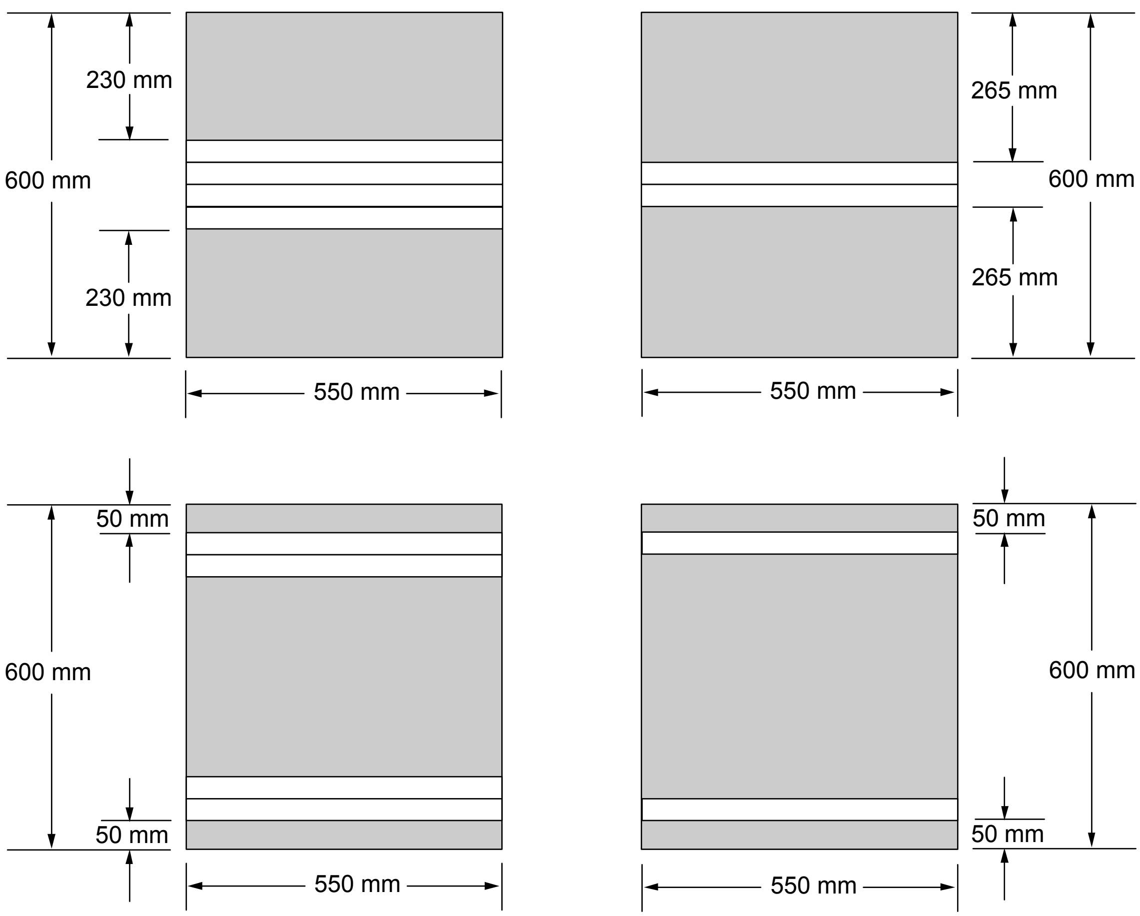

Figure 1. Diagram showing vest configurations and location of retroreflective markings.

Table 1

Chromaticity coordinates (CIE 1931), measured luminance (cd/m^2), and coefficients of luminous intensity (R_I) for the stimulus materials after equating the stimuli for differences in initial R_I by applying neutral density filters.

Retroreflective Material Color	*CIE, 1931 x*	*CIE, 1931 y*	*Measured Luminance (cd/m^2)*	R_I *(cd/lux/m^2)*
Low Intensity				
Fl Red-Orange	0.66	0.32	0.55	9.3
Fl Yellow-Green	0.50	0.49	0.46	9.7
White	0.43	0.41	0.52	10.9
High Intensity				
Fl Red-Orange	0.65	0.33	9.90	167.5
Fl Yellow-Green	0.49	0.49	6.55	135.6
White	0.43	0.43	7.02	152.7

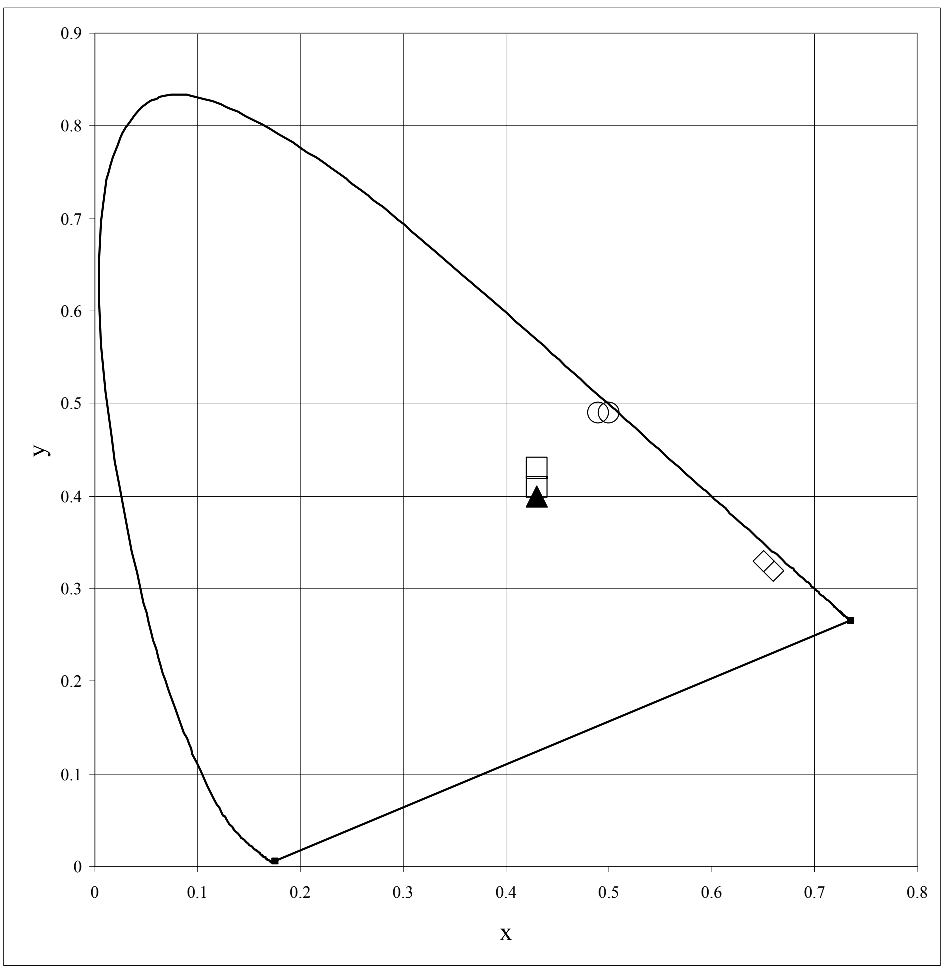

Figure 2. Chromaticity coordinates (CIE 1931) of materials used in the experiment (◇ Fluorescent Red-Orange, ○ Fluorescent Yellow-Green, □ White, ▲ Gray Fabric).

Task and Experimental Setup

This experiment involved a two-alternative, forced-choice task. Participants were presented with all possible pairs of stimuli, one pair at a time (the method of paired comparison), and asked to pick which stimulus of the pair was more "noticeable." The term "noticeable" was used in place of "conspicuous" because it was felt that noticeability was more readily interpretable by participants. Because the two terms are more-or-less equivalent, the term "conspicuous" or "conspicuity" is used throughout the remainder of the document. Participants were given approximately three seconds to view each stimulus pair. Between trials, participants were asked to look downward while the previous stimuli were removed and new stimuli were readied. Instructions to the participants were as follows:

> We are concerned with the noticeability or attention-getting properties of road worker safety vests. Your task is to choose which of the two vests shown is more noticeable. Please note that vest A is always on the left and vest B is always on the right. Please use the letter associated with the most noticeable vest when reporting your response on the data sheet provided. You will be asked to begin each trial by looking downward, toward the floor-board of the car. When instructed, please look up at the vests. You will have three seconds in which to make your assessment. Then, when instructed, please look downward again. Trials will take place in rapid succession. You will be given three practice trials.

Figure 3 provides an overhead view of the experimental setup. The study was conducted in an asphalt-paved parking lot. Participants sat in a late model sedan located 75 m from the stimuli. Participants were run in groups of three or four with two persons seated in the front seats and either one or two persons seated in the rear seats. When two persons were seated in the rear of the vehicle, they sat close enough to one another to have an unobstructed view of the stimuli. The stimuli were mounted 82 cm from the ground, presented against a matte-black background, and separated horizontally from one another by 73 cm, edge to edge. The stimuli were illuminated by two properly aimed, low-beam, tungsten-halogen headlamps that were energized by a 12.8-volt power source and mounted on a rack located 2 m in front of the participants. No other sources of illumination were present during the experiment.

Experimental Design

The experimental design in this study was primarily a within-subjects design in which the independent variables were retroreflector area (381.9 or 762.9 cm^2), distribution of the retroreflective material (solid or distributed), retroreflector color (white, fluorescent yellow-green, or fluorescent red-orange), retroreflective power or R_I (low intensity and high intensity), participant age (younger and older), and participant gender. Stimulus presentation was blocked by the two levels of retroreflective power (high and low intensity). Within each block, the order in which stimulus pairs were presented was randomized.

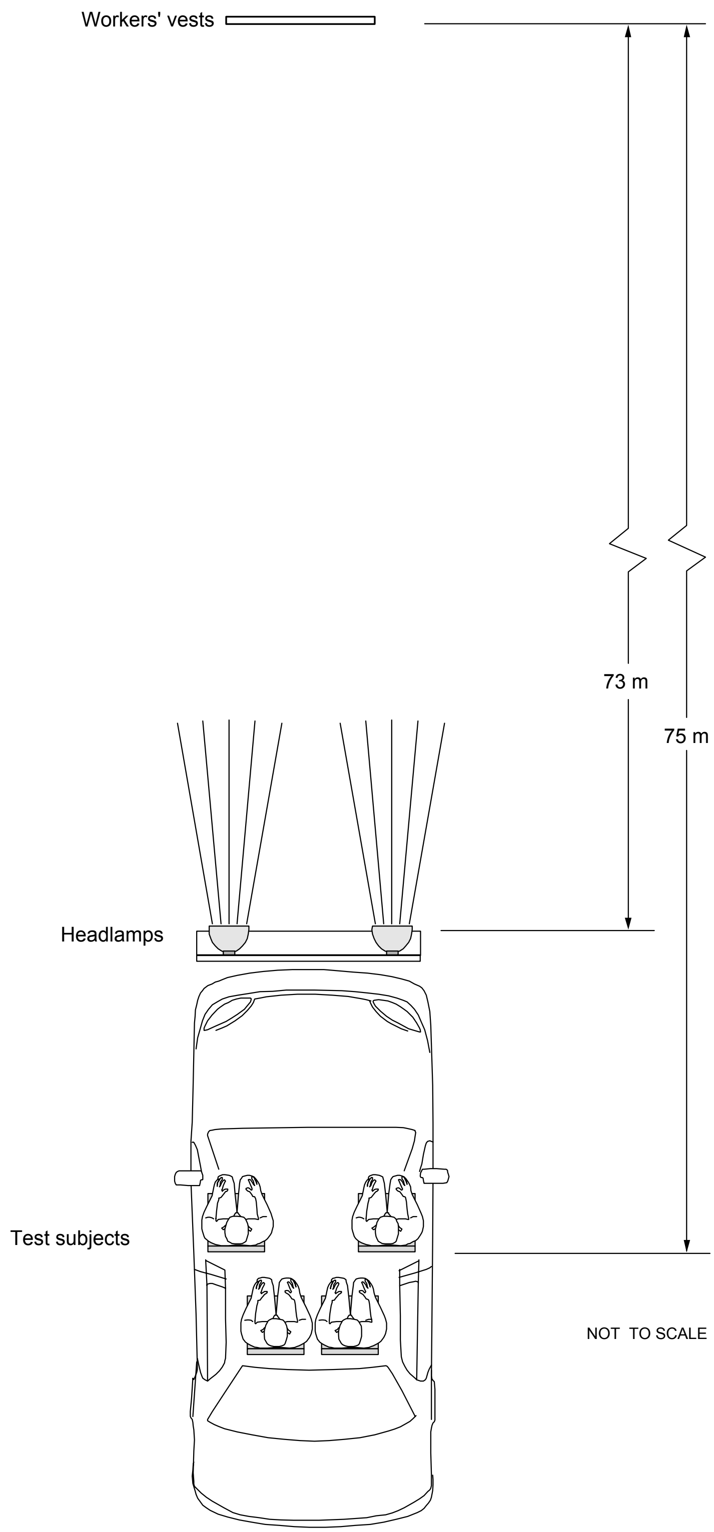

Figure 3. Overhead diagram of the experimental setup.

RESULTS

Outline

Given the extent of the analyses performed, and the number of individual procedures involved, Table 2 provides an outline of the analyses and their purpose.

Table 2
Analysis procedures performed and their purpose.

Thurstonian scaling– to develop interval scales of stimulus conspicuity
Coefficients of consistence – to measure consistency of judgments within a participant in the development of interval scales
Coefficients of agreement – to measure consistency of judgments across participants by examining the level of agreement between individual interval scales
Analytic control for retroreflective power (R_I) – the use of linear regression and interpolation to equate stimuli for differences in retroreflective power that could not be physically controlled
Analyses of variance – repeated-measures ANOVAs, performed separately for the two ranges of stimulus intensity to determine whether differences between scale values are statistically significant
Calculating color correction factors – an analytical approach to relating perceived conspicuity (based on the interval scale values) to customary luminance measures

Thurstonian Scaling Method

Results from the paired comparisons were used to develop two interval scales (representing the blocking of two levels of retroreflective power (R_I)). These scales represent how conspicuous the various combinations of color, area, and distribution of retroreflective material were judged. The method of paired comparisons is based on Thurstone's law of comparative judgment, which postulates that stimulus differences that are detected equally often are subjectively equal. The procedure used (Engen, 1971) relies on calculating the proportion of times any one stimulus is preferred over another, and z scores for these proportions are determined. Then an arbitrary value of zero is established for the lowest of the scores, producing an interval scale of perceived differences among all stimuli. In an interval scale, the intervals between scale values represent differences between the amounts of the property being measured—in this case, conspicuity. The Fahrenheit or Celsius temperature scales are often-cited examples of interval scales. Interval scales do not have an origin that represents an absolute zero amount of the property being measured (in contrast, for example, to the Kelvin scale for temperature). Therefore, interval scale differences represent the size of the difference between stimuli, as well as maintain an ordinal relationship between the stimuli, but they lack an absolute meaning (Gescheider, 1997). The mean interval scale values of conspicuity are show in Figures 4 and 5.

Coefficients of Consistence

Additional analyses performed included examining whether participants were consistent in their judgments of conspicuity. A metric known as the coefficient of consistence (ζ) was calculated independently for each participant. The consistency of participants in their judgments is important in detecting intransitive relationships among stimuli. (For example, stimulus A might be judged more conspicuous than B and B more conspicuous than C, and yet C might be judged more conspicuous than A). If intransitive relationships occur frequently, it is assumed that the task cannot be performed along a single psychological continuum (i.e., there are multiple criteria that are being used in the judgments, and those criteria cannot be combined or they are in conflict with each other). It is necessary to employ multidimensional scaling methods when intransitive relationships occur frequently (David, 1988).

The values of ζ ranged from .65 to .93 for low intensity, and from .68 to .90 for high intensity stimuli. A value of 1.0 indicates complete consistency on the part of a participant. For both intensities, all but one of the scores were .75 or higher (Table 3). The mean values of ζ were 0.82 and 0.81 for the low intensity and high intensity sets of stimuli, respectively. Therefore, individual participants were largely consistent in their judgments, suggesting that under the conditions examined the quality referred to as conspicuity could be judged along a single psychological continuum.

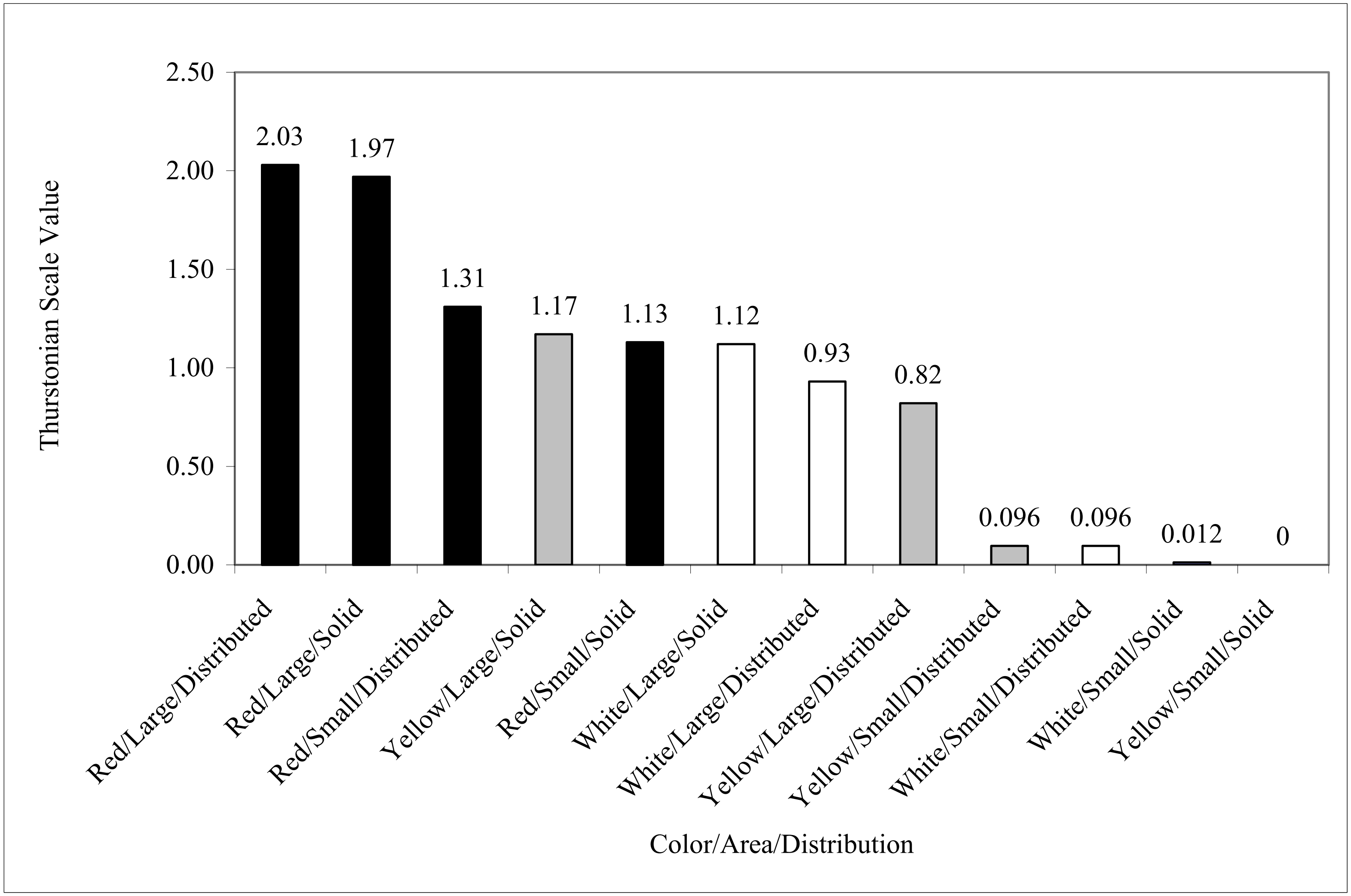

Figure 4. Mean Thurstonian scale values for the low intensity stimuli, all participants.

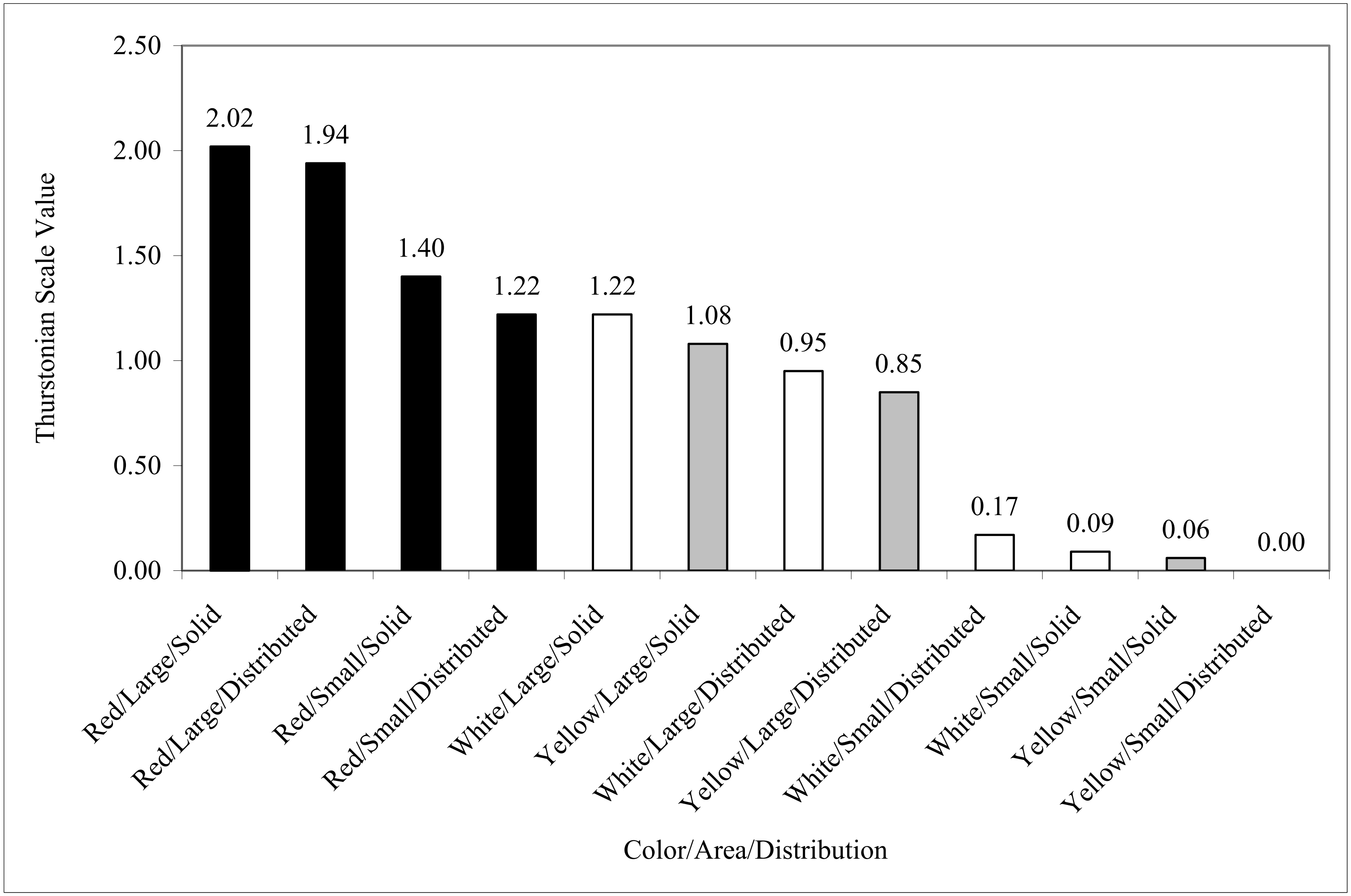

Figure 5. Mean Thurstonian scale values for the high intensity stimuli, all participants.

Table 3
Coefficients of consistence (ζ) by participant and stimulus intensity.

Subject #	Age	Gender	ζ Low Intensity	ζ High Intensity
1	75	F	0.75	0.75
2	65	F	0.65	0.68
3	68	M	0.82	0.82
4	71	M	0.93	0.81
5	18	M	0.87	0.84
6	70	F	0.85	0.85
7	22	F	0.91	0.81
8	22	F	0.83	0.83
9	22	F	0.77	0.84
10	20	M	0.80	0.90
		Mean	0.82	0.81

Coefficients of Agreement

Calculating coefficients of agreement is an analysis technique that permits examining whether judgments of conspicuity were consistent across participants in terms of the ordering of stimuli in the individually developed scales. For both levels of stimulus intensity, a coefficient of agreement (u) was calculated to provide an indication of how much agreement existed across participants. If complete agreement were to be observed, then $u = 1$. As observed agreement among the participants diminishes, u becomes smaller (David, 1988). Because each participant saw each pair of stimuli twice, it was necessary to reduce the data to make use of Kendall's calculations for u, which assumes independence of judgments. The cases in which a participant rated one stimulus of a pair more conspicuous in one trial, but reversed the rating the second trial, were dealt with by randomly selecting which stimulus of the pair was judged more conspicuous. The process of selecting the stimulus at random was completed five hundred times, each time computing a new u. Finally, at each intensity, an average u was computed. The resulting coefficient of agreement for low intensity stimuli was .58 and .53 for high intensity, suggesting that participants agree moderately well on ordering in terms of conspicuity.

Analytic Control for Retroreflective Power (R_I)

Several previous studies have attempted to control for differences in the retroreflective power (R_I) of stimuli either physically, analytically, or both. Schumann et al. (1996) and Sayer et al. (1998 and 1999) attempted both to physically (through use of neutral density filters) and analytically (through use of linear regression and interpolation) equate stimuli having different values of R_I.

The approach in the present study was initially the same as the previous studies. Specifically, neutral density filters were applied to the white and fluorescent (Fl) yellow-green stimuli so that their otherwise high R_I values would be approximately equivalent to the Fl red-orange stimuli. Fortunately, ability to physically equate stimuli for R_I in the present study was better than had been achieved in the previous studies. As a result, there was less need to analytically equate the stimuli in the present study. However, an analysis of variance (ANOVA) performed on the slopes of the calculated regression equations for stimulus color and R_I determined that the slopes across stimuli were not equal. This result further complicated the attempt to equate stimuli using an analytical approach by not permitting a single slope to be imposed in order to perform an interpolation over the entire range of R_I values.

To test that the differences in range of the R_I within the low (9.3 to 10.9) and high (135.6 and 167.5) levels of the retroreflective power variable did not result in drastically different raw Thurstonian scale values, a variation on the interpolation technique was performed. The results were collapsed across levels of stimulus area and, using the resultant linear equation that was fit to those data, an interpolation was performed within each of the ranges of $R_{I.}$ The means for the low and high ranges of R_I, 10 and 152, were entered into the linear equations to produce interpolated Thurstonian scale values associated with stimulus color, R_I, participant age, and gender. An analysis of variance was then performed using the interpolated scale values as the dependent measure, and the result was compared to an ANOVA of the raw scale values. The outcome was that results from the two ANOVAs were virtually identical, and other than those effects involving stimulus area, which had been collapsed, there were no differences in the number or size of the significant effects. As a result, all analyses that follow are based upon the raw Thurstonian scale values that were developed independently for the two levels of retroreflective power.

Analyses of Variance

Repeated measure ANOVAs were performed separately for the two sets of Thurstonian scale values as these scales had been developed independently of one another. The analyses included an adjustment of the degrees of freedom using the Greenhouse-Geisser conservative test (Winer, Brown, & Michels, 1991). Analyses for both the low and high intensity stimuli included five independent variables: three within-subject variables (color, area, and distribution of the retroreflective material) and two between-subject variables (age and gender of the participant). In the discussion below, only statistically significant effects are presented.

Low Intensity. There was a significant main effect of color, $F(1.4,8.3)$, $p < .001$. The Thurstonian scale values for each of the three colors examined are plotted in Figure 6, with Fl red-orange being judged most conspicuous, followed by white. A Student-Newman-Keuls test for differences among means revealed that Fl red-orange was judged significantly more conspicuous than either yellow or white. The difference between Fl yellow-green and white was not significant.

There was also a significant main effect of stimulus area, $F(1.0,6.0)$, $p < .001$, with larger (762.9 cm^2) stimuli being judged to be more conspicuous than the smaller (381.5 cm^2) stimuli (Thurstonian scale values of 1.19 versus .52, respectively). Figure 7 displays this result. There was also an interaction of color and area, $F(1.3,8.0)$, $p = .041$ (Figure 8). A Student-Newman-Keuls analysis revealed that most of the pairwise comparisons were significantly different from one another except for two comparisons, namely the comparisons between the Fl yellow-green and white for both values of stimulus area.

There were no significant main effects of distribution of the retroreflective material, participant age, or participant gender. There were, however, two higher order interactions, namely color by age by gender, $F(1.4,8.3)$, $p = .036$, and color by distribution by area by age, $F(1.2,7.2)$, $p = .037$.

High Intensity. There was a significant main effect of retroreflective color, $F(1.9,11.7)$, $p < .001$. The Thurstonian scale values for each of the three colors examined are plotted in Figure 9. A Student-Newman-Keuls test for differences among means revealed that Fl red-orange was judged significantly more conspicuous than either Fl yellow-green or white. This result is consistent with the main effect of color found in the low intensity condition.

There was also a significant main effect of stimulus area, $F(1.0,6.0)$, $p < .001$ (Figure 10). Consistent with the results from the low intensity stimuli, larger stimuli were judged more conspicuous than smaller stimuli (mean Thurstonian scale value of 1.19 versus .48).

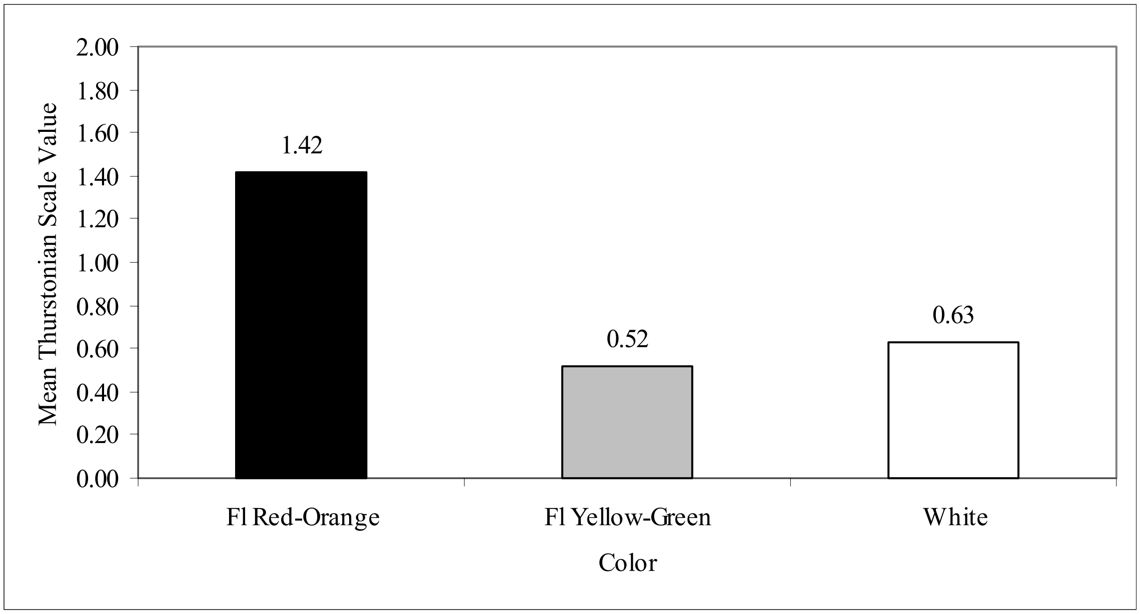

Figure 6. Mean Thurstonian scale values by color for low intensity stimuli.

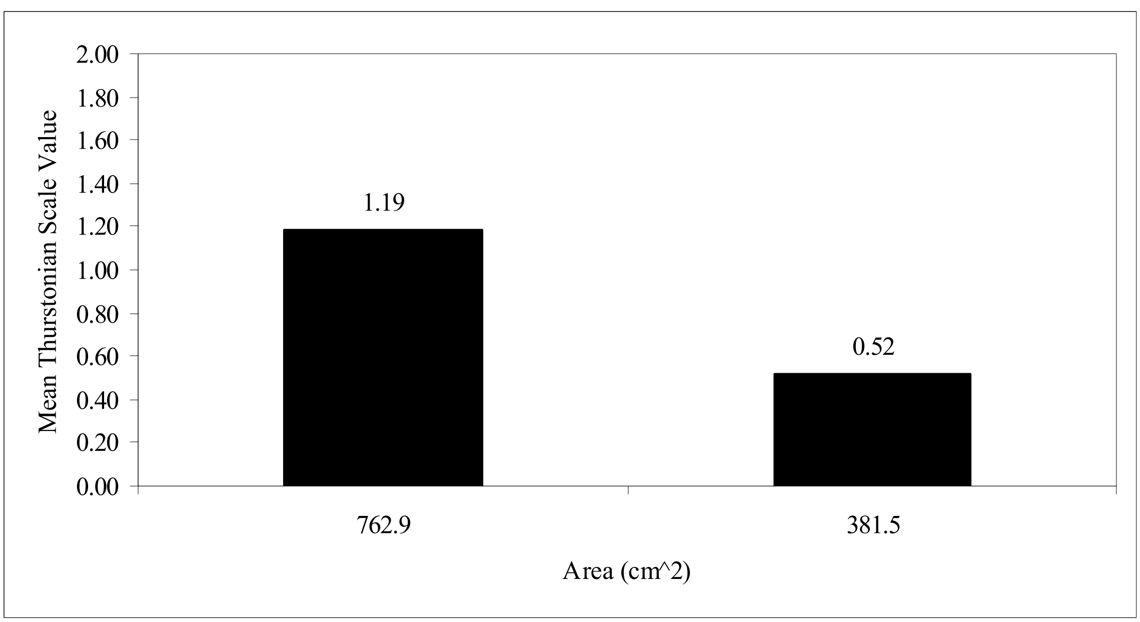

Figure 7. Mean Thurstonian scale values by area for low intensity stimuli.

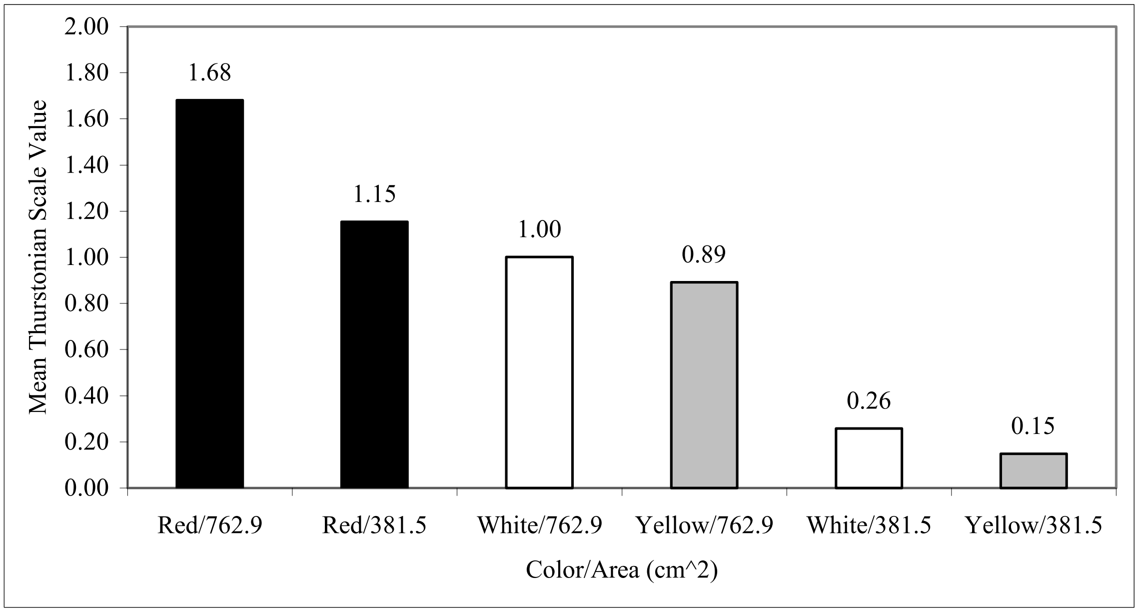

Figure 8. Mean Thurstonian scale values for the interaction of color and area for low intensity stimuli.

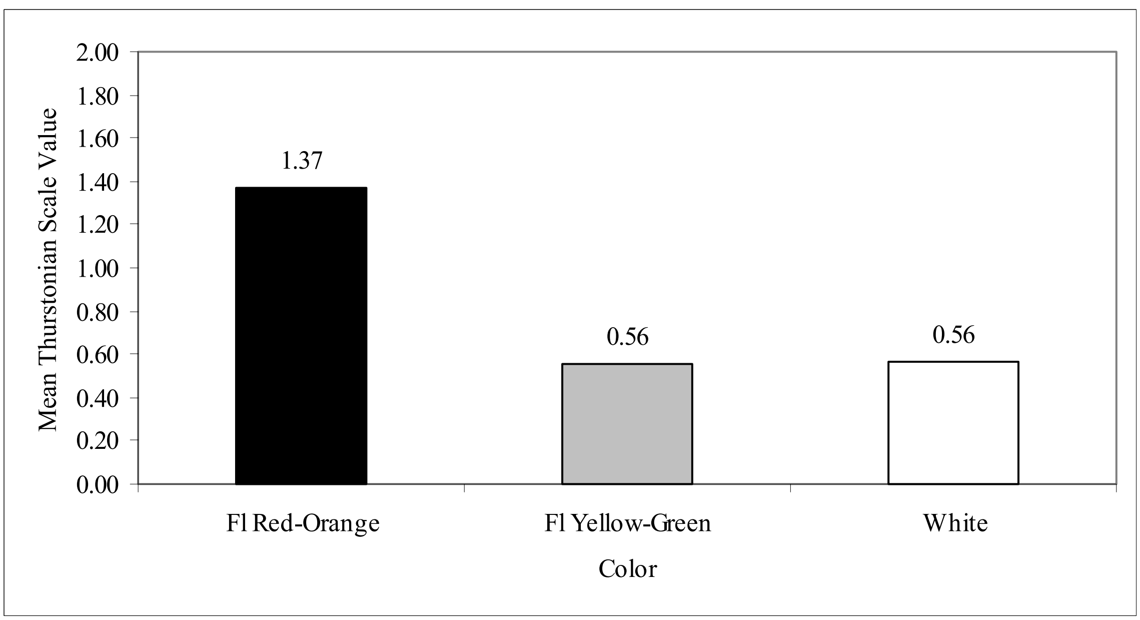

Figure 9. Mean Thurstonian scale values by color for high intensity stimuli.

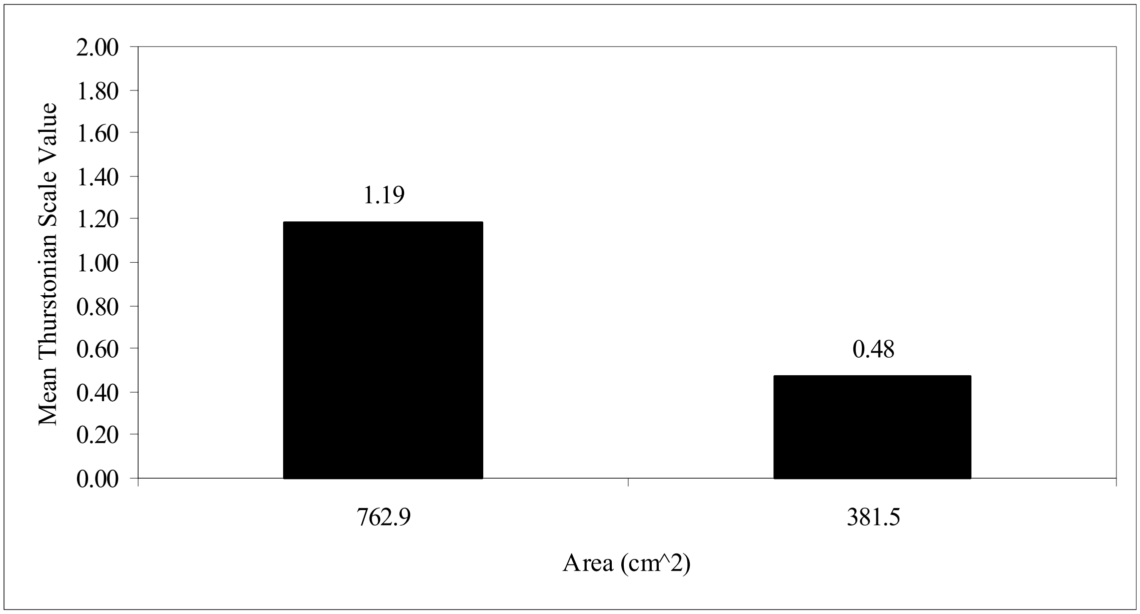

Figure 10. Mean Thurstonian scale values by area for high intensity stimuli.

There were no main effects due to distribution of the retroreflective material, participant age, or participant gender in the high intensity condition. There were, however, two statistically significant interactions of color and distribution, $F(1.9,11.6)$, $p = .005$, and area and distribution, $F(1.0,6.0)$, $p = .026$. A Student-Newman-Keuls analysis revealed that all but three combinations of color and distribution were significantly different from one another. The three combinations not significantly different from one another were: white/solid and Fl yellow-green/solid, white/distributed and Fl yellow-green/distributed, and Fl red-orange/solid and Fl red-orange/distributed (Figure 11). A Student-Newman-Keuls analysis of the interaction of area and distribution revealed that with the exception of the 381.5/solid and 381.5/distributed, all pairwise comparisons were significantly different from one another (Figure 12).

Additionally, there were two significant higher-order interactions of the following: color by distribution by age, $F(1.9,11.6)$, $p = .045$, and color by distribution by area by age by sex, $F(1.3,7.8)$, $p = .042$.

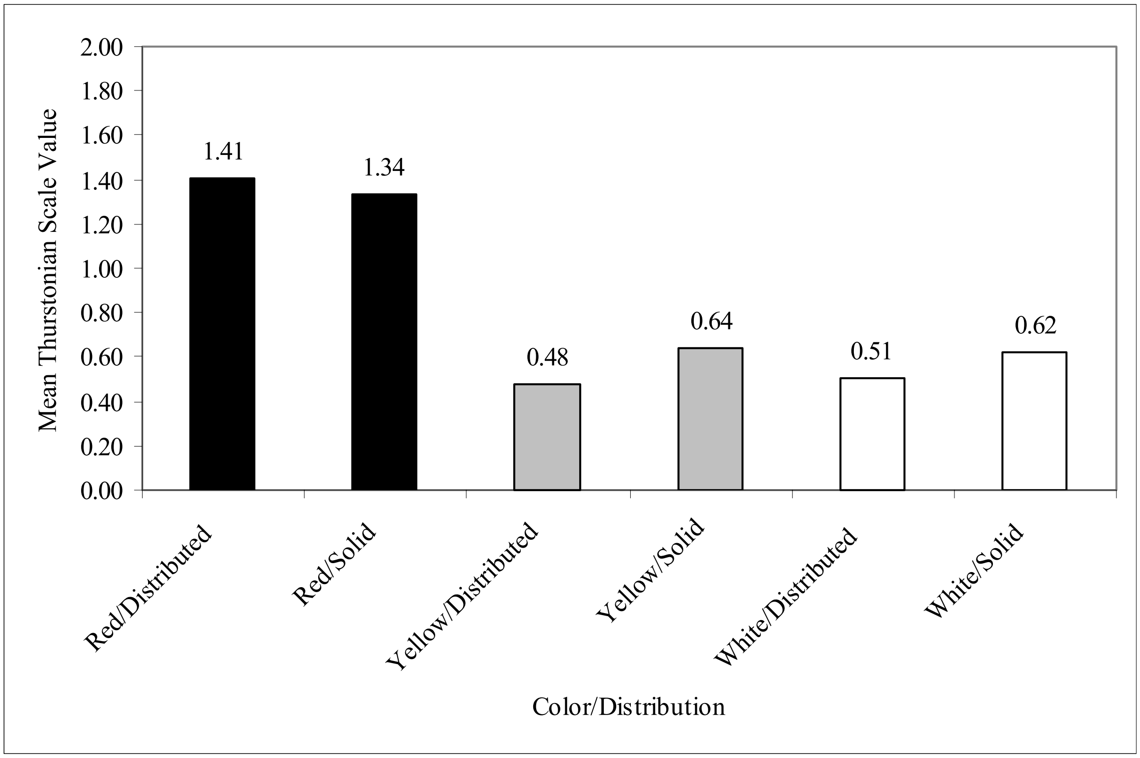

Figure 11. Mean Thurstonian scale values for the interaction of color and area for high intensity stimuli.

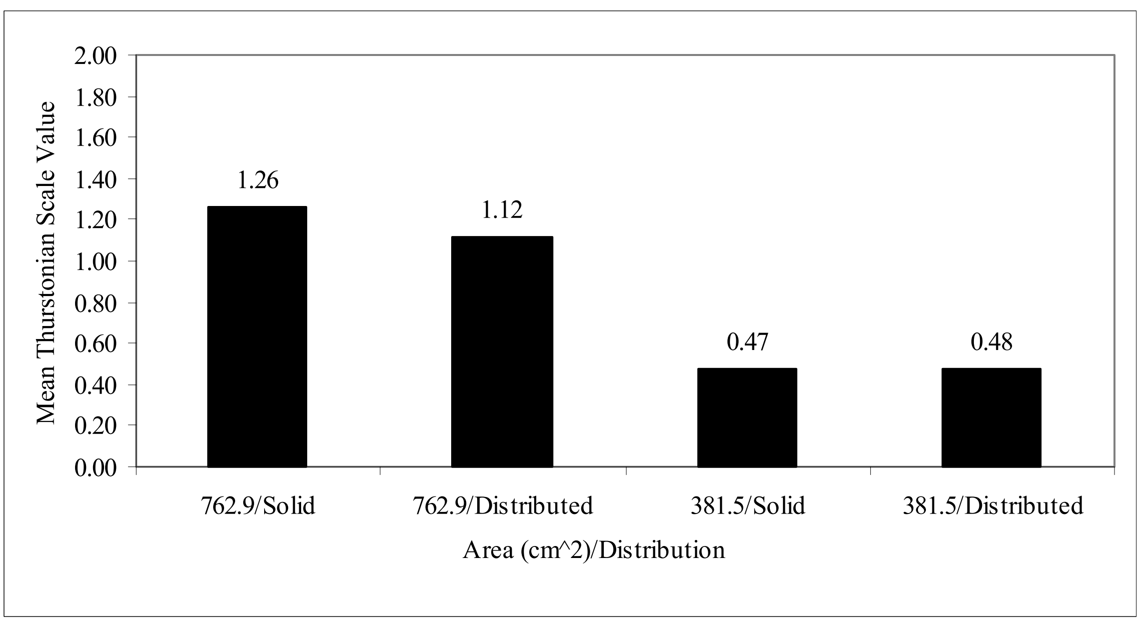

Figure 12. Mean Thurstonian scale values for the interaction of area and distribution for high intensity stimuli.

Calculating Color Correction Factors

The efficiency of retroreflective material is often expressed in terms of retroreflective power (R_I or SIA). However, it may also be expressed in terms of the coefficient of retroreflectivity (R_A or CIL) that takes in account the amount, or area, of the retroreflective material. CIL values were calculated for all combinations of color and area using the following equation:

$$C = S*A$$

Where,
C is CIL in cd/lux
A is area in m^2
S is SIA in cd/lux/m^2

Using the Thurstonian scale values previously calculated for each participant, these scale values were regressed on computed values of log CIL (performed separately for each of the two levels of intensity). For each combination of color and intensity, an average regression line was computed by averaging the slopes and intercepts of participants' individual regression lines. The slope and intercept data from the regression lines were examined to determine whether they were normally distributed to decide if using average slope and intercept data was justified. A normal probability plot (Q-Q plot) that compares expected percentile values with actual percentile values is one way to approximate normality. The Q-Q plots of the slope and intercept values revealed that the data appeared normally distributed. Therefore, color correction factors, F_c, could then be calculated separately for the two levels of intensity.

Color correction factors were calculated by selecting CIL values of .4, .6 and .8 cd/lux for low intensity stimuli and 6, 9, and 12 cd/lux for high intensity stimuli. All of these values fell within the range of the CIL values employed in this experiment (i.e., there was no extrapolation of the data). The selected CIL values were then used to interpolate and find the corresponding Thurstonian scale value for white. Using the Thurstonian scale value for white, CIL values for Fl red-orange and Fl yellow-green were found by interpolation (see Figure 13). Next, color correction factors were computed by calculating the ratio of the CIL value of the comparable white stimulus to the CIL values for Fl red-orange and Fl yellow-green. Lastly, for each combination of color and intensity, using the results of the interpolation, average CIL values were calculated for Fl red-orange and Fl yellow-green.

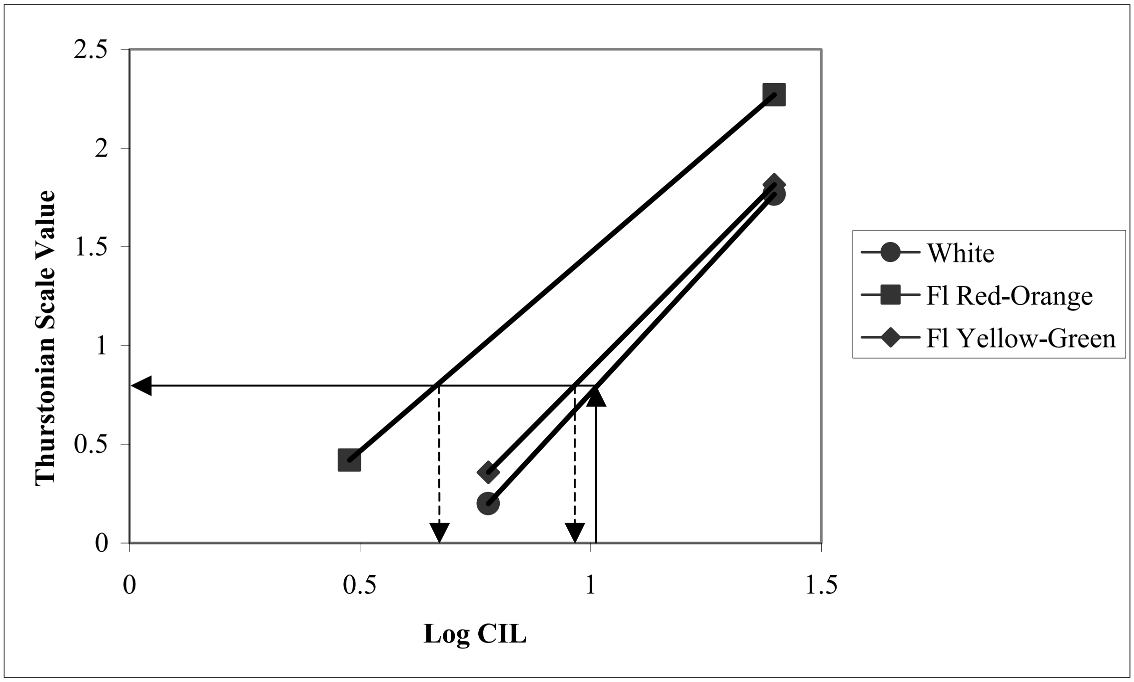

Figure 13. Example data demonstrating an interpolated Thurstonian scale value for white being used to interpolate CIL values for Fl red-orange and Fl yellow-green (indicated by the vertical dashed lines).

The calculated color correction factors (F_c) for Fl red-orange and Fl yellow-green are presented separately for the low and high levels of intensity in Table 4. The differences in F_c values due to intensity are quite small in comparison to the differences due to color. The differences in chromaticity between the levels of intensity, but within color, are similarly quite small. As a result, in the interest of simplicity and comparability with previous studies, the calculated F_c values were collapsed (averaged) across levels of intensity to produce two color correction factors, one each associated with either Fl red-orange or Fl yellow-green.

Table 4
Calculated color correction factors (F_c) for the present study.

Retroreflective Material	*CIE, 1931 x*	*CIE, 1931 y*	F_c
Low Intensity			
Fl Red-Orange	0.66	0.32	3.67
Fl Yellow-Green	0.50	0.49	1.07
High Intensity			
Fl Red-Orange	0.65	0.33	3.95
Fl Yellow-Green	0.49	0.49	1.13

Table 5 presents the reported values of F_c for red and yellow stimuli across several studies. It should be noted, however, that only the stimuli in the present study are known to be made of fluorescent retroreflective material. The stimuli used in the studies by Schumann (1996) and Sayer et al. (1998 and 1999) were not fluorescent materials. Nevertheless, there is considerable agreement across studies in the calculated values of F_c for yellow and Fl yellow-green stimuli. However, there is a great deal of variation in the F_c values across studies for the red and Fl red-orange stimuli (Figure 14).

Table 5
Color correction factors (F_c) for retroreflective stimuli.

Color	F_c *Present Study*	F_c *Sayer et al. (1999)*	F_c *Sayer et al. (1998)*	F_c *Schumann et al. (1996)*	F_c *(ASTM E 1501, 1992)*
Yellow	1.11	1.12	1.26	1.07	1.19
Red	3.81	1.22	1.44	2.56	2.28

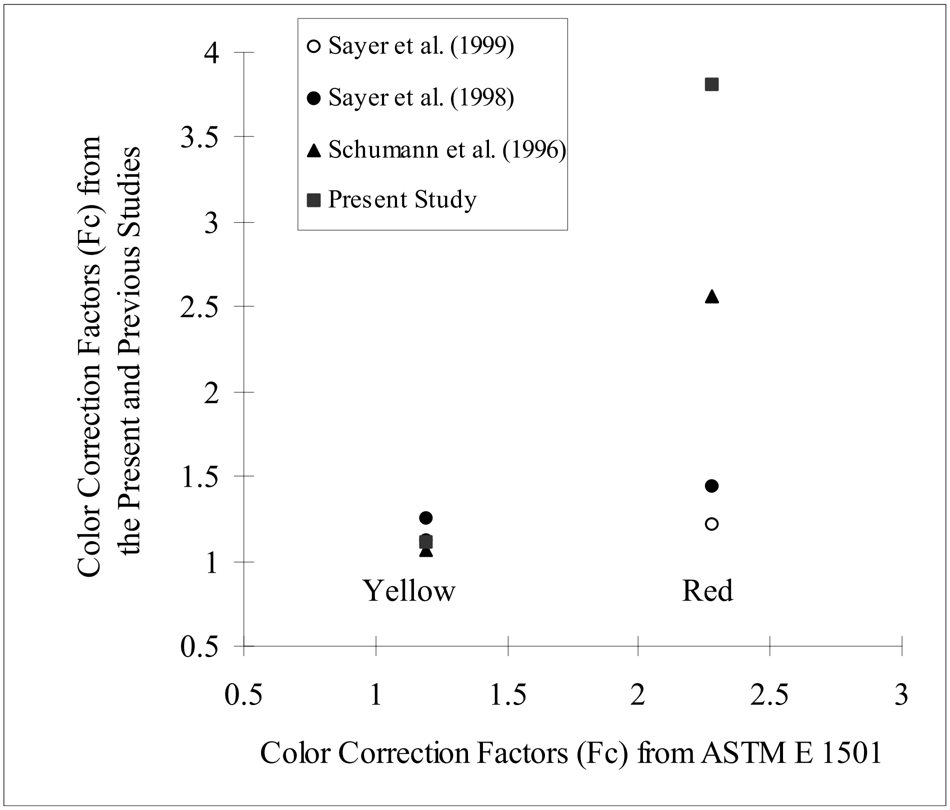

Figure 14. A comparison of color correction factors (Fc) for yellow or fluorescent yellow-green and red or fluorescent red-orange stimuli from the present study, Sayer et al. (1999), Sayer et al. (1998), and Schumann et al. (1996) with those based on ASTM E 1501.

DISCUSSION

The results of this study, in combination with the results of previous studies, have important implications for specifying the photometric requirements of retroreflective materials based on judged conspicuity. The implications of the effects of the two independent variables that were introduced in this study (the amount of retroreflective material used (area) and the distribution of the retroreflective material) will first be discussed, and then, at greater length, the effects of color and the subtended visual angle of a stimulus will be addressed. The overall conclusion of the present and previous studies is that the values of the color correction factors in ASTM E 1501 are not valid under all conditions of interest for determining the conspicuity of retroreflective materials.

The Area and Distribution of Retroreflective Material

The effects of retroreflective material area and distribution from the present study are as follows: area had a significant effect on judgments of conspicuity, but distribution did not.

The two levels of area used, 381.5 and 762.9 cm^2, were selected so that the range encompassed the areas specified by ANSI/ISEA 107-1999 for Class 1 and Class 2 safety garments for one side of a garment. It was clearly the case in all instances that the larger area was judged by participants in the present study to be more conspicuous. While this result is not surprising, the magnitude of the effect was larger than what might have been expected. This result supports the concept that larger areas of retroreflective material on safety garments will make the garment more conspicuous than a lesser amount of the same material.

Area interacted with retroreflective color to produce an unexpectedly large effect, in a direction consistent with the Helmholtz-Kohlrausch effect. For both the low and high intensity stimuli, the Thurstonian scales that resulted showed that more than twice as much white or Fl yellow-green retroreflective material was needed to be as conspicuous as the Fl red-orange material. Stated another way, half as much Fl red-orange material is more conspicuous than either white or Fl yellow-green.

While the result of the distribution variable was not significant, the material was not nearly as distributed as it could have been. Had the same amount of material been distributed in the form of a checkerboard pattern, for example, the result of the Thurstonian scaling may have been different. However, given the wide variety of possible distribution arrangements, the distribution variable is worthy of investigation(s) on its own. Additional factors that have been previously shown to affect the conspicuity of pedestrians wearing retroreflective materials, such as locating the material on the joints of the person (Owens et al., 1994; Luoma, et al., 1995), should also be considered in such an effort.

The Interaction of the Subtended Solid Angle and Color of Retroreflective Material

A primary concern in this study was the relative conspicuity of retroreflective materials of different colors, which we have expressed in terms of the color correction factors used in ASTM E 1501, F_C. Previous studies have reported differing effects of retroreflective color, and therefore different values of F_C, for both subjective and objective tasks. Table 4 and Figure 6 of the present report summarize the level of agreement of a number of these studies—including the present one—with the specific values of F_C prescribed in ASTM E 1501 for yellow/fluorescent yellow-green and red/fluorescent red-orange stimuli. While all of these studies support the use of color correction factors for saturated stimuli, the differences are especially pronounced between the results from the present study and from the two previous studies conducted by Sayer and his colleagues. For example, the ASTM correction factor in Table 4 indicates that to be equally effective as a white retroreflective marking, red or fluorescent red-orange markings should have photometric values lower than the white by a factor of 2.28 (i.e., the red value would be 44% of the white value). In contrast, the results of the present study suggest that the ratio should be 3.81 (26%), while two previous studies by Sayer et al. suggested factors that were much more modest (1.22 and 1.44, or 82 and 69%, respectively).

In discussing the results of Sayer et al. (1998), it was speculated that the discrepancy in size of the color correction factors with ASTM E 1501 might be caused by differences in the tasks used, as studies with similar tasks had previously yielded results more closely in agreement with the ASTM values (Schumann et al., 1996; Venable & Hale, 1996). However, when Sayer et al. (1999) essentially replicated the discrepancy, it seemed appropriate to consider a difference associated with the experimental task more seriously. ASTM values are supported by subjective judgments about the relative conspicuity of stimuli that were clearly above detection threshold (Venable & Hale, 1996). The ASTM numbers are also supported, at least approximately, by the results of Schumann et al. (1996), which involved a task that should perhaps be considered very similar to that of Venable and Hale: subjective brightness ratings of above-threshold stimuli. In contrast, the task involved in the studies by Sayer et al. (1998 and 1999) was to indicate the detection threshold, in terms of distance, for retroreflective markings worn by a moving pedestrian.

Thus, of the four studies that explicitly investigated the effect of color on the relative conspicuity of retroreflective markings, two employed subjective judgments with above-threshold stimuli and found relatively high color correction factors in general agreement with ASTM values (Schumann et al., 1996, and Venable & Hale, 1996), and two employed relatively objective measurements of detection thresholds and found relatively low color correction factors that could be considered not to be in agreement with ASTM values (Sayer et al., 1998, and Sayer et al., 1999). What then differed among the four studies that might account for the differences in recommended values of F_C?

Sayer et al. (1999) identified at least three aspects of experimental method that were consistently different across these two pairs of studies, and thus might account for the differing outcomes: (1) the tasks involved either subjective ratings or objective performance, (2) stimuli were either at detection threshold or well above, and (3) because of a combination of differences in viewing distance and stimulus size, the subtended solid angles of the stimuli in the detection-distance studies were considerably smaller than in the other two studies (Schumann et al., 1996, and Venable & Hale, 1996). The present study involves the subjective judgments of stimuli well above threshold, similar to the Schumann et al. and Venable and Hale experimental conditions, yet the resulting color correction factor for the saturated fluorescent red-orange stimulus is considerably larger than the red correction factors reported by Schumann et al. or Venable and Hale. Therefore, only one of the three aspects of the experimental method remained different that might account for such large discrepancies in the reported color correction factors: the subtended solid angles of the stimuli.

The Schumann et al. (1996) study involved one fixed viewing distance and two stimulus sizes, yielding subtended solid angles of 4.25 and 17.0 min^2. The Venable and Hale (1996) study involved one stimulus size and two fixed viewing distances. The angular sizes of the stimuli are somewhat difficult to define because each stimulus consisted of two horizontal stripes rather than a solid area, similar to one level of the distribution variable in the present study (in both instances the intent was to resemble the striped retroreflective markings that might be found on a safety vest or jacket). If the dimensions of a rectangle just enclosing the stimuli are used to compute the subtended solid angles, the values are 89 and 22 min^2. If only the combined areas of the two stripes are considered, the values are 49 and 12 min^2. In the interest of simplifying our analyses, the latter approach is taken.

In the 1999 study by Sayer et al., the average detection distance for the central viewing condition (102.5 m) represented a subtended solid angle of 0.90 min^2, and the subtended angles of Sayer et al. (1998) were similarly small. In the present study, the subtended solid angle is dependent on the area occupied by the retroreflective material, its viewing distance, and possibly the distribution of retroreflective material. However, regardless of whether one assumes the subtended angle is the rectangle just enclosing the stimuli or the combined areas of the two stripes, the stimuli in the present study remain considerably larger in subtended solid angle than any of the four previous studies. Again, in the interest of simplicity, the combined areas of two stripes used in the present study will be used in determining the subtended solid angle. Therefore, in the present study, the stimuli subtended either 81.7 or 161.8 min^2.

Having determined a means of equating the subtended solid angle of the stimuli across studies, values of subtended angle were plotted against the color correction factors (F_C) associated with the yellow/fluorescent yellow-green and red/fluorescent red-orange stimuli. What resulted was a moderately good linear fit between values of F_C and subtended solid angle (R^2 = .66) for the saturated (red/fluorescent red-orange) stimuli. The same attempt to fit a line to the yellow/fluorescent yellow-green values resulted in a very poor fit (recall that the value of F_C for yellow and fluorescent yellow-green stimuli has not exceeded 1.26). However, the relative difference in the size of the F_C values for the red/fluorescent red-orange stimuli with the associated subtended solid angles did not appear linear. There appeared to be a diminishing effect on increasing the subtended solid angle of the stimulus with resulting increases in F_C. As a result, a logarithmic fit of the subtended angle with F_C values was examined, and the fit did in fact improve considerably to R^2 = .81 (Figure 15).

Recalling that physical and analytical attempts to equate the retroreflective power of the stimuli in the individual studies had been performed, it was decided to attempt to equate stimuli across the independent studies. To do so, the values of the subtended solid angle were divided by a measure representing the relative retroreflective power of the stimuli (logCIL) for each red/fluorescent red-orange stimulus across those four studies that reported values of retroreflective power (Schumann, 1996; Sayer, 1998 and 1999; present study). The result was an excellent logarithmic fit, R^2 = .96, between values of F_C and subtended solid angle (Figure 16). This result suggests that the retroreflective power of the material does contribute to judgments of conspicuity for retroreflective stimuli, but to a lesser degree than has been observed with color saturation.

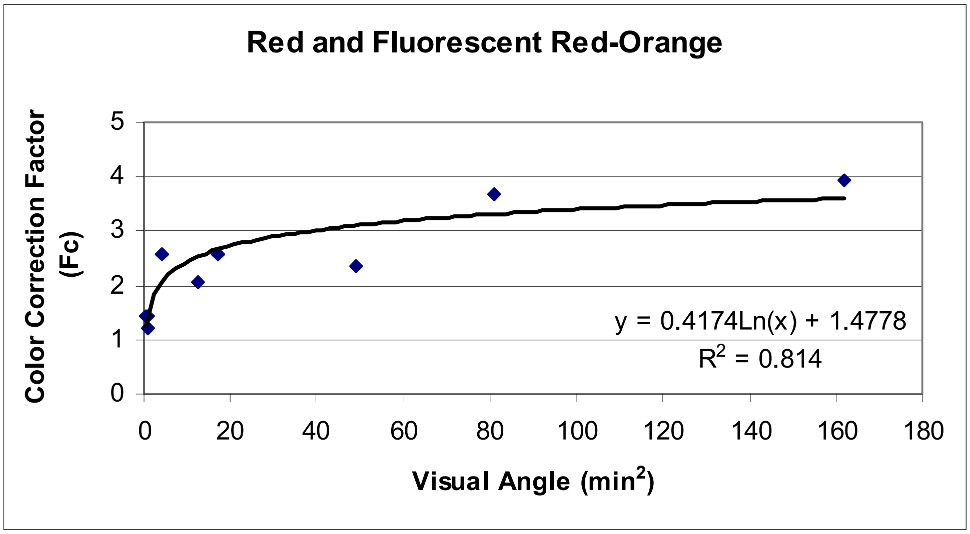

Figure 15. A plot showing a logarithmic fit of subtended solid angle and calculated color correction factors (F_c) for red/fluorescent red-orange stimuli presented in five independent studies (Schumann, et al., 1996; Venable & Hale, 1996; Sayer, et al., 1998; Sayer, et al., 1999; and the present study).

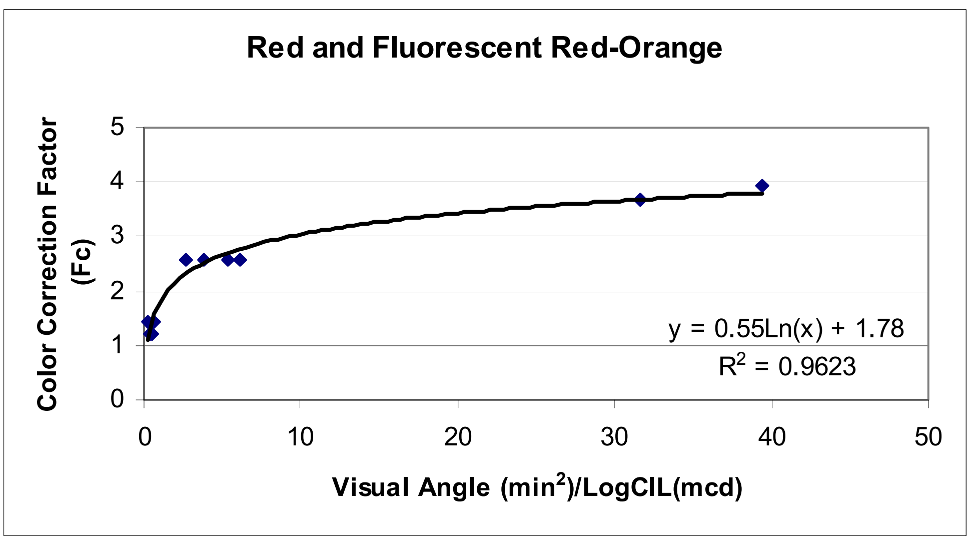

Figure 16. A plot showing a logarithmic fit of subtended solid angle, with a correction for differences in CIL values, and calculated color correction factors (F_c) for red/fluorescent red-orange stimuli presented in four independent studies (Schumann, et al., 1996; Sayer, et al., 1998; Sayer, et al., 1999; and the present study).

Thus, it appears that differences in the subtended solid angle of the stimuli largely account for the discrepancies in calculated color correction factors (F_c) reported in various studies. Although this is a tentative explanation, it is worth considering what practical implications this would have for the color correction factors prescribed in ASTM E 1501. Whether color correction factors should be applied, or what their magnitude should be, would therefore depend on what assumptions are made about the subtended angles of the retroreflective markings at the point at which they first must be detected or recognized. Relatively large correction factors would be applied—reflecting the expectation of a relatively large Helmholtz-Kohlrausch effect—when the stimuli were saturated and could be expected to be reasonably large in terms of subtended angle when first detected. When the subtended angles are smaller, in the range used in the studies and by Sayer et al. (1998 and 1999), or the stimulus was not saturated, smaller color correction factors would be used.

However, given the tentative nature of this discussion, further research on the effects of stimulus subtended angle, color, and retroreflective power should be conducted before accepting any of these arguments as definitive.

CONCLUSIONS

The results of this study indicate that within a given range of CIL values for retroreflective markings (such as one might expect to observe on a pedestrian, pedalcyclist, or roadworker), the distribution of the material, age of the participant, and gender of the participant do not affect judgments of stimulus conspicuity. These results are consistent for all three colors of retroreflective material examined (white, fluorescent yellow-green, and fluorescent red-orange). However, the amounts of material (area) examined in this study did have a significant effect on judgments of conspicuity—with more material resulting in what was judged to be a more conspicuous stimulus. The amounts of retroreflective material examined in this study were approximately equal to those amounts specified in ANSI/ISEA 107-1999 for Class 1 and Class 2 garments, suggesting that the additional materials required for a Class 2 garment do in fact improve its conspicuity relative to a Class 1 garment.

The present study and a number of previous studies indicate that color influences the conspicuity of retroreflective stimuli, as would be expected because of the Helmholtz-Kohlrausch effect, but that the results are not always in agreement with color correction factors prescribed in ASTM E 1501. The discrepancy between the empirically-derived color correction factors seems to be largely attributable to an interaction of the stimulus size (subtended solid angle) and color of the retroreflective marking. To a lesser degree, the actual retroreflective power (CIL (R_A) or SIA (R_I)) of the material will also influence the conspicuity of these materials. The ASTM correction factors may be appropriate for intermediate subtended solid angles, particularly for non-saturated colors, but smaller correction factors appear appropriate for markings having very small visual angles (approaching point sources). Similarly, larger correction factors seem appropriate for larger subtended angles of saturated stimuli. However, the overall influence of color and its interaction with subtended angle has not been fully characterized by the present or previous studies, and a more comprehensive study on the effects of retroreflective material color, size, and retroreflective power is needed.

REFERENCES

ASTM E 1501 (1992). *Standard specification for nighttime photometric performance of retroreflective pedestrian markings for visibility enhancement*. Philadelphia, PA: American Society for Testing and Materials.

Booker, R. L. (1981). Luminance-brightness comparisons of separated circular stimuli. *Journal of the Optical Society of America*, *71*, 139-144.

Commission International de l'Eclairage. (1978). *Light as a true visual quantity: Principles of measurement* (CIE Publication No. 41). Vienna: Central Bureau of the CIE.

Commission Internationale de l'Eclairage. (1988). *International lighting vocabulary* (CIE Publication No. 17.4). Vienna: Central Bureau of the CIE.

David, H. A. (1988). *The method of paired comparisons*, Second Edition (Stuart, A., Ed). London: Charles Griffin & Company.

Engen, T. (1971). Psychophysics II. Scaling Methods. In *Woodworth & Schlosbergs' Experimental Psychology*, Third Edition (Kling, J. W. and Riggs, L.A., Eds.). New York: Holt, Reinhart and Winston, Inc.

Gescheider, G. A. (1997). Psychophysics: The fundamentals, Third Edition. Mahwah, NJ: Lawrence Erlbaum Associates.

Guth, S. L., Donley, N. J., & Marrocco, R. T. (1969). On luminance additivity and related topics. *Vision Research*, *9*, 537-575.

Ichikawa, H., Hukami, K., Tanabe, S., & Kawakami, G. (1978). *Standard pseudoisochromatic plates. Part 1. For congenital color vision deficits*. Tokyo: Igaku-Shoin.

Ikeda, M., & Ashizawa, S. (1991). Equivalent lightness of colored objects of equal Munsell chroma and of equal Munsell value at various illuminances. *Color Research and Application*, *16*, 72-80.

Ikeda, M., & Nakano, Y. (1986). Spectral luminous-efficiency functions obtained by direct heterochromatic brightness matching for point sources and for 2° and 10° fields. *Journal of the Optical Society of America, A*, *3*, 2105-2108.

Insurance Institute for Highway Safety (1999). Special Issue: Pedestrian Injuries. *Status Report, 34 (3)*, Arlington, VA.

Leibowitz, H. W. & Owens, D. (1986). We drive by night. *Psychology Today*, *20* (1), 55-58.

Laborer's Health and Safety Fund of North America (1998). *Fatal Occupational Trauma Among LIUNA Construction Laborers 1988-1989*. Author: Washington, D.C.

Luoma, J., Schumann, J., & Traube, E. C. (1995). Effects of retroreflector positioning on nighttime recognition of pedestrians. *Accident Analysis and Prevention, 28*, 377-383.

Marsh, D. K., & Tyrell, R. A. (1998). Detectability and perceived brightness of commercially available colored retroreflective materials at night. In, *Proceedings of the Human Factors and Ergonomics Society 42nd Annual Meeting* (p. 1633). Santa Monica, CA: Human Factors and Ergonomics Society.

Nayatani, Y. (1997). Simple estimation methods for the Helmholtz-Kohlrausch effect. *Color Research and Application*, *22*, 385-401.

Nayatani, Y. (1998). A colorimetric explanation of the Helmholtz-Kohlrausch effect. *Color Research and Application*, *23*, 374-378.

Olson, P. L. (1988). *Minimum requirements for adequate nighttime conspicuity of highway signs* (Report No. UMTRI-88-8). Ann Arbor: The University of Michigan Transportation Research Institute.

Owens, D. A., Antonoff, R. J., & Francis, E. L. (1994). Biological motion and nighttime pedestrian conspicuity. *Human Factors*, 36(4), 718-732.

Owens, D. A. & Sivak, M. (1993). *The role of reduced visibility in nighttime road fatalities.* (Report No. UMTRI-93-33). Ann Arbor, MI: The University of Michigan Transportation Research Institute.

Sayer, J. R., Mefford, M. L., Flannagan, M. J., Sivak, M., Traube, E. C., & Kojima, S. (1998). *Effects of retroreflective marking color on pedestrian detection distance*. (Report No. UMTRI-98-8). Ann Arbor, MI: The University of Michigan Transportation Research Institute.

Sayer, J. R., Mefford, M. L., Flannagan, M. J., & Sivak, M. (1999). *Effects of retroreflective marking color on the detection of pedestrians by normal and color deficient drivers*. (Report No. UMTRI-99-6). Ann Arbor, MI: The University of Michigan Transportation Research Institute.

Schumann, J., Sivak, M., Flannagan, M., Traube, E. C., Hashimoto, H., & Kojima, S. (1996). *Brightness of colored retroreflective materials* (Report No. UMTRI-96-33). Ann Arbor, MI: The University of Michigan Transportation Research Institute.

Stalmeier, P. F. M., & de Weert, C. M. M. (1994). On the conditions affecting the contribution of colors to brightness perception. *Color Research and Application*, *19*, 192-201.

Sullivan, J. M. & Flannagan, M. J. (1999). *Assessing the potential benefit of adaptive headlighting using crash databases*. (Report No. UMTRI-99-21). Ann Arbor, MI: The University of Michigan Transportation Research Institute.

U. S. Department of Transportation (1999). *Transpiration statistic annual report 1999*, Bureau of Transportation Statistics, BTS99-03, Washington, DC.

U. S. Department of Transportation (2000a). *Traffic safety facts 1999: Pedestrians*. Report DOT HS 809 094, National Center for Statistics and Analysis, National Highway Traffic Safety Administration. Washington, DC.

U. S. Department of Transportation (2000b). *Traffic safety facts 1999: Pedalcyclists*. Report DOT HS 809 093, National Center for Statistics and Analysis, National Highway Traffic Safety Administration. Washington, DC.

U. S. Department of Transportation (2000c). *Traffic safety facts 1999: A compilation of motor vehicle crash data from the Fatality Analysis Reporting System and the General Estimates System*. Report DOT HS 809 100, National Center for Statistics and Analysis, National Highway Traffic Safety Administration. Washington, DC.

Venable, W. H., & Hale, W. N. (1996). Color and nighttime pedestrian safety markings. *Color Research and Application*, *21*, 305-309.

Winer, B. J., Brown, D. R., & Michels, K. M. (1991). Statistical principals in experimental design (3rd ed.). New York: McGraw-Hill.

Wyszecki, G. (1986). Color appearance. In Boff, K. R., Kaufman, L., & Thomas, J. P. (Eds.) *Handbook of perception and human performance. Volume I: sensory processes and perception.* New York: Wiley-Interscience.

Zwahlen, H. T. & Yu, J. (1991). Color and shape recognition of reflectorized targets under automobile low-beam illumination at night. *Transportation Research Record*, No. 1327, 1-7.