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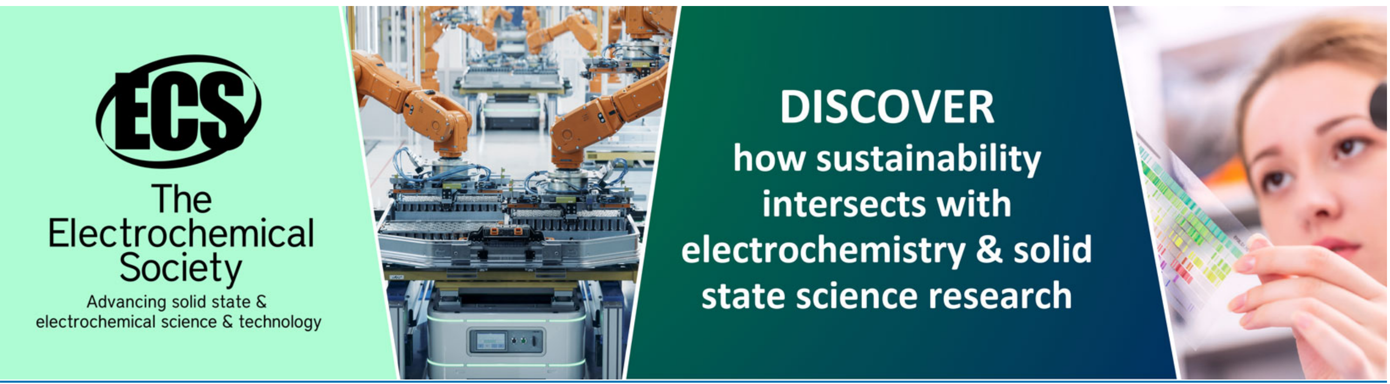

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Evaluation of retro-reflective coating performance by reflectance and perceived relative brightness measurements

Kaiva Luse[1,2], Anete Pausus[1], Varis Karitans[1,2], Maris Ozolins[1], Madara Tukisa[1]

[1]University of Latvia, Optometry and Vision Science Dept., Ķengaraga street 8, Riga LV-1063, Latvia
[2]Institute of Solid State Physics, University of Latvia, Ķengaraga street 8, Riga LV-1063, Latvia

kaiva.luse@gmail.com

Abstract. Retro-reflective properties of six types and five different colors or retro-reflective materials were discussed in this paper. Reflectance optical indicatrix of samples was determined and compared to obtained psychophyisical data of perceived brightness of human observer. Microscopic structure of the retro-reflective active regions of RR's was studied. Statistically significant differences in reflectivity and brightness of various types and colors of RR's were found.

1. Introduction

Conditions of reduced visibility have a huge impact on the rate of road traffic accidents. Retro-reflective materials are widely used in road traffic to improve safety (e.g., warning signs on the road, road markings, bicycle equipments, pedestrian clothing, etc).

Retro-reflector (RR) is a surface that reflects most of the incident light back towards its source. There are two basic structures of RR's – corner cube and cat's eye (first uses specular reflection principle and the other – refraction principle) [1]. Best possible choice of RR material and positioning on pedestrian's body can reduce drivers' noticing time interval of the RR material and recognition time interval of the pedestrian, cyclist, sign, road marking [2,3]. Generally commercially available retro-reflective materials lack instructions on usage and the average purchaser lacks knowledge on their performance and constructive differences.

Various methods have been proposed for measuring perceived brightness of different color RR's [4] and changing the coefficient of retro-reflectivity [5]. It has been shown [5] that increase of coefficient of retro-reflectivity corresponds to increase of perceived brightness of RR for a human observer however perception reveals strong nonlinearity and chromatic adaptation to visual stimulus.

It has been shown that the structure of RR affects the reflection coefficient of the sample [6]. The aim of this study was to evaluate how the structure of RR and the size of structural elements impact the optical indicatrix and perceived brightness of the sample. The obtained perceptual data and intensity data were compared.

2. Method

In total six monochromatic (white) samples of different types of RR's were evaluated:

1) 3M™ Scothlite™ (microscopic glass bead RR), abbreviation in text: 3M.

2) $3M^{TM}$ Diamond $Grade^{TM}$ (micro-prismatic RR, prism directions are alternated), abbreviation in text: DG.
3) Micro-prismatic RR (manufacturer Chief-Light Co, Ltd), abbreviation in text: MP.
4) $3M^{TM}$ Diamond $Grade^{TM}$ Translucent (wide angle prismatic lens translucent reflective sheeting), abbreviation in text - DGT.
5) Macroscopic glass bead RR from a traffic cone (abbreviation in text: GB).
6) Macroscopic prism RR (commonly used in bicycles), abbreviation in text: Bike-RR.

In total five different colors of one type of RR - micro-prismatic Chief-Light Co (MP RR) were evaluated (color coordinates in RGB color space given in brackets, st.error less than 2%):

1) White (x=0.433; y=0.412);
2) Yellow (x=0.452; y=0.498);
3) Green (x=0.341; y=0.592);
4) Orange (x=0.543; y=0.378);
5) Red (x=0.577; y=0.344).

For reflectance studies rectangular RR's with total area of 18 ± 0.5 cm^2 were used. For psychophysical studies pairs of round RR's with diameter of 6.5 ± 0.2 cm were used.

3. Experiment setup

The experiment was based on finding if the type or color of RR sample significantly affect it's retro-reflectance optical indicatrix. The measurement of reflectivity was measured by tilting the RR with step of 1 degree (see Fig.1A). The entrance angle 0^o here and further in text means normal incidence. Illumination of RR at normal incidence was 1000 lx (luxmeter Konica Minolta T-10M was used). The reflected light intensity and color coordinates were measured by Konica Minolta CS-100A chroma-meter. Distance from source of light to sample was 0.9 ± 0.02 m, from detector to sample – 1.14 ± 0.02 m. Reflectance at entrance angles from 0 to 78 degrees was recorded 5 times for each setup.

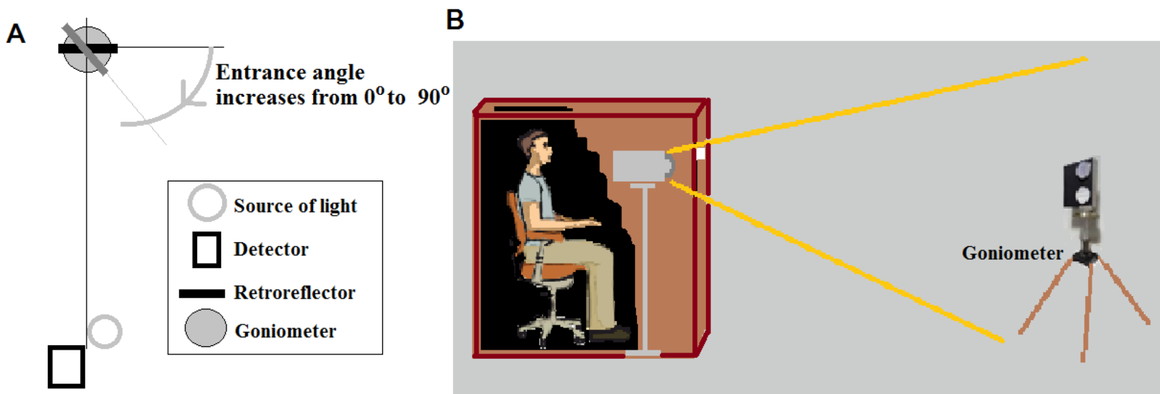

Figure 1. A – The geometry of experimental setup (from above) for evaluating reflection optical indicatrix of samples. Precise entrance angle of RR was set with a goniometer. The source of light was a projection device with a halogen bulb (exit beam diameter 3.4 cm). B – The geometry of brightness evaluation of RR's. The observer sits in a black box and views at 2 RR's through an aperture 1.0 x 1.5 cm.

The relative brightness of a pair of RRs was evaluated as depicted in Fig.1B. Two female subjects (age 22 and 24 years respectively) participated in the experiment. They had normal vision. The observer was asked if the upper RR sample is brighter than lower. Yes/No answers were recorded and psychometric response curves were obtained. Brightness at entrance angles from 0 to 80 degrees (step of 5 degrees) was estimated 10 times for each entrance angle. All 15 possible combinations of stimuli pairs were examined. The illumination of sample was 200 lx, distance from light source (and observer) to samples was 2.40 ± 0.05 m.

4. Results and discussion

The optical indicatrixes of three types of RR's are depicted in Fig.2A. The shape of the indicatrices varies significantly. MP shows highest reflectance at large angles and average results at small and intermediate angles. Narrow pronounce maxima of reflection at large angles might be caused by specular reflection at slightly wavy parts of MP. In comparison 3M shows best performance in average, especially intermediate angular regions. Origin statistic tool ANOVA one-tail was used to compare obtained data. The most reflective was 3M followed by MP and DG was least reflective in all examined region. Significance of color is shown in Fig.2B. Micro-prismatic RR's were used for this part of study. Significantly most reflective were white and yellow RR's, followed by green and orange RR's and the least reflective was the red RR.

Electron-microscopic estimate of the size of RR's active regions were made. They are depicted in Fig.2C, and Fig.2D. The size of retro-reflective regions of 3M and MP (Fig 2C and Fig.2D) are similar (diameter of a glass bead in 3M is ~ 63 microns, height of the equilateral triangle ~ 150 microns) but different construction. Fig.2C depicts cross section of 3M. Although this type of RR contains more optical medium borders than MP and DG, the materials chosen for production, show best reflectivity if RR is tilted. Microscopic image of DG resembles that of MP. The decrease of reflectivity for DG might be caused by less total retro-reflective area which is caused by the diffusely reflecting grid that separates RR regions.

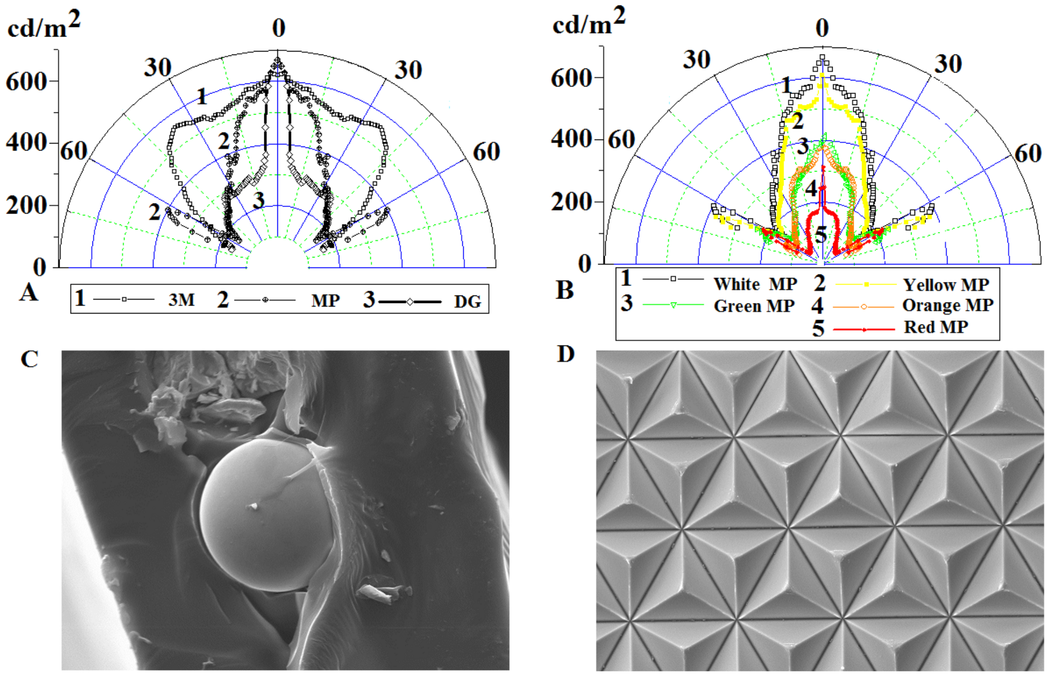

Figure 2. A – The optical indicatrices of three types of RR's samples 3M^{TM} Scothlite^{TM} - 3M (1) , Micro-prismatic Chief-Light Co – MP (2), 3M^{TM} Diamond Grade^{TM} – DG (3). B – The optical indicatrices of five colors of Micro-prismatic Chief-Light Co samples MP (1 – white, 2 – yellow, 3 – green, 4 – orange, 5 – red). C –SEM image of a cross-section of 3M. D - SEM image of MP sample. Images by K. Kundzins.

Fig.3 shows a portion of obtained psychophysical functions for the above compared three types of RR's. Fig.3A depicts brightness differences between DG and 3M. As in Fig.2A where 3M is more reflective, 3M is perceived as much brighter for range of angles between 0 and 60 deg.

Fig.3B depicts perceived brightness differences between DG and MP. For most of the entrance angle range, MP is perceived as brighter than DG. Fig.3C depicts perceived brightness differences between MP and 3M. For entrance angle range (5 – 50 deg.) 3M is perceived as brighter than MP.

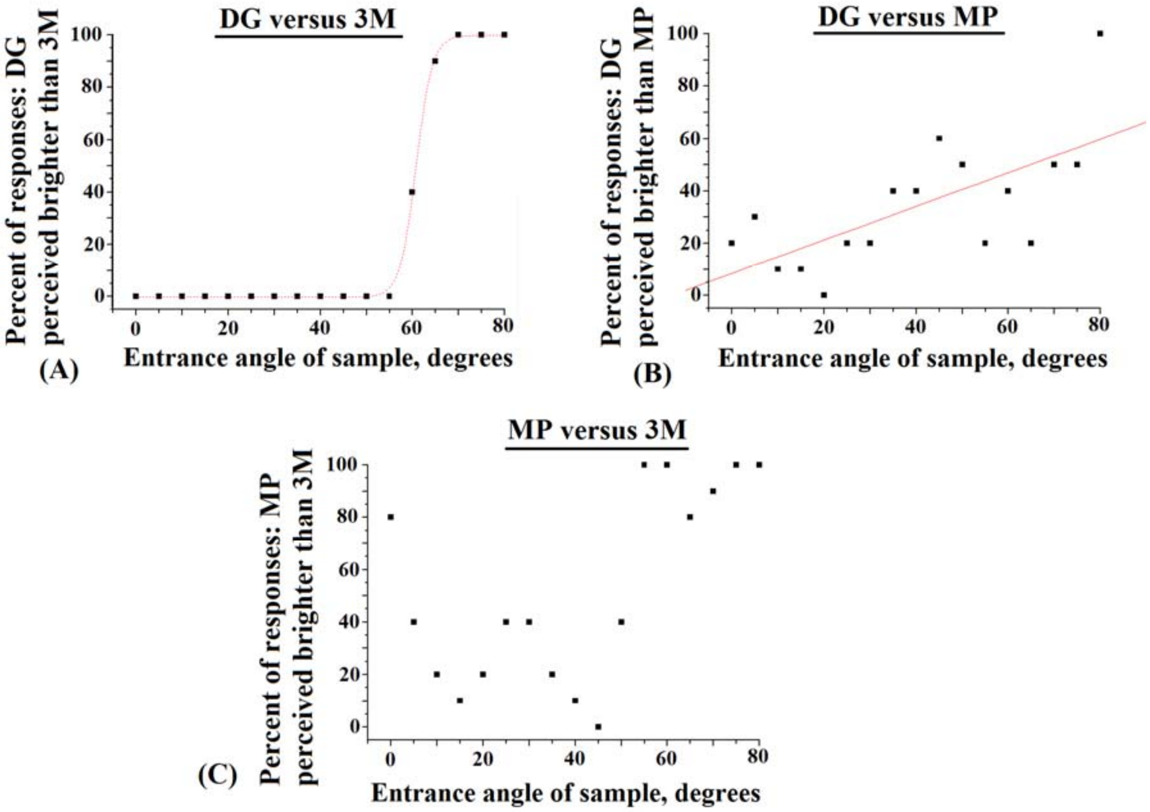

Figure 3. Psychophysical functions for RR pairs - DG and 3M (A), DG and MP (B) and MP and 3M (C).

All of these data are consistent with optical indicatrix data. That suggests a strong predictability of reflectance from brightness measurements and vice versa regardless of the strong nonlinear nature of human perception. The results of estimation of brightness of six types of RRs are summarized in table 1. The results are given as percent of total positive responses of specific RR divided by number of times the specific RR was evaluated (in other words – what is the total score of answers “this type of RR is brighter than the other” compared to all times the specific RR “competed” against another RR). Three ranges of entrance angles are shown (all, small and large entrance angle range). The difference of perceived brightness at various ranges for example for Bike-RR compared to MP is marked. Even though both RRs are prismatic, Bike-RR (macro-prismatic) is with certainty most effective at small entrance angles, while MP (micro-prismatic) – most effective at large entrance angles.

Additional research has to be done for evaluation of reflection and brightness perception of RRs if the lightning conditions are deviated (in rain, snow or fog). Authors guess that the reflectance optical indicatrix and psychophysical curve shapes would change and performance deteriorate.

Table1. Perceived brightness of RRs. Summary.

Type of RR evaluated	Percent of positive responses: All entrance angle range (0 – 80)	Percent of positive responses: Small entrance angle range (0 – 30)	Percent of positive responses: Large entrance angle range (50 – 80)
3M	55.6	58.3	37.7
DG	40.7	16.9	65.7
MP	63.5	51.4	78.0
DGT	33.6	30.0	37.1
GB	70.0	67.4	68.9
Bike-RR	36.5	76.0	12.6

5. Conclusions

1. The indicatrixes of different types of RRs differ significantly. In general the most reflective is glass bead RR, followed by micro-prismatic RR and Diamond-grade micro-prismatic RR. The angular ranges of most reflectivity for each RR differ.
2. The color of RR significantly impacts intensity of RR - the most intensive are white and yellow RRs, followed by orange and green (56% and 63% intensity of white) and the least intensive is red RR (35% intensity of white).
3. Even though the perception of human observer is nonlinear, the perceived brightness differences can be predicted from the indicatrixes of monochromatic stimuli.

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