Traffic Signal Light Detection through Sunglare Filters of Different Q Factors

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Abstract: Recent guides for use of sunglare protection filters have introduced the concept of Q factors as a measure of colour appearance distortion in viewing traffic signal lights. The adoption of Q factor values was apparently arbitrary and not firmly based on experimental data. The manner in which changes in Q factor affect colour perception and detection of signal lights has been measured and shows that detection thresholds vary with the Q factor in a manner that can only partly be explained, but that is not independent of the colour of the signal as assumed in the guides. © 1997 John Wiley & Sons, Inc. *Col Res Appl, 22, 24–31, 1997.*

Key words: traffic signal detection; sunglasses; Q factors; road signals

INTRODUCTION

A technical committee of the Comité Européen de Normalisation (CEN/TC 8 Personal Eye Protection) has prepared a European Standard[1] for sunglare protection filters for industrial use and proposed a draft standard for sunglasses for general use.[2] One section of both the Standard and the draft is concerned with the recognition of road traffic signal lights because of the way in which colours of the lights might be distorted by the spectral transmission properties of the filters if worn by drivers. To quantify the likely distortion of these filters, the **relative visual attenuation quotient** or Q factor was defined for each specific signal colour (red, yellow, green, and blue) as:

$$Q_F = \frac{\int_{380}^{780} \tau_F(\lambda)\cdot\tau_S(\lambda)\cdot V(\lambda)\cdot\phi_S(\lambda)\cdot d\lambda}{\int_{380}^{780} \tau_S(\lambda)\cdot V(\lambda)\cdot\phi_S(\lambda)\cdot d\lambda} \cdot \frac{\int_{380}^{780} V(\lambda)\cdot\phi_D(\lambda)\cdot d\lambda}{\int_{380}^{780} \tau_F(\lambda)\cdot V(\lambda)\cdot\phi_D(\lambda)\cdot d\lambda}, \quad (1)$$

where $\tau_F(\lambda)$ is the spectral transmittance of the sunglare filter; $V(\lambda)$ is the spectral visibility function for photopic vision; $\phi_S(\lambda)$ is the spectral distribution of radiation of CIE Standard Illuminant A, except for the blue signal where it is the spectral distribution of radiation of a 3200 K light source; $\tau_S(\lambda)$ is the spectral transmittance of the signal filter; and $\phi_D(\lambda)$ is the spectral distribution of radiation of CIE Standard Illuminant D65.

This is an intuitive empirical formula: it ratios the luminance of the signal through the filter to the luminance without the filter, and this is normalized with respect to a similar ratio for luminance of daylight through the filter and without the filter. The spectral luminance distribution of each signal light $(\tau_S(\lambda)\cdot V(\lambda)\cdot\phi_S(\lambda))$ is tabulated in the Standard using values for $\tau_S(\lambda)$ for a signal filter, which meets the CIE chromaticity specification.[3]

The CIE specification for D65 is a table representing a spectral radiation distribution of a phase of daylight. It has never been successfully simulated as a practical source, but the table of spectral luminance distribution $(\tau_S(\lambda)\cdot V(\lambda)\cdot\phi_S(\lambda))$ does relate to practically realizable sources defined by the convolution of the signal filter, the visibility function, and the spectrum of the lamp. The exact details of the filter transmittance are not defined, nor are they important, provided that the resultant chro-

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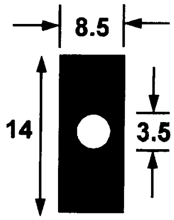

FIG. 1. Dimensions of a simulated traffic signal, which was surrounded by a uniformly illuminated background screen subtending about 30 × 27 degrees at the eye. The numbers are minutes of arc.

maticity lies within the range allowed by the CIE specification.

Hence the CEN definition of the signal is in terms of an unrealizable spectral luminance distribution, whereas the CIE specification of signals is in terms of chromaticity. To put this another way, the Q factor relates to weighted spectral power distributions, whereas practical roadside signals are defined in terms of their chromaticities. The resultant allowable variations in metamerism and colour rendering could cause problems in assessing the visual performances of lenses with similar Q factors.[4]

The traffic signal colours defined by the CIE are red, yellow, green, white, and blue. A white Q factor is not defined by the CEN Standard[1] (EN 172), which recommends a minimum Q factor value of 0.8 for the other four signal colours. The assumption is that constancy across the spectrum implies neutrality and lack of bias in recognition of the signal colours. If this concept is correct, then filters with similar Q values for a particular signal colour should evince similar visual performance. However, it was soon realized by commercial filter manufacturers that filters that did not comply with the minimum recommended by the Standard were, in some cases, apparently superior in visual performance when compared to filters that did comply. This concept has been tested in a colour-naming experiment, which is reported below.

In addition, for each filter there should be a relationship between visual performance and the Q factors. The function should be the same for each signal independently of its colour, because, by definition, the factors relate only to differences in luminance even though they refer to signals of different chromaticity. This article investigates these functions and shows them to be inconsistent.

EXPERIMENTAL DESIGN

An experimental rationale was devised in which a simulation of a road traffic signal installation was set up in the laboratory representing a lantern as might been seen in a real street scene from a distance of 200 m.

The definition of the Q factor implies the concept of visual detection thresholds in terms of luminance, but, in practice, colour thresholds are also likely to be involved. In one set of trials, an observer with normal colour vision viewed the simulated traffic lights through the calibrated Q factor filters, while the intensity of the signal was increased from below detection until it was perceived (a) as being present and (b) as its correct colour. The intensities for (a) and (b) were recorded.

The intensities of the signals at thresholds (a) or (b) were generally below the minimum intensity of 25 cd at 200 m recommended by CIE (1988) for street signals.[3] To simulate more realistic conditions, in a further experiment the signals were set to the minimum CIE recommended intensity and viewed with, and without, the calibrated Q factor filters. This time the observers were asked to assess the *quality* of the simulation through the Q factor filter, rating this quality as 100 when viewing without the Q factor filter.

APPARATUS

The observer's view of the simulated traffic signals is shown in Fig. 1. The lantern shape was represented as a black rectangle scaled down so that at the viewing distance of 2 m it would meet the CIE recommendation[3] for the visual subtense of a real signal fitting as seen at 200 m. However, in the simulation, the coloured signal, whether red, yellow, green, or white, always appeared in the center of the rectangle. The white signal, which is permitted as a traffic signal, was used only in a limited test with a selection of the sunglare filters. The blue signal light was not included at all, as it does not feature in permissive signals at road junctions and crossings.

The background screen was a board 1.0 m horizontal by 0.9 m vertical, coated with several layers of TiO_2 white matte paint, and illuminated by two 500W studio flood lamps with tungsten halogen filament lamps run at 3000 K approx. The colour temperature of the light from the background screen was raised to 4100 K by means of two theatre lighting filters, one sheet each of Rosco type 66 (Cool Blue) and 351 (Lavender Mist) in front of the flood lamps. These filters have characteristic irregularities in the long wavelength end of the spectrum, which are apparent in Fig. 2.

The signal aperture was trans-illuminated by means of a fibre-optic and a tungsten filament lamp. The chromaticity was changed by inserting selected coloured filters, and the intensity was varied with a neutral circular wedge. The wedge position and, hence, the signal intensity were controlled by a computer-driven stepper-motor. The wedge position was logged by the computer and converted into intensity by the software. Intensity calibrations were derived from NPL standards. Lamps for both the signals and the background screen were powered from the 50-Hz mains. The light output levels were maintained within ±5% of their intended values.

The relative spectral power distributions of the four signal colours (red, yellow, green, and white) and the light from the background screen were all measured by means of a Zeiss spectroradiometer calibrated with re-

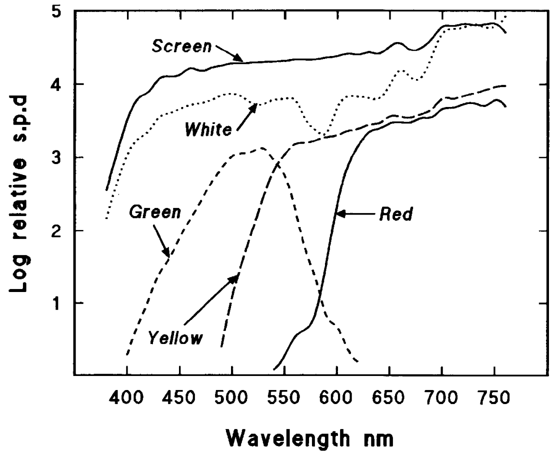

FIG. 2. Relative spectral power distributions of the four signal lights (red, yellow, green, and white) and of light from the background screen.

spect to the radiation from a tungsten lamp, which had been compared with a similar lamp calibrated at NPL. The graphs representing the spectral power distributions appear in Fig. 2. The irregular distribution for the white was produced deliberately with a didymium filter in order to generate a range of Q values. The long-wave irregularities shown in the other curves in Fig. 2 were due, as in the case of the white background screen, to the characteristics of the theatre filters used. The chromaticities were calculated from these spectral measurements, and were also checked *in situ* with a Minolta chromaticity meter. These chromaticities are shown in Table I and are within the ranges permitted by the CIE.[3] The colour-rendering index of the light diffused from the background screen was 87, at a correlated colour temperature of 4100 K. The luminance on the background screen varied from 900 cd.m^{-2} at the edges to 1300 cd.m^{-2} at the center. These conditions correspond to a phase of natural daylight illumination likely at morning or evening. Absolute measures of the luminances and intensities were obtained with a calibrated photometer (UDT, model 137).

A series of 13 coloured sunglare filters were especially made (Intercast Europe, Italy) to have a wide range of Q factors, and all the filters, including a neutral grey, had transmittances of approximately 50%. The spectral transmittances of these filters were measured at 10-nm intervals with a Lambda V spectrophotometer (Perkin–Elmer, bandwidth 2 nm) and their Q factors calculated according to Eq. (1). These are shown as "defined" Q factors in Table II. Q factors were also calculated using the spectral power distribution of the artificial daylight reflected from the background screen and the simulated traffic signals; these data are also shown in Table II as "physical" Q factors, together with the corresponding "physical" luminous transmittances (τ_V).

Figure 3 shows the spectral transmittances of 6 specimen filters as used in one of the experiments, which is described below.

METHODS

The subjects were recruited from students at the University of Westminster against the following selection criteria: they must be under 30 years of age, have normal colour vision as assessed by the Standard Pseudoisochromatic Plates for Congenital Color Vision Defects (Ichikawa, H., et al., 1st Edn. 1978, Igaku-Shoin, Tokyo & New York) and 6/6 vision in at least one eye with correction by spectrally neutral lenses, if required. There were similar numbers of men and women. The subject sat 2 m from the background screen, which was viewed with both eyes, and was shown the range of stimuli at 0.25 mcd, corresponding to an intensity of 25 cd as seen at 200 m, to familiarize him or her with the appearance and corresponding colour names which were *red, yellow, green,* and *white.* The simulated traffic signals were viewed through a pair of the Q factor filters made up into "sunglasses" in a light-weight frame. The order of wearing the Q factor sunglare filters was randomized. The signal lights were also presented in a random order, so that each appeared five times for every sunglare filter.

For the threshold measurements, the intensity of the signal was initially set below visual threshold and was increased gradually by the subject who operated a switch controlling the computer. The subject indicated orally when the signal was visible and, if possible, named the colour. The intensity at which this occurred was recorded. If the colour name was incorrect, the experimenter told the subject to try again, if necessary by increasing the intensity, until the colour was correctly identified. This intensity was recorded by the computer, which then automatically set the intensity below threshold ready for the next trial. Each signal-filter combination was repeated 5 times for all subjects.

There were two sets of threshold experiments. In the first set, 20 subjects viewed the red, yellow, and green signals through 12 filters, including the neutral filter but excluding Thrama Plus. In the second set of threshold experiments, 10 subjects viewed all four signals (red, yellow, green, and white) through 6 selected filters whose spectral transmittances are shown in Fig. 3. This set included Thrama Plus, which is a commercial filter type

TABLE I. Chromaticities of the simulated traffic signals and the background screen.

	x	y
RED	0.709	0.291
YELLOW	0.576	0.421
GREEN	0.149	0.590
WHITE	0.352	0.348
SCREEN	0.377	0.375

TABLE II. "Defined" and "Physical" Q factors of the various filters for the red, yellow, green, and white signal lights, together with their luminous transmittances.

	Defined factors			Physical factors				
	Q_r	Q_y	Q_g	Q_r	Q_y	Q_g	Q_w	T_v (%)
RED A	1.86	1.40	0.70	1.73	1.24	0.53	—	50
RED B	2.06	1.49	0.63	1.86	1.29	0.44	0.91	50
RED C	1.87	1.48	0.67	1.72	1.29	0.46	—	50
BRUNO	1.90	1.51	0.66	1.74	1.31	0.44	0.91	50
ORANGE	1.70	1.47	0.69	1.55	1.29	0.45	—	59
THRAMA PLUS	1.73	1.41	0.74	1.58	1.24	0.55	0.93	56
YELLOW	1.07	1.10	0.97	1.06	1.07	0.92	—	41
GREEN	0.64	0.77	1.17	0.69	0.83	1.34	1.07	46
BLUE A	0.57	0.71	1.19	0.63	0.78	1.39	1.09	45
BLUE B	0.79	0.80	1.12	0.88	0.86	1.25	—	44
BLUE C	0.65	0.76	1.16	0.71	0.82	1.32	—	46
BLUE D	0.72	0.78	1.15	0.78	0.84	1.30	—	48
GREY	1.00	1.00	1.00	1.01	1.00	1.00	1.01	56

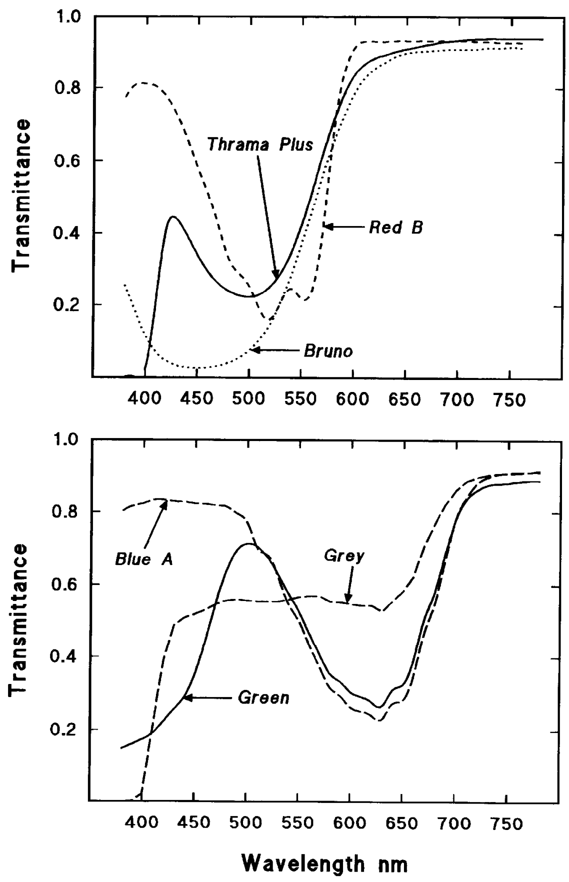

FIG. 3. Specimen spectral transmittances of six sunglare filter lenses. The top group of three illustrates their similarities down to 500 nm. The bottom group shows the close similarity between Green and Blue A down to 500 nm.

introduced because of its similarities to some of the other filters.

For the "Quality" measurements, the red, yellow, and green signals were all set to a constant 0.25 mcd, which corresponds to the minimum CIE recommended[3] intensity of 25 cd at 200 m. The subject viewed the traffic signals sequentially without the Q factor sunglare filters, and was told that they were viewing a simulation of traffic lights with the same colours as real traffic lights and that these were internationally agreed. They were then told that the colour appearance of the simulated signal, viewed without "sunglasses," was to be assigned a Quality of 100%. When wearing the "sunglasses" they would see further presentations of the same traffic signals, the appearance of which might be degraded or improved, and that they were to assign a quality value of less than 100% or more than 100% as appropriate. Then the signals were viewed through twelve of the Q factor sunglare filters (Thrama Plus was not included), worn in random order as before, and each signal colour appearance was assessed on the quality scale of the subject's own choice. The need for self-consistency was stressed. Each value was recorded, the judgment being made only once for each condition because it was considered that within one session, which lasted only ten minutes, a judgment once made was unlikely to be changed. Ten subjects took part.

RESULTS

Figure 4 is a graph of the mean threshold intensities for detecting the red signal for 20 subjects plotted against the "defined" red Q factors for the 12 filters used in the first set of experiments. The standard deviation bars have been corrected for intra-subject variation by a method that will be discussed later.

Figure 5 (top) shows the mean results for the same 20 subjects, viewing red, yellow, and green signals, plotted against the reciprocals of the respective "defined" Q fac-

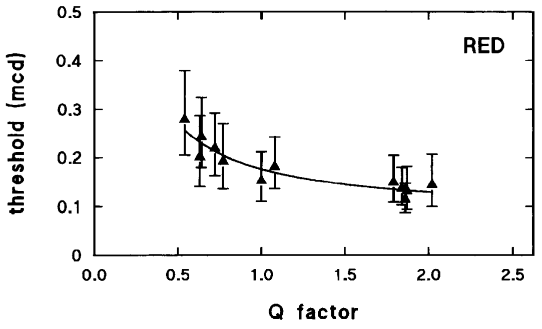

FIG. 4. Mean threshold intensity values for correct detection of red signal colour seen through sunglare filters of various "defined" red Q factors. Error bars represent standard deviations.

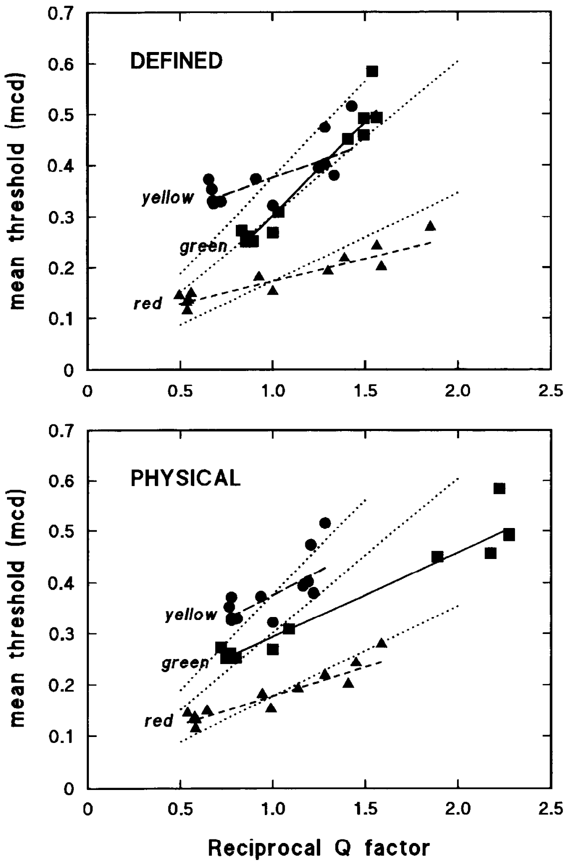

FIG. 5. Mean intensity thresholds for detection of red, yellow, and green traffic signal colours plotted against reciprocals of the respective Q factors. The top figure uses "defined" Q factors; the bottom figure uses "physical" Q factors (see text). The solid and dashed lines are fitted linear regressions, and the dotted lines represent a simple inverse relationship between the threshold intensity and Q.

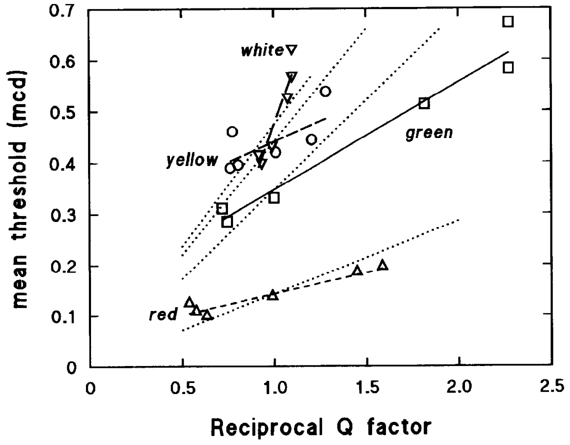

FIG. 6. Mean intensity thresholds for detection of signal colours including white, plotted against reciprocal "physical" Q factors. Regressions lines are fitted as in Fig. 5.

tors of the 12 filters. (Red, yellow, and green Q factors are plotted on the same scale.) The bottom graph in Fig. 5 replots the data from the top of Fig. 5 against the reciprocals of the respective "physical" Q factors.

Figure 6 is the same type of plot as Fig. 5, but is for the second group of 10 observers who viewed the 4 signal colours: red, yellow, green, and white. There were only 6 filters in this experiment, with the spectral transmittances shown in Fig. 3. The total number of mistakes made at threshold intensities in naming the colours of the 4 signals in this experiment are illustrated by the histogram in Fig. 7. There were 200 observer-occasions for each of the 6

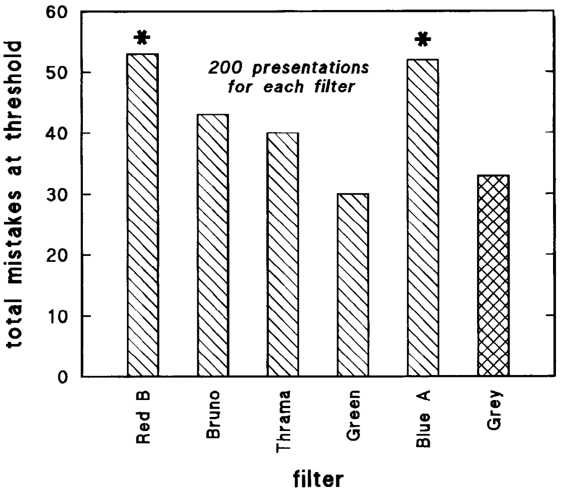

FIG. 7. Histogram showing frequencies of mistakes in colour naming of red, yellow, green, and white signals at threshold for six sunglare filters. Asterisks indicate significant differences from the Grey filter.

TABLE III. Showing the percentage of times that a coloured signal light was taken correctly as, or mistaken for, a named colour; e.g., the red signal taken as a red light in 96% of the presentations, mistaken in 2% of the presentations for yellow, 1% for green, and 1% for white.

		Signal colour			
		Red	Yellow	Green	White
. . . taken as OR mistaken for . . .	Red	96	18	1	3
	Yellow	2	71	2	14
	Green	1	1	93	6
	White	1	10	4	77

filters. The asterisks mark the two filters that produced significantly different results from the grey filter (Chi^2 test).

The errors in colour naming are presented in a different manner in Table III. This table shows that most mistakes were made with yellow signals, which were frequently mistaken for red or white, and white signals, which were often mistaken for yellow. Red and green signals were generally identified correctly.

Figure 8 shows the averaged quality results for 10 subjects, plotted against the respective "physical" Q factors of the full set of 12 filters in viewing red, yellow, and green signals.

DISCUSSION

Equation (1) for the Q factors expresses the luminance contrast between the signal and the background screen; it takes no account of the chromaticities. The experiments were devised to test the validity of this concept, as it might apply across a range of Q factors and traffic signal colours.

It was also intended to simulate, as far as practical in a simple laboratory setup, conditions that might be found in a real road scene. For this reason, the subtense of the traffic signals and their fitting were carefully scaled, to correspond with the appearance of a real signal seen at a distance of 200 m. The luminance and spectral power distribution of the background screen were typical of a phase of natural daylight, at sunrise or sunset. This might represent a wall of neutral hue, or a cloud-filled sky against which the traffic signal is seen. Lingelbach[5] has gone further in using real landscapes in his analysis. No attempt was made by the present authors to simulate changing daylight conditions.

The data presented in this article all refer to filters with luminous transmittances of about 50%. Some preliminary experiments involving both intensity thresholds and quality estimations with various filters, ranging in transmittance from 10 to 70%, had revealed no noteworthy differences in performance that could be ascribed to the transmittance. The small differences in this quantity reported in this article are, therefore, unlikely to affect the results.

In Fig. 4, the averaged threshold intensities for detecting the red signal are shown. The logarithmic means have been plotted against the "defined" red Q factor. The standard deviation error bars have been corrected for differences in sensitivity among subjects, which represented a large part of the variation. The correction was made with respect to each individual's results for the neutral grey lens. The logarithmic mean of each subject's group of five results for the neutral lens in viewing a particular signal colour (red in this example) was subtracted from the corresponding mean results of all 20 subjects for the same condition. The resultant difference was then used to correct the particular subject's five threshold readings for the corresponding red Q factors for each of the other 11 coloured filters. The process preserved the logarithmic mean intensities, while reducing the effect of intra-subject variations.

A hyperbolic function of the form $I = a/Q + b$ has been fitted (Fig. 4), where I is the threshold intensity. This relationship would be expected, if the Q factors were inversely related to the threshold. The fit appears good, but hyperbolic curves are easier to interpret if plotted on reciprocal abscissae. To proceed with the analysis of the results for the red, yellow, and green signals, the corresponding linear regressions were obtained by plotting the intensity thresholds against the reciprocals of the respective "defined" Q factors. These graphs are shown in Fig. 5 (top). For clarity, the error bars, which are similar for all three signal colours, have been omitted.

Several features may be noted. These transformed hyperbolic plots reveal that the linear regression lines are different for each signal colour. The yellow signal pro-

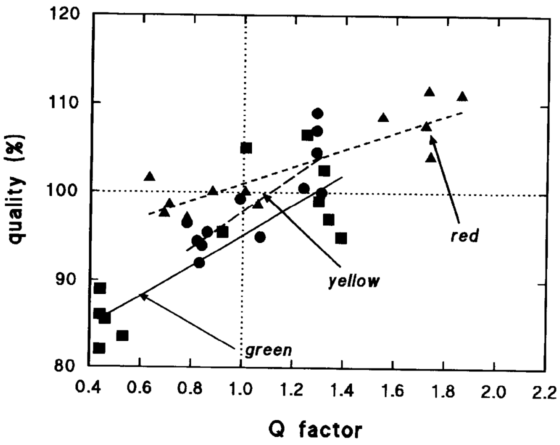

FIG. 8. Mean quality scores for assessment of red, yellow, and green traffic signals seen through sunglare filters of various "physical" Q factors.

duces the highest thresholds, the red signal the lowest, and the regression lines differ in slope. Also, none of the regressions follow the dotted lines representing the simple inverse relationship between threshold intensity and Q value that would be expected if neutral attenuation was the causal mechanism of the relationship.

Using a generic definition for Q factors, as in Eq. (1), could be regarded as a limitation with real sources that might not conform to the specification of that definition. Consequently, in order to relate more closely to the experimental conditions, these results were replotted against the "physical" Q factors. The bottom graphs of Fig. 5 show that the yellow thresholds now fit the expected simple regression better, while those for green fit worse.

The equations with the "physical" Q factors regressions are:

$$\text{RED} \quad I = 0.1123/Q + 0.06524 \quad p < 0.001$$

$$\text{YELLOW} \quad I = 0.1864/Q + 0.1895 \quad p = 0.004$$

$$\text{GREEN} \quad I = 0.1648/Q + 0.1288 \quad p < 0.001,$$

where I is the threshold intensity.

Thus, the features found with the "defined" Q factor are still present when the "physical" Q factors are used, so the above conclusions are not affected. To avoid unnecessary duplication, subsequent graphs are drawn only with respect to the "physical" Q factors.

The results do not support a unique function based on luminance detection as implied by the formulation for the Q factors expressed in Eq. (1). The equations express three distinct relationships, with different slopes and intercepts. None pass through the origin as would be expected in a simple hyperbolic relationship between I and Q.

It is perhaps to be expected that the yellow signal, being the least colourful, would produce the highest threshold values. It is noteworthy that when the red or green signals were first detected, they were almost always correctly named, while the yellow signal was often confused with red.

This suggests that the chromaticity of the signals is the dominating stimulus for their detection. Such an explanation could account for the slope of the regression lines being smaller than that of the lines corresponding to a simple hyperbolic relationship. The higher the Q factor (i.e., the lower the reciprocal Q factor) the more the filter would render the background screen similar in colour to the signal so that the judgment would be in terms of luminance contrast. Conversely, at a higher reciprocal Q factor, the greater the colour contrast between the signal and the background screen, so the threshold would be lowered. These features are demonstrated in the results described here.

This hypothesis prompted the special investigation of the threshold appearance of four signal colours including a white, which is, of course, a pure achromatic luminance stimulus. Five filters were selected from the original 12 together with a commercial filter (Thrama Plus). A further 10 subjects took part. The white signal light met the CIE specification, though it was deliberately of an irregular spectral power distribution, produced with a didymium filter. This was done to generate some variation in the "physical" Q factor. There is no "defined" white Q factor, so the "physical" Q factors of the 6 filters were calculated from Eq. (1) using the measured spectral power distributions of the experimental signals (see Fig. 3 and Table II). This set of conditions resulted in a greater range of misnaming at threshold, and it was found that the yellow signal was now frequently mistaken for white, whereas, when white was not a possibility, as in the first threshold experiment, the number of mistakes was much less.

Figure 6 shows that, even with this greater freedom, the threshold intensities followed much the same variations with respect to the yellow, green, and red reciprocal Q factors. The white intensity thresholds were high and similar to those for the yellow signal, which is to be expected for stimuli with little or no colour. Interestingly, the slope of the white threshold relationship to its reciprocal Q factor is the greatest of all and greater than the simple hyperbolic relationship would indicate. The reason for this is not understood.

It should be noted that the mean intensities for correct colour naming were not noticeably increased above the previous detection thresholds. This is because the subjects usually did not need to increase any signal greatly above its detection threshold in order to identify the colour. Often, after an initial mistake, they correctly named the signal without increasing it at all. When the subjects were told that they had made an error in colour naming, the chance that they might then correctly guess the colour was not 1 in 3, as might be supposed, because the distribution of the errors was not random (see Table III).

The histogram in Fig. 7 shows the distribution of all mistakes among the 6 filters. Noteworthy is the statistically significant difference (Chi^2 test), between the Green and Blue A filter scores, especially as these two filters have almost the same Q values, whether "defined" or "physical" (see Table II). This is because the spectral transmittances of these two filters are very similar down to 500 nm (see Fig. 3, bottom). The differences in colour appearance and visual performance are probably due to the disparity in transmittance below this wavelength, which scarcely affects the Q values. Lingelbach[4] quotes similar examples.

The Quality assessments were made, because it was realized that even the highest of the threshold intensities were much less than the CIE minimum recommended[3] value of 25 cd. This corresponds to 2.5 mcd on the scaled-down experimental apparatus and this value was used for the quality judgments. It is perhaps remarkable that the subjects were able to make consistent judgments on a quality scale, but no theoretical model has been devised to explain the observations.

The regression of the quality of the red signal is distinct in slope from that for the green. The yellow regression, though significant, is more chaotic. The main outcome of this part of the experiments was to show that even at more realistic signal intensities, Q factors again do not produce a consistent set of results that are independent of signal colour.

Clearly, Q factors do not express anything useful. The thresholds for detection and correct colour naming of traffic signals, and the assessments of signal quality, vary with Q factor in a complex and uncertain manner. As a parameter to specify permitted performance of filters used for driving, the Q factor concept is unhelpful and confusing. To quote Lingelbach,[3] "Q factors have little or nothing to do with the recognition of traffic lights · · · in any case, as a description of the quality of a sunglare filter, they are good for nothing · · · one may rejoice in the aesthetics of the mathematical formulation of the Q factors, but beyond that Q factors are of no consequence."

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