

## THE INTRAOCULAR STRAYLIGHT FUNCTION IN 129 HEALTHY VOLUNTEERS; DEPENDENCE ON ANGLE, AGE AND PIGMENTATION

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**Abstract**—The direct compensation method allows for an accurate (standard deviation below 0.05 log unit) determination of intraocular light scattering between 3.5 and 25 deg of scattering angle and is suitable for untrained subjects. The method was used to study population behaviour and individual variation in 129 volunteers between 20 and 82 yr of age, visual acuity equal to or better than one and no apparent eye pathology. The results indicate straylight to increase with the 4th power of age, doubling at 70. In addition to the age dependence, there was great variation between individuals. Part of this is due to negative correlation with pigmentation.

Straylight    Glare    Age dependence    Point spread function    Pigmentation    Visual optics  
 Light scatter    Retinal contrast    Population behaviour

### INTRODUCTION

Intraocular straylight is the phenomenon that the retina receives light at locations that do not optically correspond to the direction the light is coming from. Any medium in the optical pathway between the scenery and the retina can deflect light in different directions.

Straylight reduces the quality of vision. It causes retinal contrast reduction and, subsequently, glare. There has long existed a controversy whether for glare phenomena a physical or a neuronal explanation is appropriate. By now, however, evidence has piled up in favour of the physical interpretation; see Vos (1984). This is certainly true for angular distances larger than 2.5 deg, as used in the present study.

Straylight can be quantified by means of the point spread function (PSF). The PSF can be defined in terms of the luminance  $L$  in the outside world that is equivalent to the retinal light distribution caused by a point source of light. It is good practice to divide this equivalent luminance  $L_{eq}$  by  $E_h$ , the illuminance caused by the point source at the pupil plane. For the theory see Vos (1963, 1984). From this definition it follows that the integral of the PSF normalizes to unity. The optically ideal PSF is the Airy disk, the form of which follows from diffraction theory. The presence of intraocular

light scattering causes its shape to widen and especially the wide-angle part to rise, at the cost of the (integral of the) central part.

The term “straylight function” (SLF) will be used to refer to the peripheral part (e.g.  $\phi > 1$  deg;  $\phi$  is the scatter angle in deg) of the PSF. We will consider the PSF to be circularly symmetric and hence, dependant on just one angle;  $PSF = PSF(\phi)$ . Furthermore, only the forward half-space is considered. The normalization then reduces to:

$$\int_0^{\pi/2} PSF(\phi) \times 2 \times \pi \times \sin(\phi) d\phi = 1. \quad (1)$$

For more than half a century, the Stiles–Holladay approximation (Stiles, 1929; Holladay, 1926):

$$PSF(\phi) \approx 10 \times \phi^{-2}; \quad (2)$$

for  $\phi$  between 1 and 90 deg, has served many investigators in the field as a guideline. However, several other functional PSF proposals have been made; see Vos (1984). In 1983, the Commission Internationale d’Eclairage (CIE) took an initiative to define a standard PSF for the healthy human eye. The present work was undertaken partly as a result of that initiative.

There exists, by means of the Fourier transform, direct correspondence between the retinal PSF and the optical transfer function (OTF) of

the eye. The latter has been investigated extensively since the mid-sixties, e.g. by Campbell and Gubisch (1966), and connects directly to the contrast sensitivity function (CSF). So it is clear that better information on the PSF may be of interest to many studies involving the CSF and other parameters depending on the optics of the eye. Examples of application of the SLF can be found in van den Berg (1987) and van den Berg and Boltjes (1988).

The straylight measurement techniques used up to now, using the principle of equivalent veiling described by Cobb (1911) have been less convenient for population studies. With the direct compensation method described in van den Berg (1986) and in van den Berg and Spekrijse (1987), it became easier to carry out a population survey of straylight behaviour and study the PSF dependence on age, pigmentation and other factors of interindividual variation.

#### METHODS AND MATERIALS

The subject monocularly observed a screen at a distance of 45 cm. At the center, a 1-deg radius circular test field was visible. It was surrounded by a ring-shaped field with an outer radius of 1.5 cm (2 deg) of steady, homogeneous luminance of 30 cd/m<sup>2</sup>, called the separation ring. On the screen, one of four ring-shaped straylight sources were projected with inner radii of 1.95, 3.9, 7.8 and 15.4 cm and outer radii of 3.9, 7.8, 15.4 and 30.8 cm respectively. Taking into account the product of the measured intensity distribution in the rings and the normal angular straylight dependence, effective angular radii of 3.5, 7.0, 13.6 and 25.4 deg for the four rings result.

The straylight source was intermittent at a frequency of 8 Hz by means of a chopper. With no light source present in the test field, the subjects perceived a flicker impression in the test field, due to intraocular light scatter. This could be compensated for by adjusting a counterphase modulated light source presented in the test field. The luminance of the counterphase light which cancels or minimizes the flicker perceived centrally corresponds directly to the amount of straylight. As light sources tungsten halogen lamps were used with specified color temperatures of 2900–3150 K.

As stated in the introduction, the PSF is defined as the ratio of the equivalent (compensating) luminance of the test field,  $L_{eq}$ , over  $E_{bl}$ , the illuminance at the pupil plane caused by the straylight source. As this ratio roughly follows

an inverse square power law with respect to  $\phi$ , it is convenient to define the straylight measure:

$$sm(\phi) = \log[L_{eq}(\phi) \times \phi^2/E_{bl}(\phi)]. \quad (3)$$

In the present paper, all logarithms have base 10. In the following, for short the letters  $L$  and  $E$  will be used. In the figures not  $sm$  but the quantity  $L \times \phi^2/E$  is plotted, with logarithmical axes. Its dimension is (deg/rad)<sup>2</sup>. Some authors measure  $E$  at right angles from the direction of the straylight source, which makes a difference of a factor  $\cos(\phi)$ . For small scattering angles, this can be neglected. However, in the case of the largest straylight source used in the present study, the difference is 0.06 log unit.

The population recruitment criteria were: both eyes with a (corrected) visual acuity better than or equal to one; according to slit-lamp examination no eye pathology; completely clear lenses, but increased yellowing was accepted; no history of eye pathology. Thus, at the Rotterdam Eye Clinic, 129 volunteers were recruited, filling six age decades of 20–30, . . . , 70–80 yr. In the last decade, the criteria appeared to be too difficult: only 8 individuals (13 eyes) could be recruited, while the other decades each contain 20 individuals with both eyes (the decade 30–40 yr contains 21 individuals). To examine the relation between intraocular light scatter and pigmentation the 20–50 yr individuals were subdivided into two groups: 39 with blue, green or blue-green eyes (mean age = 34.4, SD = 8.7 yr; those will in the following be referred to as blue) and 19 with brown eyes (mean age = 37.7, SD = 7.1 yr). Additionally, 20 non-caucasian, skin-pigmented individuals in the range from 20–50 years of age (mean age = 34.2, SD = 10.5 yr) participated in the study.

The measurements were made in a dimly lit room. To avoid contributions from extra-ocular straylight, the subject's head rested in a chin rest above a black screen and the room walls were black. In control experiments extraocular straylight proved to be well below the intraocular levels. The subjects never wore glasses during the investigation. Only subjects were used that could see the test field more or less sharply according to their own account. Afterwards, this precaution proved to be unnecessarily strict if glasses were clean. The subject's retinal image unsharpness because of refractive errors is unimportant because of the two degree diameter of the test field. Natural pupils were used. The test field compensating luminance was adjusted by means of a one-turn dial operated by the examiner.

For each of the four scattering angles, six measurements were made. Three times the disappearance point of the central flicker percept was measured (the investigator turned the compensation light up) and three times the reappearance point was measured (at this point the straylight is overcompensated by the light in the central field). As a check on the subject's correct understanding, we used as a criterion whether the three values differed by more than 0.13 log unit. The six thus obtained values were linearly averaged and corrected for  $\phi^2$  and  $E(\phi)$  to obtain the straylight measure  $sm(\phi)$  according to (3). Thus, for each eye measured, four  $sm(\phi)$  values were obtained, one for each angle.

By analysis of variance, no important difference (see below) between left and right eyes was

found. In the following, the mean for left and right eyes will be presented except for the cases in the oldest age decade for which only one eye matched the criteria.

## RESULTS

Unless otherwise stated, the population referred to is the caucasian group. In Fig. 1, the age-dependence for the four measured straylight angles is plotted. A small, statistically significant difference in shape between the four plots exists. Since the difference is rather small and for reasons of simplicity the same shape was fitted to the data and is shown in the figures. This shape is:

$$sm(\phi, a) = sm(\phi, 0) + \log[1 + (a/c)^4], \quad (4)$$

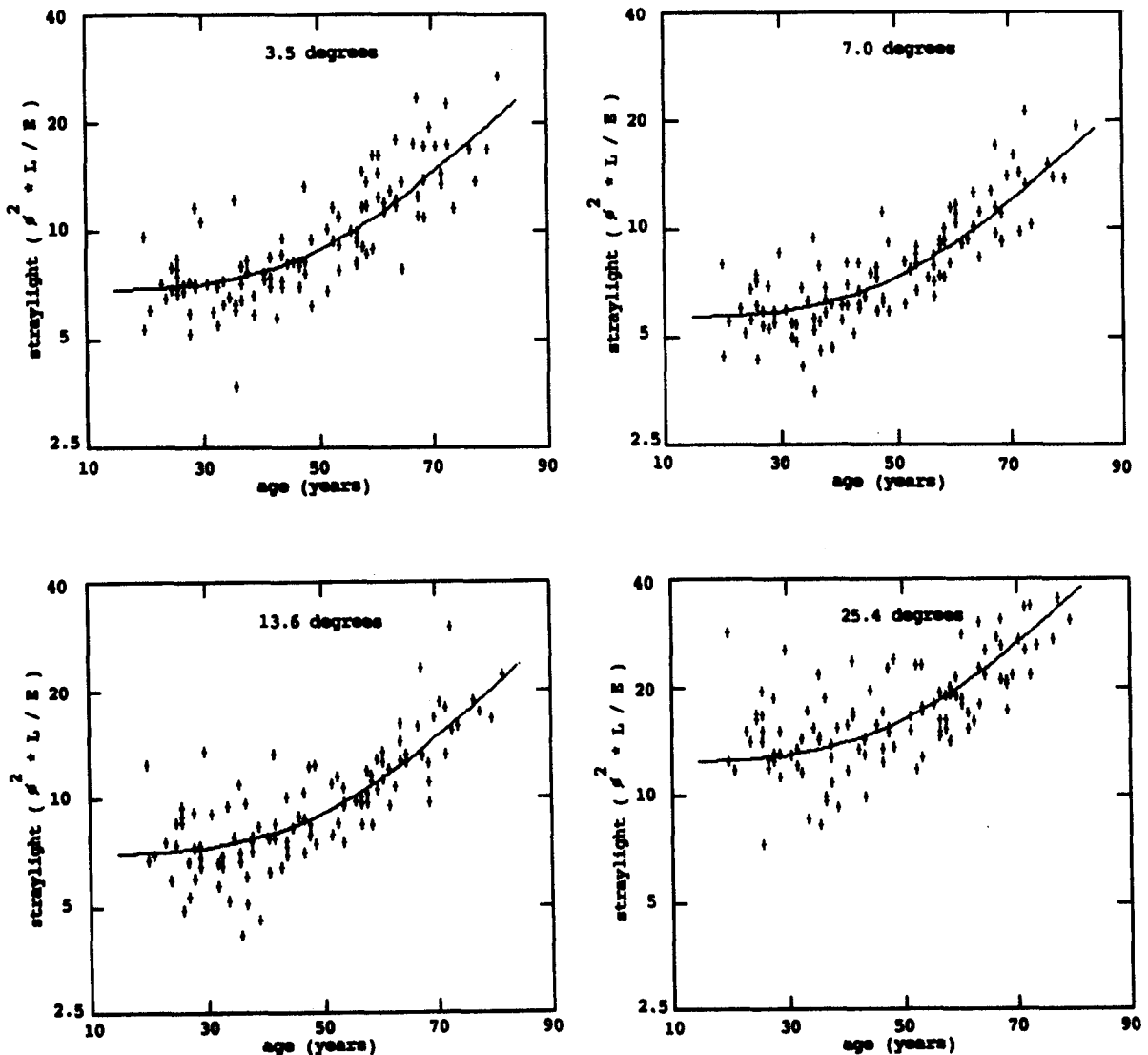


Fig. 1. Straylight as a function of age for four glare angles. Averaged left and right eye data are plotted for 112 normal caucasian subjects. The line represents the best fit of function (4) to the data (see text).

with  $a$  the age in years and the fitted parameters:

$$c = 68.7 \pm 0.4 \text{ yr;}$$

$$sm(3.5, 0) = 0.838 \pm 0.005;$$

$$sm(13.6, 0) = 0.846 \pm 0.003;$$

$$sm(7.0, 0) = 0.752 \pm 0.003;$$

$$sm(25.4, 0) = 1.096 \pm 0.006.$$

Initially, the exponent was also an estimated parameter. Its value turned out to be  $4.3 \pm 0.2$ . This value does not significantly deviate from the value of 4.0, as given by Vos (1984) on the basis of the data of Aulhorn and Harms (1970) and also by Blackwell and Blackwell (1980). We fixed the exponent at 4.0 for the present analysis.

In Fig. 2, the angular dependence of the same function is plotted as a function of angle, with the SD. As in Fig. 1, statistically significant differences between the age groups exist in the shape of these curves. But again these differences are so small as compared to the total interindividual variation in these plots that they were neglected in the analysis. The plotted SD was calculated over the age range from 20 to 82 yr as a whole [after correction for (4)], since there was no indication that interindividual variation was different between decades (apart from the 70 yr and above group, in which case the variation was larger). The SD values for 3.5, 7.0, 13.6 and 25.4 deg are 0.092, 0.080, 0.094 and 0.104 log unit respectively. Furthermore, for each decade, the straylight functions of five individuals are shown. Analysis of variance showed that highly significant ( $P < 0.001$ ) differences existed between individuals, also within each decade. However, the differences proved to be differences in level and much less in shape of the individual SLF.

In Fig. 3, the straylight data are plotted for the three pigmentation subgroups. The short horizontal bars represent mean and standard error of the mean. No correction was made for the slight differences in mean age between the pigmentation subgroups since the age effect is small below 50 yr. The means for these three groups are:

Caucasian blue-eyed	Caucasian brown-eyed	Non-caucasian skin-pigmented
$sm(3.5) = 0.882$	$sm(3.5) = 0.820$	$sm(3.5) = 0.744$
$sm(7.0) = 0.806$	$sm(7.0) = 0.737$	$sm(7.0) = 0.654$
$sm(13.6) = 0.916$	$sm(13.6) = 0.807$	$sm(13.6) = 0.703$
$sm(25.4) = 1.193$	$sm(25.4) = 1.069$	$sm(25.4) = 0.806$

Since in this study no repeated measurements were performed, no real estimate for error behaviour can be made. However, it is possible to derive upper bounds for the experimental error in the following way.

For each subject, four left eye minus right eye values were obtained. From these values over the 112 subjects, four mean intra-subject SD's of 0.064, 0.045, 0.045 and 0.048 log unit for the four straylight angles in ascending order, were derived.

These values do not contain inter-subject variation but only inter-eye variation and experimental error. They provide an upper bound for the experimental error. It was noticed that at the angle of 3.5 deg it was generally more difficult to obtain compensation. The inhomogeneity over the central 1 deg radius field resulting from the nearby straylight source might account for this.

Upper bounds for the experimental error can also be arrived at in the following way: for each subject, the four straylight values were corrected for (4) and for the subject's mean difference with (4). Again using standard statistical calculation mean intra-subject SD's per eye were derived, resulting in 0.081, 0.040, 0.047 and 0.086 log unit. These values are somewhat different from the ones above. Especially the value at 25.4 deg is much higher (0.086 as compared to 0.048). This is indicative for a source of variation affecting the shape of the SLF. A likely candidate for this is the subject's state of pigmentation. At present, we are studying the way ocular pigmentation affects the shape of the SLF and are finding important influences among the normal population, especially at large angles.

## DISCUSSION

In cases that age dependence of a visual function is estimated, one cannot be careful enough in interpreting and using these. The result could be directly dependent on the population selection criteria: in the present study, one must expect to find steeper increase in straylight with age when the criteria would have been chosen less strictly. On the other hand, if the criteria would have been chosen more strictly, chances are that the straylight increase would have been more shallow. But, of course, in that case even less subjects would have been admitted to the oldest age group. We have chosen criteria to comply with general ideas for

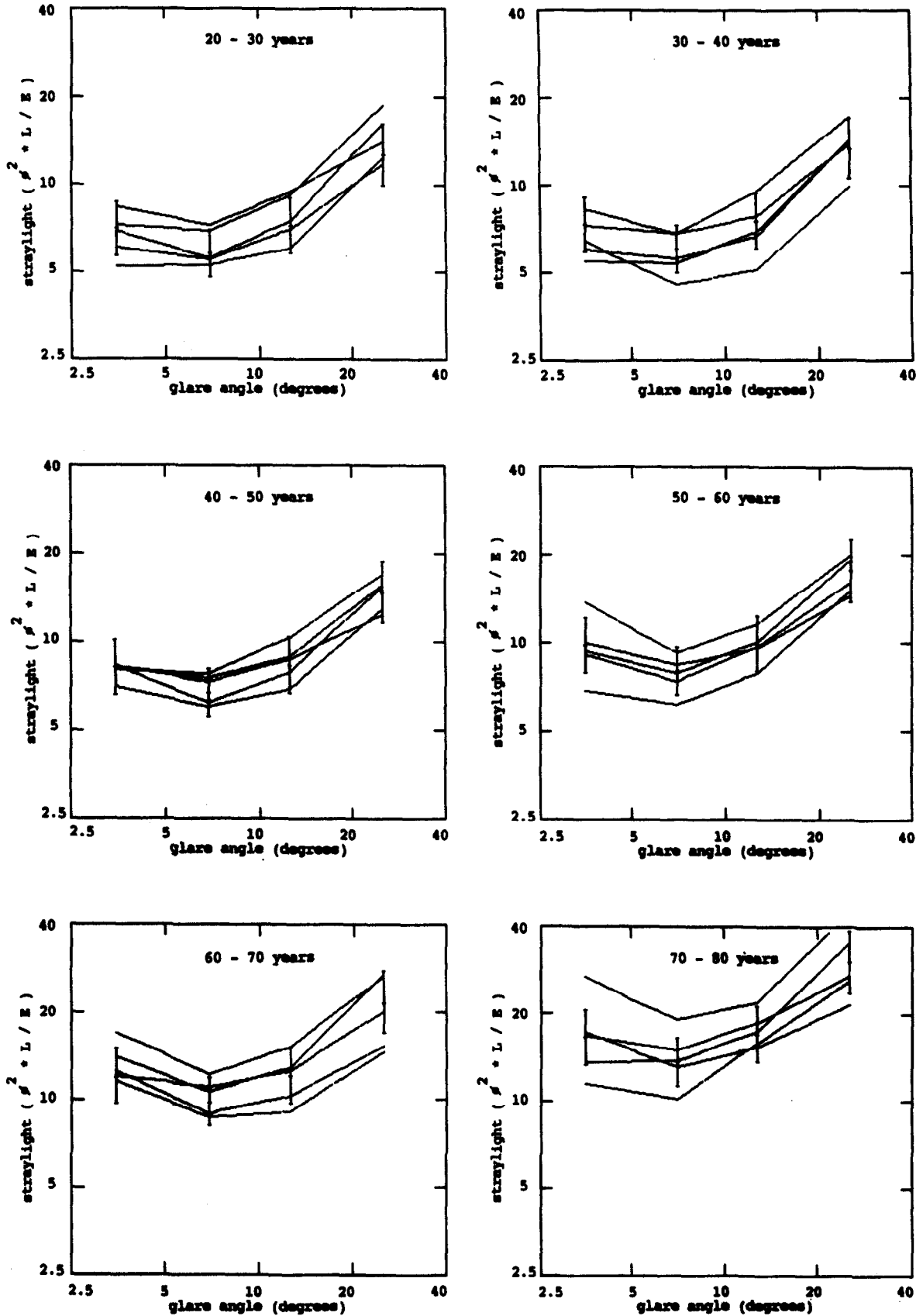


Fig. 2. Straylight as a function of glare angle for six age decades (same data as in Fig. 1). For clarity, for each age decade data of only 5 subjects are presented; the vertical lines represent function (4)  $\pm 1$  SD.

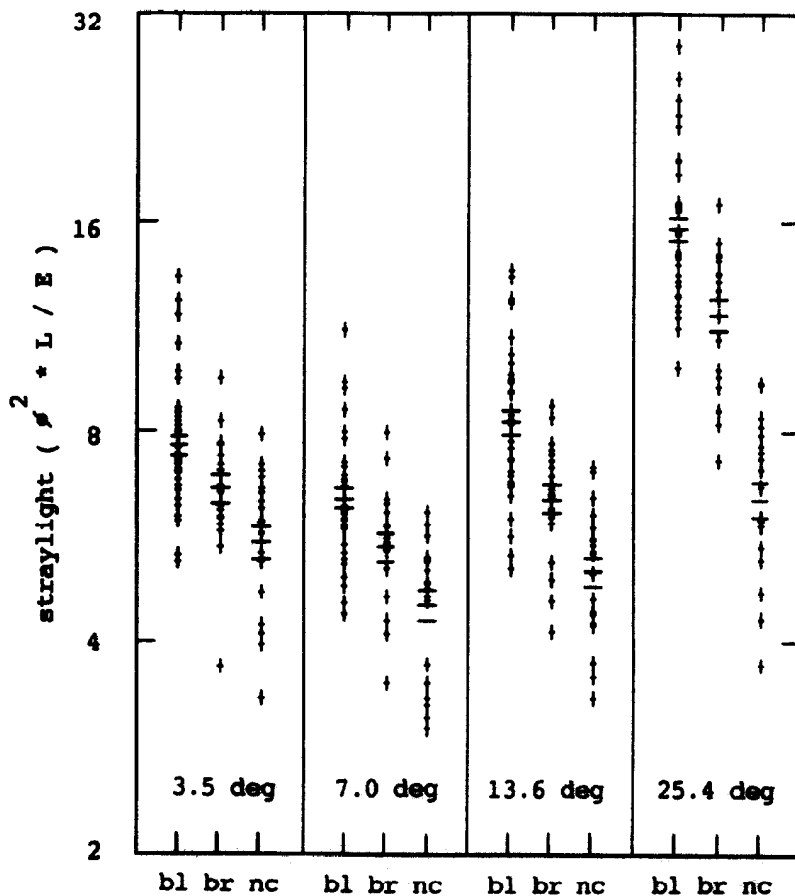


Fig. 3. Dependence of straylight on pigmentation for each of the four glare angles. Only data for subjects with ages under 50 years of age are plotted. Horizontal bars: subgroup means  $\pm 1$  SEM; "bl" = blue-eyed caucasians ( $n = 39$ ); "br" = brown-eyed caucasians ( $n = 19$ ); "nc" = non-caucasians with pigmented skin ( $n = 20$ ).

normality. So, maybe the present population study and age model can be used as a database for other studies involving caucasians.

On the other hand, the possibility must be considered that the age dependence is not only lenticular of origin but also influenced by pigmentation changes with age. Figure 3 shows pigmentation differences between 20 and 50 yr of age to be important. Schmidt and Peisch (1986) and Weiter, Delori, Wing and Fitch (1986) found important losses in ocular pigmentation with age.

A more fundamental objection against the present age model can be made because of the notion "normality" itself. Figure 1 shows that it is "normal" to have at the age of 80 more straylight than at the age of 20. "Normal" is used here in the sense of usual (with the criteria used). But is it also "normal" in the sense that it is to be accepted? In the same way, cataract at 80 yr is "normal" in the sense of usual, but it is not "normal" in the sense that it is to be accepted. Cataract surgery often follows. We

must realize that increased straylight causes lower retinal contrast and increased glare disability. It would be unjust to simply put these aside as "normal". By the way, with cataract surgery advancing, the present population result may no longer be called "normal" in the future. It is with these hesitations that the present model for "normal" behaviour is presented.

A more physical objection to the model is the following. The whole point spread function  $PSF(\phi) = L(\phi)/E(\phi)$  is normalized to unity by integrating over angular space. The extreme case is the ideal forward diffusor. In that case  $PSF(\phi) = 1/(2 \times \pi)$  independent of angle. Up till now we implicitly assumed the illuminance at the retina to be directly proportional to  $L$  at the test field. However, this only holds if the central part (0–1 deg) of the straylight function integrates to the same value for all subjects. The central part is the "measuring stick" since it is used as the reference stimulus. If at the retina the reference is weaker, more of it is needed to reach compensation. So  $L/E$  should

be multiplied by this central integral (a similar correction should be applied to all results in literature). In order to apply this correction, one needs the integral from 0 to 1 deg (or from 1 to 90 deg, as this is complementary). For the young normal eye this integral can be estimated using the PSF formulated by Vos (1984). Its value is 0.90. If we assume the found age dependence to hold over the 1–90 deg range, a correction can be derived:

$$sm(\phi, a) = sm(\phi, 0) - \log\{d + 1/[1 + (a/c)^4]\}; \quad (5)$$

with  $a$ ,  $c$  and the  $sm(\phi, 0)$  values as in (4) and  $d = 0.11$ .

For high ages more and more of the central peak of the PSF is lost towards the 1–90 deg region. Following this model to the extreme would predict at very high ages complete loss of the central peak and an increase from 1 to 90 deg by a factor of  $1/d = 9$ . This is, of course, unrealistic. Extrapolation must be limited to, say, 90 yr of age. For practical application formula (4) may often be the better choice: to judge contrast loss in a test field, because of

sources of straylight in the periphery, it is the ratio between the two retinal illuminances that is important. Formula (4) reveals this ratio more directly.

How do the present results compare with data in the literature? In Fig. 4 our results as summarized by formula (4) (pluses: the values for 35 yr of age) are compared with data from the literature. The proposal of Vos and Bouman (1959) was left out because the refined proposal of Walraven (1973) coincides with it over the angular region of Fig. 4.

The data of Fig. 4 were measured under different circumstances, using different methods; see for a review Vos (1984). The differences in the results are also considerable. We were unable to really pinpoint the reasons for the differences, but several potential causes of discrepancy can be indicated.

#### Subject ages

Our results are plotted for 35 yr of age. For age 50 formula (4) gives an increase of 0.08 log unit. All other curves are for subjects presumably below 50, but not all authors mention the ages of their subjects.

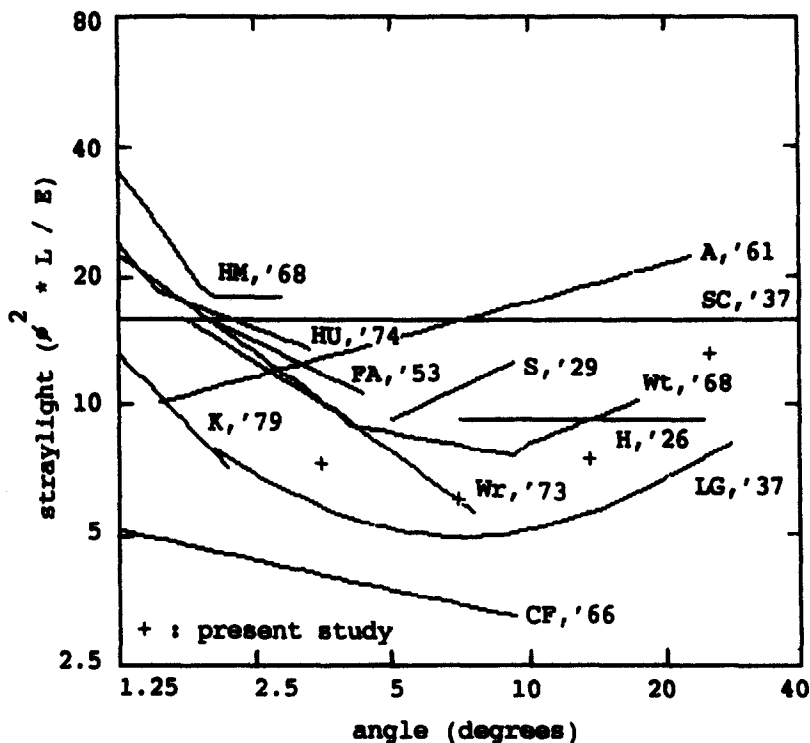


Fig. 4. The drawn lines represent straylight angular dependencies as given by various authors. (+) Present study's caucasian model (4) for 35 yr of age. H = Holladay (1926); S = Stiles (1929); SC = Stiles and Crawford (1937); LG = le Grand (1937); FA = Fry and Alpern (1953); A = Adrian (1961); CF = Christie and Fischer (1966); WR = Walraven (1973), a refinement of Vos and Bouman (1959); WT = Watson (1968); HM = Hartman and Moser (1968); HU = Hartman and Ucke (1974); K = Kirschbaum (1979).

### Interindividual differences

We found the SD of interindividual differences to amount to around 0.1 log unit. Several of the studies were performed on only a limited number of subjects.

### Pigmentation differences

Figure 3 shows blue-eyed caucasians to differ with pigmented non-caucasians by 0.1–0.4 log unit depending on angle. No authors revealed the state of pigmentation of (the eyes of) their subjects.

### Foveal versus extrafoveal viewing

Straylight is foveally presumably less effective as compared to extrafoveally because of the Stiles–Crawford effect. This also depends on the degree to which rod vs cone vision is used; see Vos (1963). This is often hard to judge.

### Pupillary differences

In a series of investigations that is presently in progress we found straylight to increase for dilated pupils as compared to natural pupils (mean 3.5 mm in our experiment) by around 0.1 log unit. Presumably the periphery of the eye lens scatters more (cataract formation often starts peripherally). Several studies were performed at relatively low light levels, but it is hard to judge the effect on pupil size.

Maybe some bias is present in our material: we averaged (see the Methods section) the flicker disappearance point and the flicker reappearance point. Control studies gave indications that the real point of cancellation may in fact be closer to the reappearance point.

With respect to the *mean level* of the SLF, we conclude that significant interindividual differences exist because of age, pigmentation and other (unknown) causes. Added to that is the difference in foveal vs extrafoveal sensitivity to straylight and the pupillary dependence. For accurate calculations of the retinal light distribution, differences seem to be too important to use just one SLF (or PSF).

With respect to the *shape* of the SLF the collected data of Fig. 4 do not point to a strict  $\phi^{-2}$  dependence. Scrutiny of the original data of Stiles and Crawford (1937), SC in our Fig. 4, shows a corresponding deviation from  $\phi^{-2}$  for Stiles; not for Crawford. Instead, above 10 deg the data point toward an exponent in between  $-2$  and  $-1$ . But as

suggested by Fig. 3, the shape of the SLF depends on pigmentation also. This is being studied further.

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