

# Pupil Size and Retinal Straylight in the Normal Eye

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**PURPOSE.** Glare problems originating from bright lights are generally experienced more strongly at night. The typical disability glare is known to result from retinal straylight. In this study, the effects of pupil diameter and, especially in the case of small pupils, of eye wall translucency on the amount of retinal straylight were investigated.

**METHODS.** Straylight was measured as a function of pupil diameter ranging from 1.3 to >8 mm in five normal subjects by using a white-light, CRT-based system for scattering angles of 3.5°, 7°, and 14°. In the study of red-free light, a yellow-LED based system was used with the same five subjects for scattering angles of 3.5°, 10°, and 28°. Data were analyzed to assess effects of (1) inhomogeneity of light-scattering over the pupil plane, (2) translucency of the eye wall, and (3) effects of the periphery of the lens. To estimate the order of magnitude of pupil contraction in the typical glare situation, pupil reflexes resulting from the sudden appearance of headlight-equivalent bright lights were recorded in three subjects in a laboratory environment.

**RESULTS.** For natural pupils (between 2 and 7 mm diameter), straylight weakly depends on pupil diameter (within 0.2 log units). For large scatter angles and small pupil diameters, eye wall translucency contributes significantly to straylight in a wavelength- and pigmentation-dependent manner. Pupil diameters decreased to photopic values under typical night-driving glare conditions.

**CONCLUSIONS.** In normal eyes, straylight values measured with photopic pupils are by approximation also valid for mesopic and scotopic pupils, such as in night driving. Measurement of straylight under large angle and small pupil conditions can be used for quantitative assessment of eye wall translucency. (*Invest Ophthalmol Vis Sci.* 2007;48:2375–2382) DOI:10.1167/iovs.06-0759

As a general rule, glare problems originating from bright lights, such as the headlights of cars, are experienced more strongly at night. The obvious reason may be that at night the eye has to adapt to the general darkness, and the state of dark adaptation may be obviated by the glaring lights. One might argue that in darkness pupil dilation allows more glaring light to have an effect on the retina. This argument, however, is misleading, because larger pupils also allow more light from

the dark scenery to reach the retina, thus counteracting, the effect of the glaring light. In fact, one might expect both effects to balance out precisely, because quantitatively the increase in glare light would equal the increase in direct light. Moreover, the glare light may cause the pupil to shrink to smaller diameters, so that pupil size would be less of a problem. For the present discussion, pupil size effects on wavefront aberrations are disregarded.

For a discussion of these questions, it is important to realize that glare originates from the phenomenon of light-scattering in the eye's optical media. The scattered-light results in a veil of straylight over the retina, which in turn reduces the contrast of the retinal image.<sup>1–3</sup> This not only leads to glare while driving at night, but also to other complaints such as haziness of vision. Different structures in the eye have been identified as sources of retinal straylight. Along the normal optical path, the cornea, crystalline lens, and vitreous may scatter light. Moreover, light reflected more or less diffusely from the fundus also contributes to retinal straylight. Of special significance in the present study is that the eye wall is not completely opaque, but transmits part of the light falling on it.<sup>4</sup> This effect of partial translucency may be more important in the case of small pupil sizes. Straylight and its associated complaints have been documented to increase strongly with age<sup>1,3,5</sup> as well as with other ocular conditions, such as cataract, corneal dystrophies, refractive surgery, and corneal edema.<sup>2,6–10</sup> The present study concerns only the normal eye.

In the present study, straylight was measured as a function of pupil diameter and straylight angle in brown- and blue-eyed subjects, using a CRT-based system<sup>11</sup> (van den Berg TJTP, et al. *IOVS* 2005;46:ARVO E-Abstract 4315). Straylight was also measured in the same subjects with an LED-based system,<sup>12</sup> since the translucency effect (for small pupil sizes) may depend on the color of the light.<sup>4,13</sup> White light is used in the CRT-based system, whereas yellow LEDs are used in the LED-based system. The data were analyzed to assess the effects of (1) inhomogeneity of light-scattering over the pupil plane, (2) translucency of the eye wall, and (3) effects of the periphery of the lens.

In a discussion of pupil effects on nighttime blinding, the pupillary reflex cannot be omitted. It can safely be assumed that the pupil reacts with contraction each time the eye is blinded by bright lights. This may counteract potential effects of the large mesopic pupil. An extra experiment was added to the present study to estimate the order of magnitude of pupil contraction in the typical blinding situation. In the laboratory, pupil reflexes in reaction to the sudden appearance of headlight-equivalent bright lights were recorded in three of the subjects.

## METHODS

### Straylight Theory and Model

Straylight can be quantitatively described in terms of the point-spread function (PSF). The PSF gives the angular distribution on the retina of light originating from a point source, normalized to unity. In fact, straylight is *defined* as the outer skirt of the PSF. In this definition, the PSF is considered in a *functional* way, as the visually effective shape of the light distribution.<sup>1,5,14</sup> The outer skirt, say from 1° to 90°, normally comprises approximately 10% of the total

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amount of light.<sup>5</sup> At approximately 10°, the PSF drops off in proportion to the inverse square of the angle (Stiles-Holladay approximation).<sup>14</sup> In contrast, the central peak of the PSF represents the direct imaging of the scene on the retina.

Assuming that straylight in the normal eye originates from light-scattering in the lens and cornea only and that this light-scattering is uniform over the pupillary surface, the PSF would be independent of pupil size. Consequently, pupil size would affect the overall light intensity, but not the quality of the retinal image. As mentioned earlier, wavefront aberrations are disregarded in the present discussion, because they dominate only the central peak to approximately 20 min arc. That is, for uniform light-scattering over the pupil plane little effect of pupil size would be expected, because both direct (useful) light from the scenery and the scattered (disturbing) light veil from a headlamp would increase in direct proportion to each other with increasing pupil size. In other words, the ratio between the useful and disturbing light, and thus the contrasts in the scenery, would remain constant, even when the Stiles-Crawford effect<sup>15</sup> is taken into account.

However, there are several reasons to doubt the constancy of straylight with pupil size. First, light-scattering may not be homogeneous over the pupil plane, also in normal eyes. Second, retinal straylight does not originate solely from the optical media. The eye wall is partly translucent, adding a more or less isotropic (independent of angle) veil of light on the retina.<sup>4</sup> This *normal* translucency is weak compared with pathologic translucency,<sup>13</sup> but is still significant in a functional sense, especially in blue eyes.<sup>4</sup> Pathologic translucency is often rather localized and not uniform over the whole eye wall, thus limiting its visual effectiveness. The absolute value of this normal translucency straylight component can be assumed to be more or less independent of pupil size, as opposed to the fraction of light entering through the pupil itself. So, this component becomes increasingly important with smaller pupils. Since straylight, as part of the whole PSF, is defined in a relative way (the total PSF is normalized to unity), this means that straylight increases as a result of translucency. Because of the large difference in angular dependence between the translucency component (independent of angle) and the remainder of the PSF (approximately dependent on angle<sup>-2</sup>), this component will dominate the PSF for larger angles, starting at an angle dependent on the individual and on the pupil size. This angle is referred to as the crossing point in this article. As a consequence, a large-angle, small-pupil straylight measurement could in fact be used to estimate the translucency in an individual.

A third phenomenon that may play a role as an extra source of straylight is the zonular area of the eye lens. In very large pupils, the extreme periphery of the eye lens comes into play. Previous work in the laboratory has demonstrated that, with pupil diameters 8 mm and above, the zonular area scatters light much more strongly than more central parts of the lens (van den Berg TJTP, unpublished data, 1992).

### Model for Pupil Dependence of Straylight

The straylight value is defined<sup>5</sup> as the “straylight parameter”  $s$  (unit, square degrees per steradian [deg<sup>2</sup>/sr]). Simply stated, the straylight parameter reflects how much of the light entering the eye is not focused by the optical media to form a retinal image, but is instead scattered by disturbances in the internal optical elements, causing a veil of light over the retina and leading to a reduction of retinal image contrast. The relation between the straylight parameter and the PSF is given by  $s(\theta) = \theta^2 \cdot \text{PSF}(\theta)$ , with  $\theta$  the visual angle in degrees. Because of the approximate Stiles-Holladay law (described earlier), the straylight parameter only weakly depends on  $\theta$ . Note that because of this definition of the straylight parameter, the total amount of light entering the eye cancels out, since the PSF is normalized to unity. So, pupil size per se does not influence the straylight effects, as discussed earlier in this section. Throughout this article the base 10 (Briggs’)  $\log(s)$  will be given.

In a previous study of ocular wall translucency, the relationship between the straylight parameter  $s$  and the so-called diffuse filter value

$dfv$  of a certain piece of ocular wall was derived.<sup>4</sup> The  $dfv$  is defined as the total fraction of light transmitted through the layer under consideration. In other words, the  $dfv$  is the ratio between the total amount of light transmitted by a layer and the total amount of light falling on that layer. Because the eye wall is a very turbid layer in the optical sense, the light exiting at the interior of the eye can be assumed to be fully diffuse. In that case, the following calculation was derived

$$dfv = \frac{\pi \cdot s_t}{\theta^2} \cdot \frac{\text{pupil area}}{\text{wall area}}, \quad (1)$$

with  $s_t$  the contribution to the straylight parameter of the piece of eye wall concerned<sup>4</sup> (e.g., in a light-blue-eyed individual, the  $dfv$  of the iris for red light is found to be 0.01). Note that in both the eye-white and the iris, the pigmented layers on the interior side are the dominant factors for the amount of transmitted light. In that study, ocular wall area was approximated by the area of an annulus around the iris. Because the exact value of the wall area is not well defined, an alternative way to express the amount of transmitted light is used in this study, by calculating the size of a hole in an otherwise opaque eye wall that would transmit the same amount of light. The size of this equivalent hole would correspond to  $dfv \cdot (\text{wall area})$ , or to derive it more directly from the translucency part  $s_t$  of the straylight parameter  $s$  itself

$$\text{equivalent hole area} = \frac{\pi \cdot s_t}{\theta^2} \cdot \text{pupil area}. \quad (2)$$

From the data given in an earlier article (see Ref. 4, Fig. 3), the size of this hole can be derived for the respective cases. For the iris and eye-white of the light-blue-eyed individual, hole areas of respectively 0.19 and 0.51 mm<sup>2</sup> follow. In the blue-eyed individual, the respective values are 0.12 and 0.24 mm<sup>2</sup>. In the same study, the straylight contribution for the combination of iris and eye-white was also determined. From the results given in the same Figure 3,<sup>4</sup> the equivalent hole sizes for the combination are 0.70 and 0.35 mm<sup>2</sup> for the light blue and blue eyes, respectively, virtually identical with the mathematical sum of the equivalent hole sizes for iris and eye-white separately. Note that the size of the equivalent hole is a property of the eye wall and is therefore independent of the pupil area.

In the present study, the different parts of the eye wall were not differentiated. We were interested only in the total amount of light penetrating the eye through the eye wall. This value does not change much with pupil size. The examples just given show that the eye white dominates the iris in this respect. Moreover, because the equivalent holes are much smaller than normal pupil sizes, they gain importance only with very small pupils.

In mathematical terms, the pupil-size dependence of straylight can be formulated as follows. In the midregion of pupil sizes, where neither translucency nor lens periphery plays a role, a simple assumption could be that  $\log(s)$  is linearly related to pupil diameter  $p$ . In mathematical terms

$$\log(s_m) = a \cdot p + b, \quad (3)$$

with  $s_m$  the part of  $s$  that does not originate from translucency. In practice, this assumption worked well (see the Results section). The parameters  $a$  and  $b$  should be fitted for each angle and subject. In fact, the slope parameter  $a$  was found not to vary significantly between different angles. This would correspond to a rule of constancy of the light-scattering material characteristics over the pupillary plane. Only the *amount* of light-scattering material would have to change (for  $a \neq 0$ ).

If we reverse the formula (equation 2) that derives the equivalent hole as a function of  $s_t$  (the part of  $s$  that originates from translucency) we obtain  $s_t = (\text{equivalent hole area})/(\text{pupil area}) \cdot \theta^2/\pi$ . If this

component is added to the mathematical model for pupil size dependence of the straylight parameter (equation 3) we obtain (Fig. 1):

$$s = s_{nt} + s_t = 10^{a \cdot p + b} + \frac{\text{equivalent hole area}}{\text{pupil area}} \cdot \frac{\theta^2}{\pi} \quad (4)$$

This function was fitted to the straylight parameter data of the present paper as a function of pupil diameter  $p$ , using a least-squares criterion on a logarithmic basis (i.e., the log of this equation was fitted). For each subject, all angles were simultaneously fitted, resulting in one estimate per subject for the slope parameter  $a$  and the equivalent hole area. Parameter  $b$  was estimated for each angle separately. The angles available with the CRT-based setup were 3.5°, 7°, and 14° and, with the LED instrument, 3.5°, 10°, and 28°. When the parameters in the model are known, the angle at which the translucency part starts to dominate the linear part can be calculated. This value was denoted as the crossing point and calculated for small, intermediate, and large pupil diameters (2.5, 5, and 7.5 mm, respectively). Note that translucency results in a uniform veil of light over the retina. In case the light source is a point, the total light distribution (PSF) at the retina consists of the typical central peak, sloping off to the periphery according to the approximate Stiles-Holladay  $1/\theta^2$  law, summed with the uniform translucency background. The crossing point corresponds to where the sloping portion reaches the same value as the uniform background originating from translucency.

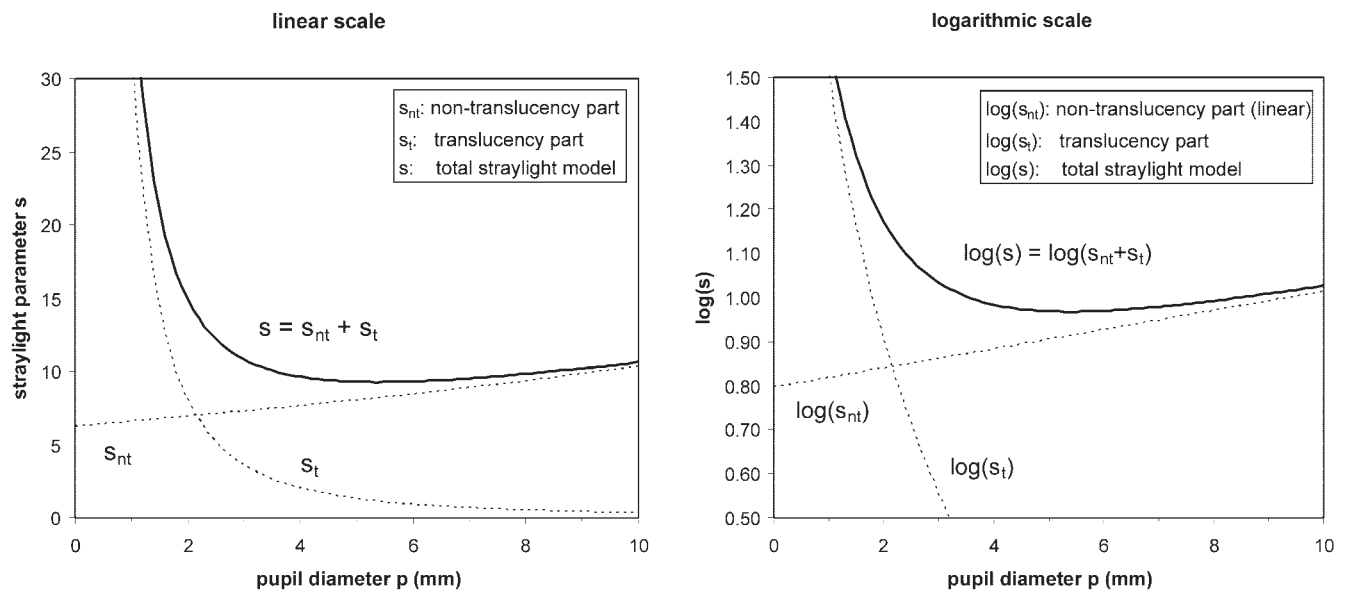
**Experiments**

In short, both the CRT and LED straylight assessment systems involve the presentation of a flickering ring to the subject. Because of light-scattering in the eye, part of the flickering light from this ring also reaches the center of the retinal projection of this ring. Therefore, the subject perceives a (faint) flicker in the center of the ring. With counterphase modulating light added to the center, this straylight flicker can be silenced. The amount of counterphase modulating light needed for silencing directly corresponds to the strength of retinal straylight in this particular individual. This approach was originally implemented in the direct-compensation (DC) method. In this method, the subject adjusts a knob until the flicker is silenced. A noncommercial LED-based desktop instrument, employing this method,<sup>12</sup> was used

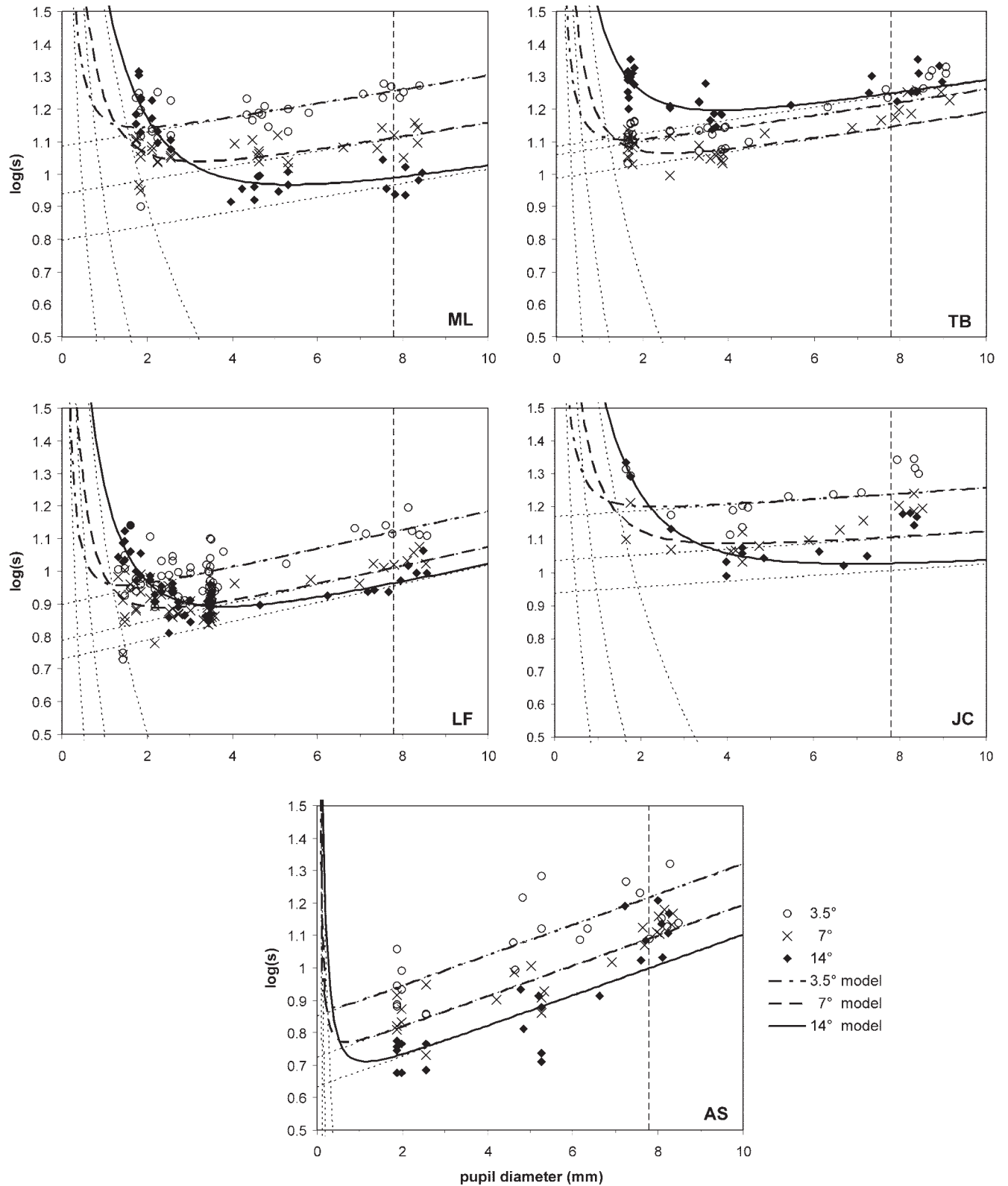
in the present study. Because the DC method proved to be difficult for many subjects naïve to this measurement, the method was changed into a two-alternative, forced-choice approach called compensation comparison (CC)<sup>11</sup> (van den Berg TJTP, et al. *IOVS* 2005;46:ARVO E-Abstract 4315). A CRT-based computer implementation of this method was used in the present study. Recently, a market instrument using white LEDs was manufactured (C-Quant; Oculus GmbH, Wetzlar, Germany).

Five subjects (ages 29, 31, 37, 37 and 59 years) participated in the study. They were all coworkers, including the authors. All subjects were without ocular defects. Testing was performed monocularly on the subject’s preferred eye. Refraction ranged from -5 D to emmetropic. Refractive correction was performed with trial glasses. It must be noted that straylight measurement does not require refractive correction to be precise. Corrections were chosen for comfortable viewing, resulting in a +2 near addition for the older subjects in case of straylight measurements using the CRT-based system, since these tests were performed at a distance of 32 cm from the stimulus screen. Near correction was not needed in the LED-based system,<sup>12</sup> because in that case the stimulus is effectively viewed at approximately 1 m. The measured straylight values were in the normal range for the respective ages.<sup>5</sup> Miosis was obtained with pilocarpine 2.0% and thymoxamine 0.5%. Dilation was obtained with phenylephrine 5% and tropicamide 0.5%. A CCD camera was used to record pupil diameter. The study adhered to the guidelines of the Declaration of Helsinki for research in human subjects.

For the pupil reflex experiments, three subjects were exposed in the laboratory to 1-second flashes of bright light simulating a typical car low-beam headlight glare situation. Pupil reflexes were recorded with an infrared camera, allowing pupil diameters to be extracted from the camera images with image-analysis software. During the whole experiment, the subject was looking at a test field of 1 cd/m<sup>2</sup>, typical for a roadway at night illuminated by roadway lighting or own low-beam car headlights.<sup>16,17</sup> The glare light was placed at a 3° visual angle, and produced an illuminance of 1.1 lumen/m<sup>2</sup> at the location of the eye, which is typical when facing low-beam headlights on a two-lane road at night.<sup>16-18</sup> Because higher values are sometimes encountered for low beams, an illuminance of 4.4 lumen/m<sup>2</sup> was also used.



**FIGURE 1.** Model for pupil-size dependence of straylight. The model consists of two parts: a part that accounts for the scatter by cornea, lens, and fundus (dotted curve  $s_{nt}$ ) and a part that accounts for the translucency of the eye wall (dotted curve  $s_t$ ). The total model (solid curve  $s$ ) consists of the sum of both parts (equation 4, left graph). In practice, the logarithm of the straylight parameter  $\log(s)$  is used. Therefore, the results in this article are presented on a  $\log(s)$  scale, as in the right graph.



**FIGURE 2.** Straylight values as a function of pupil diameter in the five subjects, measured with a white-light, CRT-based system at 3.5°, 7°, and 14° scattering angles. Measurements were made in natural pupils as well as with artificially dilated and artificially constricted pupils. *Solid and dashed lines:* model fits for the respective scatter angles. *Straight dotted lines:* the linear, nontranslucent part of the model. *Dotted lines curving upward* at small pupil diameters give the translucency part of the model. Measurements at pupil diameters above 7.8 mm were excluded from the model fit. Numerical results of the fit are given in Table 1.

TABLE 1. Model Parameters for the Straylight Measurements at Different Pupil Diameters in the Five Subjects

Subj.	Age (y)	Iris Color	Slope <i>a</i> 1/mm	Parameter Values White Light (CRT)			Translucency (Equivalent mm <sup>2</sup> )	Crossing (deg.)			Yellow LEDs Translucency (Equivalent mm <sup>2</sup> )
				Constant <i>b</i>				2.5 mm	5 mm	7.5 mm	
				3.5°	7°	14°					
ML	29	Light blue 3	0.022	1.08	0.94	0.80	0.40	19	41	66	0.07
TB	59	Blue 5	0.020	1.06	0.99	1.08	0.23	29	61	97	0.11
LF	31	Blue-green 8	0.029	0.90	0.79	0.73	0.16	27	59	96	0.04
JC	37	Blue-green 11	0.009	1.17	1.04	0.94	0.42	21	43	66	0.10
AS	37	Pigm. brown 23	0.047	0.85	0.72	0.63	0.00	152	348	598	0.02

The numbers in the 3rd column (iris color) represent an iris color ranking value (explained in a forthcoming paper [in preparation]). The parameters *a* (4th column) and *b* (5th-7th columns) account for the straylight part that does not originate from eyewall translucency. The translucency parameter (8th column for the white-light, CRT-based setup; 12th column for the yellow-LED based setup), expressed in equivalent hole area, accounts for the straylight part originating from eyewall translucency. The crossing parameter (9th-11th columns) gives the scatter angle above which the translucency straylight part dominates the nontranslucency part, for three different pupil diameters (2.5, 5, and 7.5 mm).

## RESULTS

Figure 2 gives the log(*s*) values for the CRT-based setup for all five subjects as a function of pupil diameter. Results are given for 3.5°, 7°, and 14°. It is clear that straylight weakly changed with pupil size. For most subjects/angles, straylight varied a few tenths of a log unit. Note that this is much less than the variation that would result if the straylight parameter were proportional to pupil area (see the introduction). In that case, an increase over a factor of 16 or 1.2 log units would result if pupil size increased from 2 to 8 mm. On close inspection, some systematic variations can be seen. Note the difference in behavior between the 3.5° and 14° data. The 3.5° data all show a rectilinear course all the way down to the smallest pupil sizes. The 14° data often show a strong uplift at small pupil sizes. When the earlier-mentioned two-component model is fitted (continuous and dashed lines) these systematic variations become clearer. Both components of the model are plotted separately as dotted lines. The straight dotted lines give the linear part of the model (*s<sub>n</sub>*). The dotted lines curving upward at small pupils give the translucency part of the model (*s<sub>t</sub>*). Numerical results of the fit in Table 1 show a linear increase with pupil size in all cases (fourth column). On average, the increase was 0.025 log units per mm of pupil diameter increase.

Note that the rectilinear portion of the experimental data suggests no change in angular dependence of the straylight values with pupil size. This would translate into an identical slope parameter *a* for all angles. An originally adopted fit of independent *a* parameters for each angle/subject combination did not result in significantly different *a* values between angles. Therefore, a single slope parameter was fitted for each subject.

For small pupils, the effect of translucency sets in, reversing the drop toward smaller pupil sizes, especially for the largest angle of 14° (closed dots). Table 1 gives the corresponding values (eighth column). The translucency values for the four more lightly pigmented subjects average around 0.30 mm<sup>2</sup>. The brown-eyed, pigmented-skinned individual had 0.00 mm<sup>2</sup>, in correspondence with the earlier direct measurements.<sup>4</sup>

Table 1 shows the crossing values (9th to 11th columns), which are the angles at which the straylight originating from eye wall translucency equals the nontranslucency straylight part, calculated for pupil diameters of 2.5, 5, and 7.5 mm. It is clear that the values for subject AS are not physically realistic. This emphasizes that translucency is negligible in all angular domains in this subject.

The straylight measurements with the LED instrument (Fig. 3) gave systematically lower translucency (Table 1, 12th column). This result is understandable, since the eye wall transmits only the long wavelength part of the visual spectrum (see

the Discussion section). Again, the lightly pigmented eyes show much higher values compared with the brown eyes.

The third anticipated effect, an increase in straylight due to the lens periphery for large pupil diameters, is not very prominent (Fig. 2). In the two youngest subjects, ML and LF, the data above 7.8 mm did not deviate from the linear trend estimated on the basis of the data up to 7.8 mm. Only the two oldest subjects, JC and TB, showed clearly higher values above 7.8 mm pupil diameter. The remaining subject AS showed an indecisive increase above 7.8 mm.

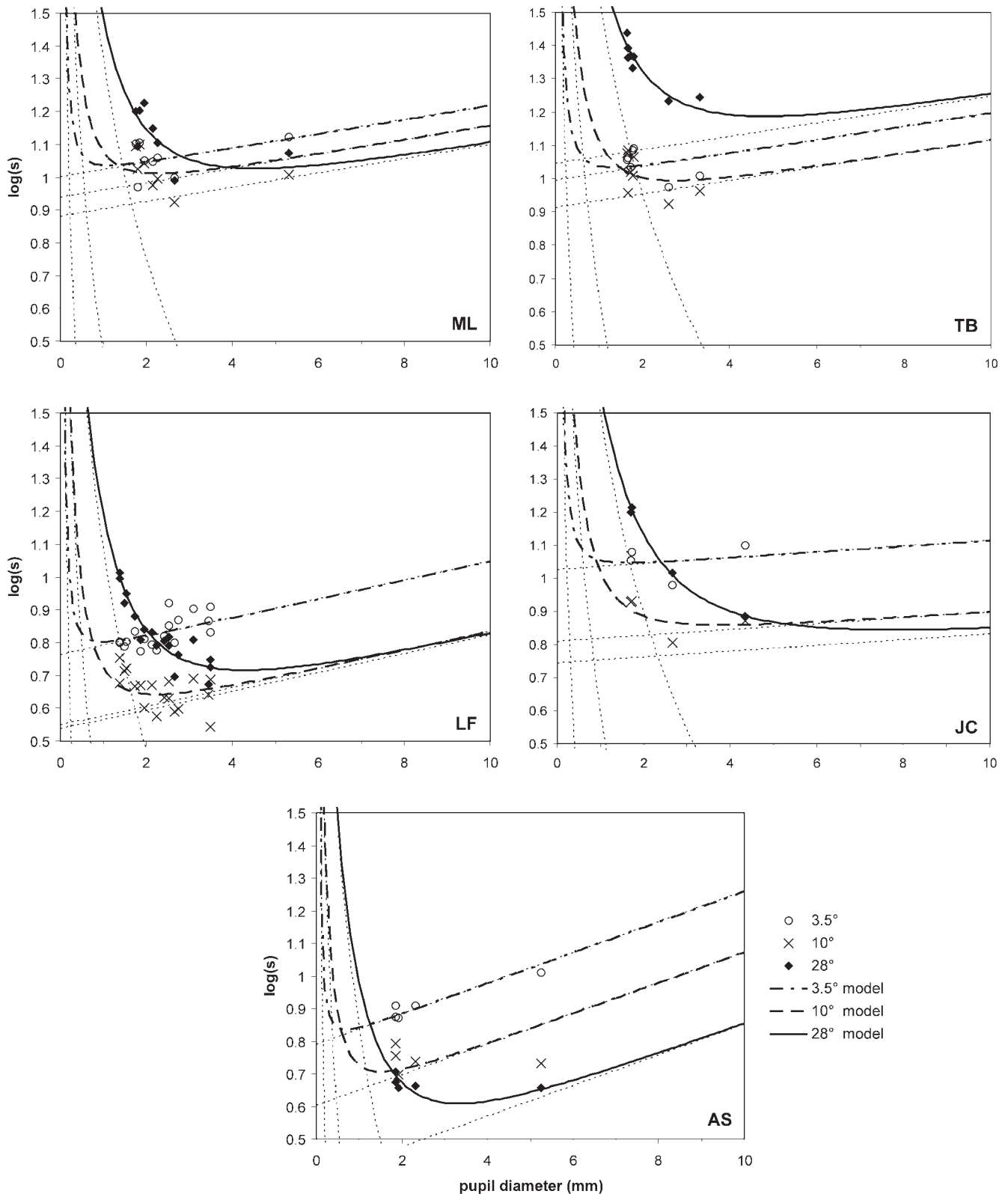
Figure 4 shows the deviations of the experimental data from the model fit for the white-light measurements (Fig. 2). This figure can be used to assess the goodness of fit of the proposed model. The figure shows that the experimental data do not systematically deviate from the model until the pupil diameter exceeds 8 mm. This result shows that the model is supported by the data, at least in mathematical sense. Above 8 mm (outside the range of the fit) some deviation can be seen. Some extra increase in straylight occurs here in the older eyes. For these large pupil diameters, the lens periphery effect starts to play a role, which was not accounted for by the model.

Figure 4 also shows the random errors. For small pupil diameters, the spread of data points around the model values seems larger than that for the intermediate pupil diameters (see the Discussion section).

Figure 5 shows the results of the pupil reflex experiments for the 1.1 lumen/m<sup>2</sup> glare illuminance. In two subjects, the pupil diameter decreased from approximately 7 mm (adapted to 1 cd/m<sup>2</sup> roadway luminance) to a minimum of 4 to 5 mm during the 1-second glare flashes. In the third subject, the pupil diameter decreased from a little >5 mm to approximately 3.5 mm. The figure shows that the glare effect invokes significant pupillary contraction, and that the contraction makes the pupil size approach daylight situations. For the 4.4-lumen/m<sup>2</sup> glare illuminance, pupil contraction was found to be more severe. One subject changed from 7 to 3.5 mm, another subject changed from a little more than 5 to approximately 2.5 mm.

## DISCUSSION

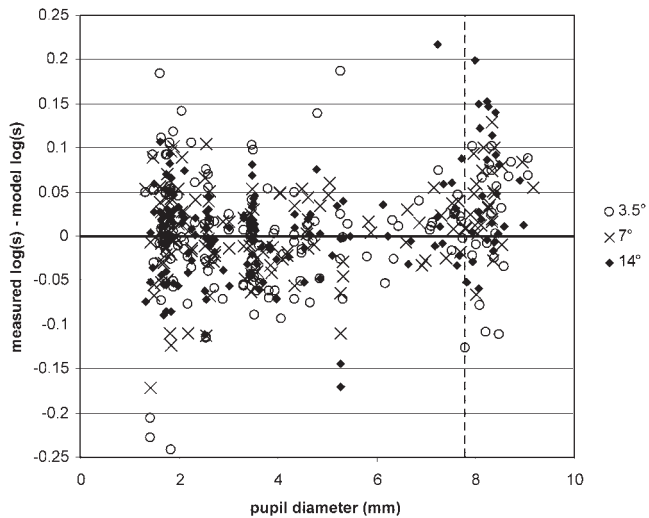
In the present study, the dependence of straylight on pupil diameter for normal eyes was assessed. Figures 2 and 3 show that the straylight parameter log(*s*) does not change much for pupil diameters between 2 and 8 mm. However, at larger angles and at pupil diameters smaller than 2 mm, straylight may increase considerably. This was explained by the (nonpathologic) translucency of the eye wall, which contributes significantly to the total amount of straylight. The effect varied



**FIGURE 3.** Straylight values as a function of pupil diameter in the five subjects, measured with the yellow-LED based system at 3.5°, 10°, and 28° scattering angles. Measurements were made with both natural and artificially constricted pupils. The curves have the same meaning as in Figure 2. Translucencies resulting from these measurements are given in the last column of Table 1.

considerably among the subjects. The figures show that this effect is virtually zero if the eye is more strongly pigmented. The variation is in agreement with earlier work,<sup>4</sup> in which eye

wall translucency was shown to vary by orders of magnitude between normal-eyed subjects, being very low in well-pigmented eyes.



**FIGURE 4.** Plot of residuals for the white-light measurements (Fig. 2, CRT-based system). Deviations of the experimental data from the model fit for all the five subjects are presented. Data points with pupil diameters above 7.8 mm were excluded from the model fit.

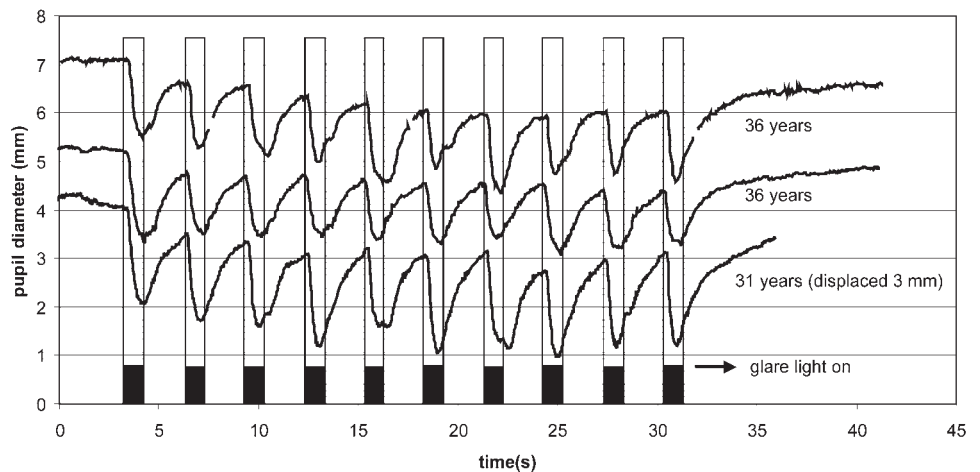
Note that the *b* values in Table 1 (fifth–seventh columns), which can be regarded as the straylight part not originating from eye wall transluency, are lower in the subjects with lower transluency values (LF and AS, eighth column). Speculatively, this can be understood as follows. Earlier studies<sup>1,4</sup> concluded that light scattered back from the fundus also contributes to retinal straylight. Because fundus reflectance is highly pigmentation dependent, the eyes of those two subjects probably contain a relatively high amount of pigment, causing both transluency and fundus reflectance to be low, giving rise to relatively low *b* values.

Eye wall transluencies for yellow light were found to be much lower than those for white light (Table 1, 8th and 12th columns). To account for these differences, the wavelength-dependent light absorption characteristics of the eye wall should be considered. The eye wall contains hemoglobin, which acts as a high-pass filter (in terms of wavelength) with a cutoff wavelength of approximately 620 nm. This means that wavelengths below 620 nm are much more strongly absorbed than wavelengths above 620 nm. The yellow LEDs used in the LED-based instrument have a peak wavelength at 570 nm and a full width at half maximum of 30 nm.<sup>12</sup> So, most of the light emitted by these LEDs is absorbed by the layers in the eye wall.

The white light of the CRT-based setup is produced by three types of phosphors, one of which emits most of the light at narrow peaks around 625 and 710 nm.<sup>19</sup> This light is much less absorbed by the eye wall layers, and probably dominates the total amount of light transmitted through the eye wall, and it may have caused the eye wall transluency to be much higher in the CRT-based setup than in the yellow-LED setup.

When the transluency data for white light from the earlier work<sup>4</sup> are expressed in equivalent hole areas (0.70 and 0.35 mm<sup>2</sup> for the light blue and blue eyes, respectively), as explained in the Straylight Theory and Model section, they appear to be in the same order of magnitude as the values found in the present study (0.16–0.42 mm<sup>2</sup>, Table 1, 8th column, for light blue to blue-green eyes). A precise comparison may not be valid, since the spectral characteristics of the white light were not the same in both experiments (CRT versus halogen with specified color temperatures of 2900–3150 K). The white light in the earlier experiments may have had a stronger red component, causing the transluency values to be higher. One particular subject participated in both the earlier and the present experiments. His transluency was lower in the current experiment (0.23 vs. 0.35 mm<sup>2</sup> equivalent hole area), also pointing in the direction of a stronger red component.

Differences between subjects in the data presented in Figures 2 and 3 and Table 1 can be interpreted as variations in the characteristics of the light-scattering elements in the crystalline lens. As explained in the Straylight Theory and Model section, the linear part of the model represents the normal scattering behavior of the eye lens material. Variation in the offset parameter *b* in this model was particularly clear in the oldest subject (TB): His 14° curve was relatively high compared with the curves of the other two angles. Note, however, that these differences are not large. They are on the order of 0.06 log units (factor 1.1), whereas the first-order effect ( $1/\theta^2$  or Stiles-Holladay law) is of the order of 0.6 log units (factor 4). Detailed knowledge about the physical properties of the lens material would be needed to explain these types of differences. Because the 14° curve was the lowest for most subjects and transluency is relatively more important at this angle, this curve crossed the curves for the other angles with the exception of subject TB, whose 14° curve was already high. In addition, the slope parameter *a* showed some variation between the subjects. A positive value indicates that the relevant eye scattering processes (particles) were more abundant in the periphery than in the center of the eye lens. This concept holds for all subjects. These local differences, however, were less important in some subjects, especially JC, who had the lowest slope parameter, as opposed to AS, who had the highest



**FIGURE 5.** Pupil reaction for 3 subjects in a laboratory simulation of typical low-beam headlight glare. While adapted to a constant luminance of 1 cd/m<sup>2</sup>, the eyes were exposed 10 times to 1-second duration low-beam headlight-equivalent bright lights (3° visual angle, 1.1 lumen/m<sup>2</sup> illuminance at the eye).

slope parameter. Note, however, that the absolute values of the slope were not high. For the subject with the highest slope, AS, the variation in straylight from a 2- to 8-mm pupil diameter was less than a factor of 2. Again, more detailed study of the eye lenses would be needed to understand the local differences within the lens.

It is clear from Figures 2 and 3 that the largest straylight increases are to be expected for extremely small pupil diameters. In fact, these pupil diameters are so small that they cannot be produced by the human eye, not even with the help of miotic drops. One might think that artificial pupils could help to acquire data in this pupil range. However, since these artificial pupils would cover not only part of the pupil but also the complete eye wall, they cannot be used for these types of experiments.

As mentioned in the Results section, the residual plot of Figure 4 shows that for small pupil diameters the spread of data points around the model values seems larger than intermediate pupil diameters, perhaps because, with small pupils, the total amount of light entering the eye is smaller, which makes the flicker comparison task more difficult for the subject. Note that the flicker comparison task is performed at relatively low luminance levels. These levels are on the order of the straylight light level. The formula given earlier<sup>5</sup> can be used to calculate that if  $\log(s) = 1.0$ , the equivalent luminance of the straylight light level is 1.3% of the luminance in the ring. With this luminance equal to approximately  $96 \text{ cd/m}^2$ , the (equivalent) luminance of the test field is approximately  $1.25 \text{ cd/m}^2$ . For natural pupils, this is at mesopic levels. In miotic pupils, this corresponds to much lower luminances, say  $0.1 \text{ cd/m}^2$  or even lower with a 1.3 mm diameter pupil. At such low luminances, flicker sensitivity drops strongly, which may explain the increased uncertainty in this area.

The pupil reflex experiments show that the appearance of bright lights simulating headlights under typical nighttime lighting conditions causes natural pupils to contract to daytime diameters. This supports the general conclusion of this study that pupil diameter is not an important factor when considering the amount of straylight hindrance at night. A more important aspect of this pupil contraction may be that aberrations that are most troublesome for wide-open pupils, such as spherical aberration, will be a much less serious problem for the headlight condition, because they tend to be blocked as the pupil closes. This means that certain types of aberrations are only of concern when the ability to perceive low-contrast objects during nighttime driving is reduced because the pupil remains fully open. When a car approaches, its headlights cause the pupil to contract, reducing the amount of aberrations. In this way, the problem of aberration is, as it were, replaced by a problem of disability glare.

Two general conclusions can be drawn from the present study. First, measurement of straylight in large-angle and small-pupil conditions clearly shows the effects of eye wall translucency. Second, in natural pupils, say between 2 and 7 mm in diameter, straylight can be regarded as rather weakly dependent on pupil diameter (within 0.2 log units). In a practical

sense, this means that straylight values, measured under photopic conditions, such as with the straylight meter (C-Quant; Oculus), are also valid under mesopic and scotopic circumstances, such as in night driving. If very precise values are needed though, pupil diameter must be taken into account.

## References

- Vos JJ. Disability glare: a state of the art report. *Commission International de l'Eclairage Journal*. 1984;3/2:39-53.
- van den Berg TJTP. Importance of pathological intraocular light scatter for visual disability. *Doc Ophthalmol*. 1986;61:327-333.
- Elliott DB, Bullimore MA. Assessing the reliability, discriminative ability, and validity of disability glare tests. *Invest Ophthalmol Vis Sci*. 1993;34:108-119.
- van den Berg TJTP, Ijspeert JK, de Waard PW. Dependence of intraocular straylight on pigmentation and light transmission through the ocular wall. *Vision Res*. 1991;31:1361-1367.
- van den Berg TJTP. Analysis of intraocular straylight, especially in relation to age. *Optom Vis Sci*. 1995;72:52-59.
- de Waard PW, Ijspeert JK, van den Berg TJTP, de Jong PT. Intraocular light scattering in age-related cataracts. *Invest Ophthalmol Vis Sci*. 1992;33:618-625.
- Veraart HG, van den Berg TJTP, Ijspeert JK, Cardozo OL. Stray light in radial keratotomy and the influence of pupil size and straylight angle. *Am J Ophthalmol*. 1992;114:424-428.
- van den Berg TJTP, Hwan BS, Delleman JW. The intraocular straylight function in some hereditary corneal dystrophies. *Doc Ophthalmol*. 1993;85:13-19.
- Elliott DB, Fonn D, Flanagan J, Doughty M. Relative sensitivity of clinical tests to hydrophilic lens-induced corneal thickness changes. *Optom Vis Sci*. 1993;70:1044-1048.
- Beerthuisen JGG, Franssen L, Landesz M, van den Berg TJTP. Straylight values one month after LASIK and PRK. *J Cataract Refract Surg*. In press.
- Franssen L, Coppens JE, van den Berg TJTP. Compensation comparison method for assessment of retinal straylight. *Invest Ophthalmol Vis Sci*. 2006;47:768-776.
- van den Berg TJTP, Ijspeert JK. Clinical assessment of intraocular straylight. *Appl Opt*. 1992;31:3694-3696.
- La Hey E, Ijspeert JK, van den Berg TJTP, Kijlstra A. Quantitative analysis of iris translucency in Fuchs' heterochromic cyclitis. *Invest Ophthalmol Vis Sci*. 1993;34:2931-2942.
- Vos JJ, van den Berg TJTP. The large angle course of the disability glare function and its attribution to components of intraocular scatter. *CIE Collection*. 1997;124:11-29.
- Wyszecki G, Stiles WS. *Color Science*. 1982. Wiley, New York.
- van den Berg TJTP, van Rijn LJ, and GLARE consortium. *Relevance of Glare Sensitivity and Impairment of Visual Function among European Drivers*. www.glare.eu. 2005.
- Flannagan MJ. *Subjective and Objective Aspects of Headlamp Glare: Effects of Size and Spectral Power Distribution*. UMTRI-99-36. Ann Arbor, MI: University of Michigan Transportation Research Institute; 1999; available at <http://dmses.dot.gov/docimages/p62-133369.pdf>
- Smith G. Disability glare and its clinical significance. *Optom Today* 2002;(April 19)34-37.
- Golz J, MacLeod DI. Colorimetry for CRT displays. *J Opt Soc Am A Opt Image Sci Vis*. 2003;20:769-781.