History of ocular straylight measurement: A review

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Abstract

The earliest studies on 'disability glare' date from the early 20th century. The condition was defined as the negative effect on visual function of a bright light located at some distance in the visual field. It was found that for larger angles (>1degree) the functional effect corresponded precisely to the effect of a light with a luminosity equal to that of the light that is perceived spreading around such a bright source. This perceived spreading of light was called straylight and by international standard disability glare was defined as identical to straylight. The phenomenon was recognized in the ophthalmological community as an important aspect of the quality of vision and attempts were made to design instruments to measure it. This must not be confused with instruments that assess light spreading over small distances (<1 degree), as originating from (higher order) aberrations and defocus. In recent years a new instrument has gained acceptance (C-Quant) for objective and controllable assessment of straylight in the clinical setting. This overview provides a sketch of the historical development of straylight measurement, as well as the results of studies on the origins of straylight (or disability glare) in the normal eye, and on findings on cataract (surgery) and corneal conditions.

Geschichte der Messung des okularen Streulichts: Eine Übersicht

Zusammenfassung

Am Anfang des 20. Jahrhunderts wurden umfangreiche Untersuchungen zur „physiologischen Blendung“ durchgeführt, definiert als die Beeinträchtigung des Sehens durch eine helle Lichtquelle, die in einem bestimmten Abstand innerhalb des Gesichtsfelds gelegen ist. Es wurde herausgefunden, dass für größere Winkel (>1Grad) der Funktionseffekt genau dem Effekt eines Lichtes mit einer Helligkeit entsprach, die der des Lichtes gleich ist, das als um eine solche helle Quelle herum sich ausbreitend wahrgenommen wird. Dieses um eine Lichtquelle herum wahrgenommene Licht wurde Streulicht genannt und als internationaler Standard wurde die physiologische Blendung als identisch zum Streulicht definiert. Das Phänomen wurde in der ophthalmologischen Gemeinschaft als wichtiger Aspekt der Qualität des Sehens erkannt und es wurde versucht, Instrumente zu entwerfen, um sie zu messen. Die Instrumente zur Streulichtmessung dürfen nicht mit solchen Instrumenten verwechselt werden, die sich in kleinem Winkel (<1 Grad) ausbreitendes Licht messen, welches durch Aberrationen (höherer Ordnung)

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und Defokussierung entsteht. Seit einigen Jahren gibt es ein Instrument (C-Quant) zur objektiven und kontrollierbaren Bestimmung von okularem Streulicht in der Klinik. In diesem Überblick werden die historische Entwicklung der Messung des okularen Streulichts, der Untersuchungen zum Ursprung von Streulicht (oder physiologischer Blendung) im normalen Auge sowie die Ergebnisse für Katarakte (Chirurgie) und Korneakonditionen skizziert.

Keywords: Glare, straylight, intraocular light scatter, quality of vision, contrast sensitivity

Schlüsselwörter: Streulicht, physiologische Blendung, greller Glanz, intraokulare Lichtstreuung, Qualität des Sehens, Kontrastempfindlichkeit

I Introduction

This paper provides an overview of the developments in the field of glare and straylight measurement that led to the recent insights in straylight and its measurement, using compensation techniques. As early as the first half of the 20th century, studies were carried out that have led to the since then generally accepted view that disability glare can be fully understood on the basis of the optical phenomenon of light scattering in the eye, leading to a veil of light at the retina. Consequently, the CIE (Commission Internationale de l'Eclairage) *defined* disability glare as straylight. Both are quantified by means of the psychophysically measurable value L_{eq}/E_{bl} [1,2] (detailed below), used as the basis of present day straylight assessment [3]. The commercial C-Quant straylight meter is the latest step in the development of these techniques. To be precise, straylight is a functional measure. It is a measure for what is *seen* (the intensity of light spreading). It is not directly a measurement of retinal light levels, but closely linked. The CIE also developed the Standard Glare Observer [4]. Today it is realized that ocular straylight constitutes a visual handicap of a much more general nature than glare alone. Patient complaints may include problems of "hazy vision", contrast and color loss, difficulty with face recognition when looking against the light, halos around bright lights, etc. Straylight also adversely affects visual function tests, such as contrast sensitivity [5], visual field [6–8], and pattern electroretinogram (PERG) [9]. Since the development of a clinical straylight instrument was unsuccessful for a long time, dozens of glare testers have been defined as alternatives. These instruments do not assess straylight or disability glare, but a more or less related score [10,11]. It has also been proposed to assess straylight with a double pass technique using infrared light [12], but this is not correct [13,14]. However, a current study, using visible light and other improvements, shows promising results [15]. The present paper will review only approaches that meet the CIE definition, not the glare testing approaches. For an overview of optical techniques for measuring ocular scattering - with their advantages and disadvantages, please see Pinero et al. [16].

Basic Principles

Since the beginning of the 20th century, the importance of straylight for visual function has been recognized by many investigators. Cobb [17] introduced the concept of "equivalent veiling luminance" (L_{eq}) as an apt way to define straylight (see section Direct Compensation below and Figure 1 for details). Disability glare/straylight, as defined by the CIE, is now quantified by means of this equivalent luminance, i.e. the (external) luminance that has the same visual effect as the glare source at some angular distance [1]. Holladay [18] and Stiles [19] applied this concept to their measurements and formulated a disability glare formula that was widely used. Nowadays, straylight can also be defined as the outer skirt of the point spread function (PSF) [4,20–22], outside approx. 1°, although straylight is defined in a *functional* sense by L_{eq}, since it defines what is *perceived*. It is generally accepted that it corresponds closely to optics based on much earlier study [1] and recent verification [23]. Straylight corresponds to a veiling luminance over the whole retina that adds to the retinal projection of the visual scene, thereby reducing the contrast of the retinal image.

The first attempts to measure ocular straylight by means of equivalent luminance involved two types of threshold measurements: thresholds in the presence of a distant glare source and thresholds in the presence of a homogeneous background luminance. From such a series of measurements the equivalent luminance could be derived, defined as the luminance yielding identical thresholds as the glare source (equivalent veil method) [1]. This method was laborious and therefore unsuitable in practice, such as for clinical applications or driver-licensing, with large variation reported between the older studies [2]. However, the method continued to be used in experimental applications [24,25]. Alternatives were designed to circumvent the problem of the disproportionate amount of

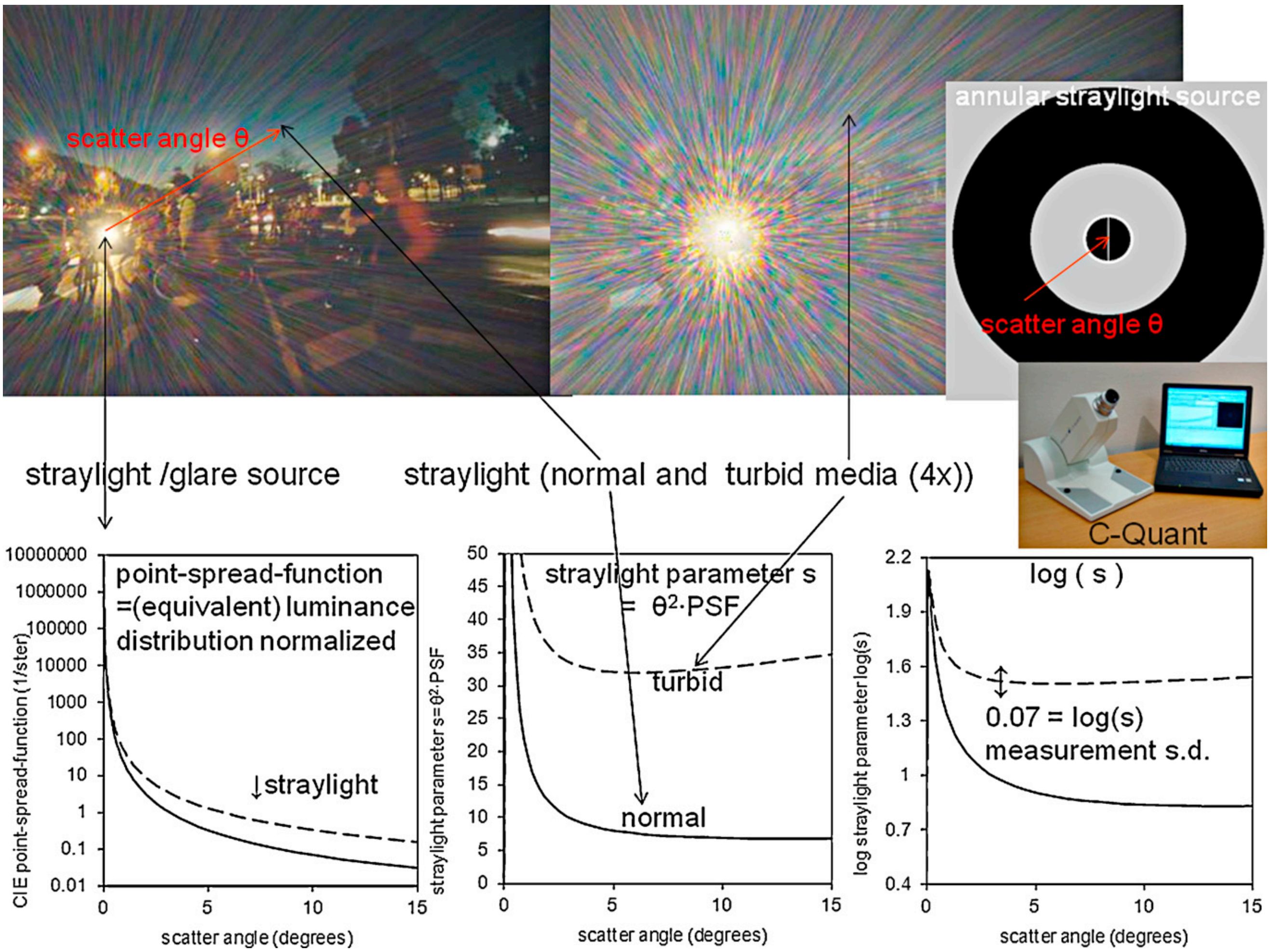

Figure 1. Basics of straylight quantification. At the top a street scene is depicted as it would be seen by an eye with normal straylight (left), and by an eye with 4x increased straylight (right). The 3 figures at the bottom give the point-spread-function according to the CIE for average age-best eyes. The PSF is given using 3 corresponding definitions: the normal (left), the straylight parameter s linearly (middle), and the same logarithmically (right). The continuous line is for an average 35-year-old Caucasian eye; the dashed line is for a caucasian eye with media turbidity increasing straylight 4x, mimicked using the CIE function for a 95-year-old. At the top right the stimulus lay-out is shown as used in the C-Quant.

measurements [26–32], which led to a discussion of matters of validity [11,33–35]. The alternative method of Paulsson and Sjöstrand (P&S) was used particularly widely [27]. As even more easy-to-use alternatives, so-called ‘glare testers’ were introduced, usually consisting of a visual acuity (e.g., ETDRS [36–38], Ferris-Bailey [39], Bailey-Lovie [40,41], or Regan [40] charts) or contrast sensitivity (e.g., sinusoidal gratings [36,40,42–44], Landolt rings [36,45–48], or Pelli-Robson charts [32,39,40]) test, with and without a glare source presented at some angular distance in the visual field. Some studies utilized a laboratory setup based on the same principles, with visual field stimuli [49–51], a flashing test field [52], sinusoidal gratings [53], or low contrast letters [54] as targets, and also for specific nighttime conditions [55]. Although occasionally glare testers got favorable reviews [40], more often they yielded unreliable results, with outcomes that did not correlate well with various validity measures, such as outdoor visual acuity in bright sunlight [36,44], a questionnaire assessing perceived visual disability [39,45], or directly measured forward light scatter [40,45]. Also, the repeatability and discriminative ability of the glare tests studied were found to be inadequate [40,45,56,57]. The glare test data were omitted from the final results of the large multicenter PERK study [58], because the glare tester was not sufficiently sensitive to detect small but significant amounts of light scattering [40,59,60]. As a result of all these issues, a standard glare measurement test was never adopted, and papers discussing glare test problems appeared [10,11,61–64].

Direct Compensation Method

To improve this situation, a new psychophysical method was designed, called the Direct Compensation method [5]. In short, this method works as follows: A bright ring-shaped flickering light source around a (dark) test field is presented. Due to intraocular scatter, part of the light from the bright ring-shaped source will be projected on the retina at the location of the test field, inducing a (weak) flicker in the test field. To determine the exact amount of straylight, a variable amount of *counterphase* compensation light is presented in the test field. By adjusting the amount of compensation light, the flicker perception in the test field can be extinguished. In this way, the straylight modulation caused by light scattered from the glare source is "directly compensated for".

In 1990, the Direct Compensation (DC) technique was implemented into a small portable device, called the Straylight Meter, as a service to other researchers [3,65,66]. This led to publications, notably by the groups of Elliott, Kooijman, Schallhorn and Alexander, on a variety of subjects. Moreover, some research groups conceived (slightly) modified DC versions. [67–73]. The first publications about the Direct Compensation method appeared in 1986/1987 [5,74]. Since then, many studies on ocular straylight have been published using this approach, such as on normal population aging effects [75,76], on the use of red (yellow) glasses [77], on diaphany of the ocular wall [78,79], on the effects of ocular pigmentation differences [80], on populations with different kinds of cataracts [42], etc.

The unit for quantifying straylight in these studies is explained in Figure 1. The top left image of a street scene illustrates how straylight presents itself most clearly, as light spreading from a bright source. Depending on the strength of the source and the condition of the eye, the spread of the light obviates proper vision of other objects. To the right the same scene is illustrated for an eye with media turbidity. The essential feature of the spreading light is its brightness. The photometric unit to quantify brightness of normal objects is luminance in cd/m^2. So to precisely define the strength of the straylight, one would want to assess its luminance value. However, the brightness seen is not actually there, so it cannot be measured by a photometric instrument. As mentioned above, Cobb [17] introduced the concept of *equivalent luminance* L_{eq}, i.e. the luminance that is visually identical. By this definition, the obtained value is very meaningful as it can be used to derive, e.g., the loss of contrast suffered in the street scene. L_{eq} depends both on the strength of the light source and on the eye. If L_{eq} is divided by the illuminance E_{bl} in lm/m^2 caused by the light source on the eye, a quantity is obtained that only depends on the condition of the eye, independent of the light source. Moreover, it integrates to unity, which is the proper way of normalization of the point-spread-function PSF. The PSF is defined as the way a certain (unit) amount of light is redistributed. The lower left graph gives the PSF according to the CIE age standard [4]. The continuous line is for 35 years of age. The dashed line is for 95 years of age, serving as model for media turbidity with 4x increased straylight. The PSF declines strongly with angle θ, and resembles s/θ^2 for a large part. This was also found to be true for media disturbances such as cataract, including normal lens aging [20], corneal pathologies [81], and haze from refractive surgery [82]. The middle graph in Figure 1 illustrates this by multiplication of the same curves with θ^2. So, for most practical applications one parameter suffices, called the straylight parameter s, defined by:

straylight parameter $s = \theta^2 \cdot L_{eq}/E_{bl} = \theta^2 \cdot \mathrm{PSF}$.

Using this parameter has several advantages, in particular to make differences more clear [20]. For a precise comparison between the different studies, the angle at which s is measured should be specified. Normally, s is given logarithmically, as log(s), which is comparable to giving visual acuity as logMAR. See the right graph at the bottom of Figure 1. Normal values are around log(s) = 0.9, but with lens aging and other conditions log(s) values as high as 2.5 (40x) are found.

II Compensation Comparison method

In general, the Direct Compensation method has given a boost to the study of ocular straylight. Moreover, it was emphasized in the literature that this technique offers much greater sensitivity than glare tests, for example in patients with corneal edema [83] and posterior capsular opacification [84]. It was also used as a gold standard to assess the validity of glare tests [40]. However, outside the laboratory it sometimes proved to be a difficult technique [84,85], but which was nevertheless favored in a recent study where straylight was measured in keratoconus patients [86]. In a field study involving 112 subjects drawn from the patients and visitors of the outpatient departments of three clinics, the standard deviations of differences between repeated measurements found in such a field study were 0.15 and 0.18 log units, for two different implementations of the Direct Compensation method [45,56,57]. It appeared that the method has some important drawbacks for routine clinical or large-scale use. It was not patient-friendly, and there was no control over an individual's measurement reliability. As a result the use of the straylight meter remained limited in its use. For large scale use, such as clinical diagnosis or occupational health testing, the test must be easy to understand, easy and quick to perform, easy to explain, and fraud resistant. Also it must be criterion-independent, so that the values have universal validity and allow comparison of results from different locations.

A new psychophysical approach was defined in 2003, called *Compensation Comparison* (CC). It was patented [87] and implemented in a commercial instrument, dedicated to straylight measurement, by the German company Oculus Optikgeräte GmbH (Wetzlar, Germany)', called C-Quant. In the C-Quant the straylight source is an annulus (Figure 1 top right) with a radius of 5 to 10 degrees, resulting in an effective average angular value of 7 degrees [20]. The essential difference was that this new approach is suitable for random subjects and for routine clinical use. Moreover, the new approach enabled control over the reliability of the assessment. It was no longer possible to influence the measurement outcome, and quality control factors could be defined. A large study took place from 2003 to 2004. More than 2400 subjects were measured in 5 centers in Europe (Amsterdam, Barcelona, Tübingen, Salzburg and Antwerp) [88–93] and a reference database was established. The measurement values closely corresponded to those found in the earlier studies. An important conclusion was that high levels of straylight are found frequently in the population, even in individuals with decimal visual acuity = 1.0 or better. The amount of increase is often considerable. If one realizes that glare hindrance is already a problem for young eyes, it is clear that a straylight increase by a factor of 4 constitutes a serious handicap. Yet such an increase was often found [89]. Usually, straylight is quantified by means of the so-called straylight parameter *s*, defined above, and given logarithmically as log(s) (compare logMAR). With normal values around log(s) = 0.9, as criterion values for driving 1.5 (4x), for pilots 1.2 (2x), and for cataract surgery 1.4 (3x) are proposed.

In essence, the Compensation Comparison method presents exactly the same stimuli to the subject as the Direct Compensation method. Note that in the Direct Compensation method, the amount of compensation light is varied until the straylight flicker has disappeared. In other words, in the Direct Compensation method, the subject compares different stimuli *sequentially*. Contrarily, in the Compensation Comparison method, two stimuli of the Direct Compensation method are presented to and compared by the subject *simultaneously*. In this way, the Direct Compensation method is implemented as a two alternative forced choice (2AFC) approach. The characteristics of the psychometric function for this 2AFC method have been described [94,95]. This function determines what comparisons would be the best to use. The Compensation Comparison method has been summarized in a 2005 ARVO abstract [96]. A full description is given by Franssen et al. [94] and the reliability of the method is discussed by Coppens et al. [97,98]. Independent reliability studies with the C-Quant were performed by Cervino et al. [99] and Guber et al. [100]. A study investigating the effect of pupil size on straylight measurements found no significant effects [101]. An overview of straylight findings using the DC and CC methods and other approaches will be given in the following paragraphs. In all cases either the DC or CC method is used unless stated otherwise, in which case the method used will be named.

III Straylight in Normal Eyes

One of the first subjects that was studied was the *age dependence* of straylight in the normal population. Earlier studies had shown a clear increase with age [48,102], but the variability in the results proved to be too large for an accurate quantification of the effect. For a review, see Vos [1]. With the Direct Compensation technique, it became possible to study straylight in larger populations with better accuracy [76]. Straylight/disability glare increases with age *A* by a factor

$$\left[1+\left(\frac{A}{D}\right)^4\right],$$

with *D* the age at which the amount of straylight doubles. Values for *D* were found to be between about 62.5 and 70 years. This age dependence was later implemented in a more extensive model including pigmentation as a second parameter [20]. For pigmentation, the color of the iris was used, and a grading scheme for iris color was developed[103]. The model was further refined in a CIE Collection paper, including age dependency formulas of different levels of complexity, applicable in different angular validity domains [22]. This led to a proposal to the CIE for a Standard Glare Observer [4], which was accepted as CIE standard a few years later [104]. See the appendix of the present paper for details. A large study among European drivers was conducted, resulting in straylight prevalence values for such a relatively healthy population, showing little deviation from the earlier age characteristics [88,89]. In the C-Quant, D is set at 65. The improved accuracy enabled detection of statistical differences in straylight between fellow eyes, which were shown to increase with age [93].

The main topic in the CIE '97 report [22] was the evaluation of the classical Stiles-Holladay approximation for the *angular dependence* (proportionality to θ^{-2}), especially for larger glare angles. Vos [1] had adopted the θ^{-2} course in the large angle domain from Stiles and Crawford's [105] classic work. However, van den Berg and coworkers [76,106] found evidence for a more gradual fall off beyond about 10°. Also, data from earlier studies show deviations from the Stiles-Holladay approximation, including data from Stiles and Crawford themselves [2]. The apparent controversy induced Vos and van den Berg [22] to perform deeper analysis of large angle scattering. The experimental controversy could be virtually eliminated because the Stiles and Crawford data, when corrected for the perspective narrowing of the pupil, showed roughly the same deviating trend from θ^{-2}. Furthermore, both the large angle dependence and the dependence on eye pigmentation could be reasonably well understood on the basis of a significant contribution of scattering at the ocular fundus to the straylight veil [80]. In lightly pigmented subjects, a contribution of light entering via the iris and sclera serves to further complete the picture [80,101]. The convergence of experimental evidence thus obtained, combined with the theoretical analysis, confirmed the reality of the upward deviations from the classic θ^{-2} course. The theoretical analysis then allowed extrapolation into domains of glare angle and pigmentation that were not thoroughly covered by experimental data [22].

In their population study, IJspeert et al. [76] identified *pigmentation* as a source of the variation reported regarding straylight in normal eyes. The straylight values of blue-eyed caucasians were found to be 0.1-0.4 log units higher than those of pigmented non-caucasians, depending on angle. Elliott et al. [107] found similar results. Van den Berg et al. [80] found that this pigmentation dependence is partly caused by variations in transmission of light through the ocular wall. For dark-brown eyes of pigmented individuals transmission was found to be several orders of magnitude lower than for blue-eyed individuals. Furthermore, the authors speculated that variations in fundus reflectance are also partly responsible for pigmentation dependence of straylight. Straylight was also measured in patients with clinical forms of translucency (also called diaphany of the iris), associated with X-linked megalocornea [78], Fuchs' heterochromic cyclitis [79], or albinism [108]. In all cases, both straylight and eye wall translucency were found to be significantly increased compared to healthy subjects.

A subject that has long escaped proper understanding is the *wavelength dependence* of straylight. Characterizing wavelength dependence was felt to be important as a clue to what processes in the eye might cause straylight. A strong wavelength dependence would signify scatter in the optical media to originate from particles of sizes in the same range as, or smaller than, the wavelength of light. Since the results from earlier (psychophysical) studies were contradictory, Wooten and Geri [25] carefully measured wavelength dependence of straylight for an annulus of 3-8 degrees, using a version of the equivalent veil method summarized above. They found no effects whatsoever over 420-650 nm. Later, also Whitaker et al. [26], using a similar method, but with a white test target, failed to find effects. However, van den Berg et al. [80] found the earlier mentioned pigmentation dependence, and effects of color dependence associated with it. For lightly pigmented eyes red light was found to produce more straylight than green light, for angles of 3.5 to 25.4 degrees, and the conclusion was that, depending on pigmentation, eye-wall transmittance and fundal reflections introduce a straylight component with a wavelength dependence of the opposite sign to what would be expected from small-particle scatter. They hypothesized that one dependence might have negated the other in the earlier studies. This was supported by the later finding, *in vitro*, that scattering by the human eye lens indeed shows wavelength dependence typical of small particles [109]. *In vivo* verification was obtained as this conclusion proved to form an explanation for a well-known visual phenomenon: the so-called ciliary corona. This is the radiation of sharp needles of light we perceive subjectively around a bright point light source [110]. Moreover, the human cornea was concluded to exhibit the very strongly wavelength dependent Rayleigh type of light scattering [111], in accordance with studies on rabbit corneas [112]. Direct evidence for the small particle type of wavelength dependence of straylight was obtained after the introduction of the CC-method [113].

From the previous paragraph, it may be clear that different *components* contribute to straylight in the human eye. This had already been surmised [1], but now more quantitative insights began to emerge. A model was formulated, which described, for the normal human eye, all four anatomical structures contributing to straylight, namely cornea, lens, eye wall transmittance and fundus reflectance. [20] With respect to the contribution by the lens, *in vitro* studies showed quantitative values of light scatter in the lens to correspond to values that were expected on the basis of *in vivo* data [114]. However, for *in vivo* measurements, the only accessible variables are the degree of pigmentation and the age of the subject. Note that between normal eyes significant differences in straylight exist, and the task of the model was to explain or predict these differences. A mathematical formula was derived to describe differences in *in vivo* data on the basis of the age and pigmentation of the subject [20].

IV Cataract

The *cataract dependence* of straylight was measured in patients with cortical, nuclear, or posterior subcapsular cataract. Straylight was shown to be increased for all three types compared with control subjects without cataract [42]. When cataract severity in the subpopulations was equated on the basis of visual acuity, on average the posterior subcapsular type showed the largest straylight increase, but individual results varied considerably, more or less in accordance with results from Elliott et al. [28] using the P&S method from the group of Sjöstrand. Sjöstrand and coworkers had earlier studied straylight increase specifically in the posterior subcapsular cataract group, using this method [27,30]. A common finding is that in many patients straylight may be increased considerably while visual acuity is retained, whereas in other patients the opposite may be the case. The angular dependence was found to be about the same for the different cataract types [42]. Van den Brom et al. [115] found similar results. The angular dependence of the straylight increase in case of cataract was found to be similar to the situation in normal aging, and it was concluded that, at least with respect to straylight, cataract can be modeled as early aging of the crystalline lens [20,116]. These data were also used as a reference in a search for light scattering filters that could be used to simulate the straylight characteristics of cataract [117,118]. Straylight increase due to cataract is also an important factor for visual functioning in the driver population. For this reason the prevalence and association of cataract (and pseudophakia) with visual impairment in the driver population was investigated [91,92]. Also, in this context the use of the C-Quant as a screening tool for straylight in the driver population was assessed [119,120].

Straylight values (in references [121,122] using a modified DC method) after cataract surgery were found to be significantly decreased compared to preoperative values, but still about a factor of 2 above normal levels, which was attributed to posterior capsule opacification (PCO) [121–123]. In a large population study, important variation between pseudophakic eyes was reported [89]. A comparison between monofocal and multifocal intraocular lenses (IOLs) using a modified DC method yielded no significant difference [124]. Recent studies found clear [125], small [126] or no [127,128] straylight increase in diffractive multifocals. An early in vitro study also found a clear increase in the diffractive modality [10]. Also no differences were found between multifocal lenses with different optical add power [129], between spherical and aspheric IOLs [130–132], and in a model study on monofocal add-on IOLs [133]. A case study found a considerable increase in straylight after multifocal IOL implant [134]. Recently dramatically increased straylight values were reported in IOLs from Bausch and Lomb called “Hydroview”, due to opacification of the IOL because of deposit formation [135], whereas visual acuity was relatively unchanged.

In a pseudophakic group without PCO, equal levels of straylight compared to a normal reference group were found [136]. In studies on the straylight effects of capsulotomy, only in case of wide capsulotomy a significant decrease in straylight values was found [137] (in references [138,139] using a modified DC method). Studies on the clinical use of straylight measurement (in reference [140] using a modified DC method) for cataract assessment [40,63,140,141], PCO assessment [84,140,142–144], influence of capsulorhexis size on straylight [145–147], and low vision rehabilitation [148], concluded that functional severity can be properly documented with straylight measurement, and the suggestion was made that straylight measurements should be used as a gold standard for clinical evaluation of cataract [40,141]. Recently the subjective importance of straylight compared to visual acuity was studied using questionnaires in patients scheduled for cataract surgery [149]. It was found that straylight is almost equally important as visual acuity, stressing that straylight should feature in the indication for cataract surgery [149]. The cataract induced general reduction of sensitivity in visual field examination, in particular the blue-yellow type, was found to be highly correlated with straylight values [150,151]. The background of straylight effects on the visual field stimulus was discussed [6], also by the group of Wild, who use the P&S technique [31,152–154].

Straylight was also studied in patients with *retinitis pigmentosa* (RP). These patients frequently develop lens opacities, most commonly posterior subcapsular cataracts (PSC), on top of having retinal degenerative changes that are typical of RP. Indeed, in one study a patient with still good visual acuity was found to have increased straylight levels by about a factor of 3 (0.5 log units) [77]. This study was intended to evaluate the use of red glasses, which had been reported to subjectively improve visual function. No positive functional effects were found in these patients, in particular no suppression of straylight. Alexander and coworkers found that patients with RP or choroideremia, who had minimal or no lens opacities by slit-lamp evaluation, also showed increased straylight levels, caused, they speculated, by subclinical changes in the PSC region of the lens as a consequence of photoreceptor cell degeneration [155–157]. A note of clinical significance must be made here. For patients with a retinal condition, such as RP or macular degeneration (AMD), increased straylight is a more serious handicap as compared to patients without a retinal condition. The functional effect of straylight is a reduction of retinal sensitivity, aggravating the condition of the RP or AMD patients.

V Conditions increasing straylight in the cornea

The *cornea* proved to be a particularly sensitive organ for straylight increase. Elliott et al. [83] investigated the sensitivity of straylight to (experimentally) hydrophilic contact lens-induced corneal edema. On average, a 10% corneal swelling induced a 50% increase in straylight. Variability in this relationship was speculated to be due to changes in the epithelium caused by the contact lens. After contact lens removal, individual straylight values decreased linearly with time, on a similar time scale as the decrease in corneal swelling. This effect was also found in a later study by Fonn et al. [158]. In earlier studies, the effect of habitual contact lens wear on straylight was investigated by Elliott and coworkers [107,159]. Straylight scores in established contact lens wearers were found to be significantly higher than in age-matched non-wearers, but did not correlate with the amount of lens deposits. Rigid gas permeable (RGP) contact lenses were shown to induce more straylight than hydrophilic contact lenses. However, scores from hydrophilic lens wearers after removal of their lenses were significantly higher than results from RGP wearers after removal of their lenses and from age-matched non-wearers, suggesting the presence of subclinical corneal edema in some of the wearers. Using an approximate equivalent veil method, Applegate and coworkers had also found significantly increased straylight in some hydrogel contact lens wearers [160], but not in all [161]. Nio et al. [162] found an increase in straylight of, on average, 0.22 log units, comparing contact lens wear to spectacle wear. Recently, Cerviño et al. [163] found slightly increased straylight values in sport-tinted contact lenses. Other authors found normal straylight values for soft contact lens wearers and increased straylight values for RGP contact lens wearers [164]. Although straylight is increased in RGP contact lens wear, the type of material and cleaning agents used for RGP contact lenses have shown to minimally influence the straylight outcome [165]. Ocular lubricants were reported to have no adverse effects on straylight [166]. Habitual glasses were found to induce as a rule less straylight than is already present in the eye [167].

Pathological conditions of the cornea may induce increased light scatter, but the degree strongly depends on the type of disease. In central crystalline dystrophy, straylight was found to be much increased while visual acuity was relatively well-preserved [5,81]. In posterior polymorphous dystrophy, straylight was not increased, even with impaired visual acuity [81]. In macular and also lattice dystrophy, straylight and visual acuity were affected in a similar way [81]. Using the DC method, for deep lamellar endothelial keratoplasty (DLEK) and penetrating keratoplasty (PK), on average small differences were found between pre- and postoperative straylight values [168]. Other studies investigating straylight outcome after DSEK and PK for Fuch's dystrophy showed a significant improvement [169–171], also for long term follow-up [172]. Whereas Cheng et al. showed comparable outcome after PK and DSEK regarding straylight [169], another study showed straylight values to be higher after DSEK than after PK [173]. Keratoconus patients can show increased straylight values which could not be explained by age or scarring and is supposedly related to structural degradation of the cornea [86].

Ever since the introduction of *laser refractive surgery*, much concern has been expressed with respect to light scattering/straylight problems regarding this type of corneal surgery. In radial keratotomy (RK), mean straylight increases by a factor of 1.4 (0.15 log units) in eyes with 4-mm sized pupils and a factor of 2 (0.3 log units) for 8-mm sized pupils was found [82]. These values may be considered to be functionally significant increases. Using an approximate equivalent veil method, Applegate et al. [29] even found increases of a factor of 6 (0.8 log units). Studies on photorefractive keratectomy (PRK) provided a less clear picture of whether functionally significant straylight increase occurs. Older studies did not show a significant increase on average over the population [59,85,174,175], but in some cases a significant straylight increase was found for individual patients [85,174,176]. Newer studies on straylight (see [177–185], and reference [186] where a modified DC method was used) after PRK and laser-assisted *in situ* keratomileusis (LASIK) show a similar picture. However, more precise measurements in larger patient groups may be needed to investigate the prevalence of these individual increases after PRK or LASIK. Epithelial ingrowth after LASIK occurs in 1-20% of all cases and is a familiar complication that can cause an increase in straylight [187]. Surprisingly, in some studies a decrease in the average straylight value after LASIK/LASEK [188–190] was observed. Rozema et al. collected C-Quant data on large numbers of non-ophthalmological subjects in the Gullstrand project, including several biometrical parameters [191]. They found increased levels for preoperative LASIK subjects, correlated with the myopic refractive error. Lapid et al., too, found elevated straylight in preoperative myopes [188]. The improvement after treatment might suggest that ill-tolerated contact lenses are to blame for the elevated preoperative levels. The same is suggested for part of the straylight reduction after phakic anterior chamber IOL implantation [192]. In another study on anterior chamber lenses for the correction of high myopia no significant effect on straylight was found [193]. Recently, for "corneal refractive therapy" (orthokeratology or corneal reshaping) it was reported that straylight values decreased slightly but significantly during 15 days and 1 month of follow up [194].

VI The vitreous

Floaters are present in all eyes and are known to scatter light and should thus contribute to straylight. In normal eyes this contribution may be small. However, an increase in floaters may yield a significant increase in straylight. Recently, a study quantified straylight in eyes with floaters and showed increased straylight values [195]. Furthermore, this study showed improvement in straylight values after vitrectomy [195].

VII Forward and backward scatter

Straylight reflects the effects of forward light scatter in the eye media. There are a number of methods by which the condition of the eye media may be assessed using *backward light scatter*. In fact, the basic ophthalmological tool to evaluate the eye media (the slitlamp) is based on back scatter. Other examples are Scheimpflug slit-image photography, Lens Opacity Meter, and the lens opacities classification system (LOCS). One may wonder whether backward light scatter faithfully reflects the functional effect of light scatter in the eye, which is determined by forward light scatter. To address this question, *in vitro* measurements of light scatter in human donor lenses were performed, which showed that backward and forward light scatter are governed by different processes [196,197]. This might explain why the correlations are weak in many patient studies comparing different measures of backward light scatter and forward light scatter [32,42,83,107,157,176,198–200]. Also for the cornea comparisons between backward and forward scatter (straylight) were made, but no relationship was found [201]. It must be noted here that we consider forward scatter not in a very narrow forward direction, but over angles of more than 1°. For more closely forward angles (smaller than 1°) we approach the domain that can be captured with other techniques, such as double-pass and wavefront-sensing approaches.

VIII Summary and outlook

Ocular straylight has been known since the early 20th century as an important aspect of quality of vision. Its study originated from studies on disability glare. By international (CIE) appointment disability glare is since quantified by means of straylight, straylight being a solid quantity, like visual photometry, albeit assessed psychophysically. Straylight study in the laboratory and in the clinic has long been hampered by the fact that the tests were laborious, and lacked controllable reliability. This changed over the past 20 years with the introduction of new psychophysical techniques, culminating in 2005 in the appearance of a clinical instrument (C-Quant). This has raised the interest in straylight, and many studies have appeared in recent years on basic issues as well as clinical questions.

Straylight is an issue also in healthy eyes. Many clinical conditions can be viewed as aggravated forms of the normal light scattering by different parts of the eye. The typical example is the aging crystalline lens. Also in eyes with good visual acuity (logMAR = <0) straylight increases with age to 2x its young value at 65 years of age, and to 3x at 77 years. Straylight shows pigmentation in the eye to be of functional significance. In lightly pigmented eyes straylight is elevated as compared to darkly pigmented eyes, because of stronger light back scatter from the fundus, and more light transmission through the eye wall. The cornea is in the healthy eye the 3rd important source of straylight, but its contribution normally remains constant through life.

In the clinic cataract formation is the most general cause of straylight-based complaints such as hazy vision, glare hindrance, difficulty recognizing faces, contrast and color loss. With respect to its straylight characteristics, cataract can be compared to early aging. For the cataract population, subjectively straylight increase is about as important as visual acuity loss. Since straylight is impaired in many patients with good visual acuity, much more patients would be eligible for cataract surgery if this objective criterion would be added to the diagnostic arsenal. Straylight can be increased in patients with pigmentation defects, such as albino's. Iris print contact lenses can help to address this. Many corneal conditions exist that can enhance straylight, in particular (Fuch's) dystrophy, and haze after refractive surgery, but also contact lenses were found to increase straylight in many cases. For the Fuch's patients, surgery proved effective to reduce straylight.

It seems that straylight study has become of age, not only in the laboratory, but also in the clinic. It can be expected that the C-Quant will be accompanied by other instruments in the future. The studies up till now have made clear that straylight is an important issue in the clinic, but have also left us with many intriguing questions. E.g. after cataract surgery, one could expect straylight to return to the value of one's youth, or even lower (because the lens is removed), a form of super vision. However, in absence of PCO, straylight returns on average to log(s) = 1.1 to 1.2, values normal for a healthy 60 year old phakic eye. What causes this significant elevation in the pseudophakic eye? And how can this be improved? There are indications that the IOL can have an influence, such as in case of a diffractive design, and good studies into the effects of IOLs on straylight are needed. As another example, many different treatment modalities for presbyopia are being researched, some involving the cornea. But the cornea is a very sensitive organ for straylight effects, and the question is what effects these treatment modalities have.

Straylight is part of functional quality of vision. As such it can directly be used for justification of clinical intervention, or for licensing applications. Since the straylight test cannot be influenced (as opposed to e.g. visual acuity), it is objective and robust. Moreover, the preop straylight value is predictive for the intervention result. The important question to be resolved here is, what criterion values must be set for the different types of intervention. For cataract surgery one study found a break-even point at log(s) = 1.2, and for DSEK in case of Fuch's another study found a break-even point at log(s) = 1.33, but many more such studies are needed. Also for licensing applications where glare sensitivity is an issue criteria must be set. We have proposed a limit of log(s) = 1.5 for driver licensing, and 1.2 for demanding professions such as pilots, and much study is to be expected on this application.

Financial Support

None

Proprietary Interest

The Royal Academy owns a patent on straylight measurement, which it licenses to Oculus for the C-Quant instrument.

Appendix

CIE Standard Glare Observer

As mentioned in the introduction of this overview, the CIE has adopted standards for the glare of the normal observer. Because these standards are not easily accessible, and for the sake of completeness, the CIE equations will be given here. The total glare function proposed by Vos and van den Berg (as equation 8 in the CIE report [4]) does actually give the complete PSF. It reads:

$$PSF = [L_{eq}/E_{gl}]_{total} = [1 - 0.08 \cdot (A/70)^4] \cdot \left[\frac{9.2 \cdot 10^6}{[1 + (\theta/0.0046)^2]^{1.5}} + \frac{1.5 \cdot 10^5}{[1 + (\theta/0.045)^2]^{1.5}}\right] + [1 + 1.6 \cdot (A/70)^4] \cdot \left\{\left[\frac{400}{1 + (\theta/0.1)^2} + 3 \cdot 10^{-8} \cdot \theta^2\right] + p \cdot \left[\frac{1300}{[1 + (\theta/0.1)^2]^{1.5}} + \frac{0.8}{[1 + (\theta/0.1)^2]^{0.5}}\right]\right\} + 2.5 \cdot 10^{-3} \cdot p \quad [sr^{-1}],$$

where θ is the glare angle in degrees, A the age in years and p a pigmentation factor ($p = 0$ for very dark eyes, $p = 0.5$ for brown eyes, and $p = 1.0$ for blue-green Caucasians; see also [20]).

Figure 2 shows the angular course of the total glare function for three age/pigmentation conditions. Note that the total dynamics of the PSF span a range of about 10^9, or 1,000,000,000. Due to this enormous range, differences between various conditions of the eye may seem subtle,

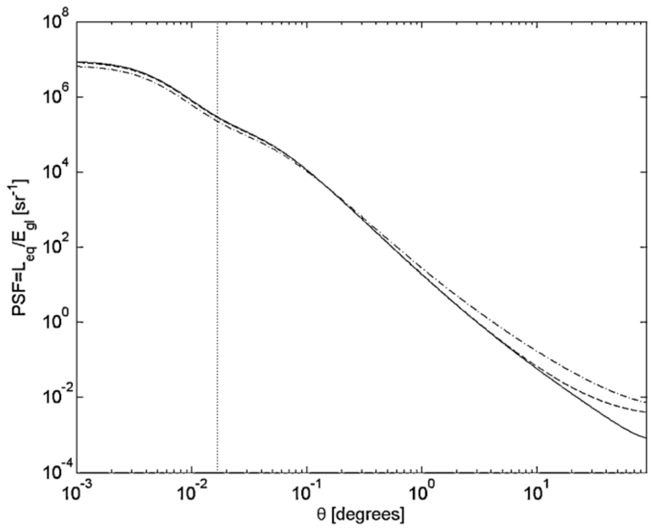

Figure 2. The CIE 1999 total glare function for a 35-year-old negroid (continuous line), a 35-year-old blue-green eyed Caucasian (dashed line) and a 80-year-old blue-green eyed Caucasian (dash-dotted line). The vertical dotted line indicates 1 minute of arc. This is customarily assumed to be the smallest detail that can be resolved by an eye having a visual acuity of decimal 1.

when for subjective vision they are in fact very noticeable. The differences become more clear when the curves are presented in terms of the straylight parameter *s*. In this way, the approximate $1/\theta^2$ angular dependence is taken into account. In Figure 3, the PSF of the total glare function, multiplied by θ^2 is shown. This is the straylight parameter, *s*, that is also used to represent the outcome of a straylight measurement. In Figure 4, another useful representation of the total glare

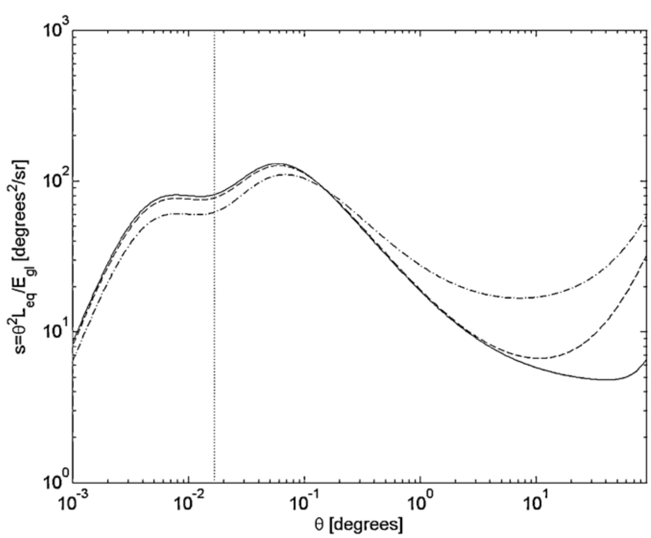

Figure 3. The CIE 1999 total glare function (PSF) multiplied by θ^2 to represent it in terms of the straylight parameter for the same age/pigmentation conditions as in Figure 2 (Reprint with permission of encyclopedia of the eye, Darlene A. Dartt ed.).

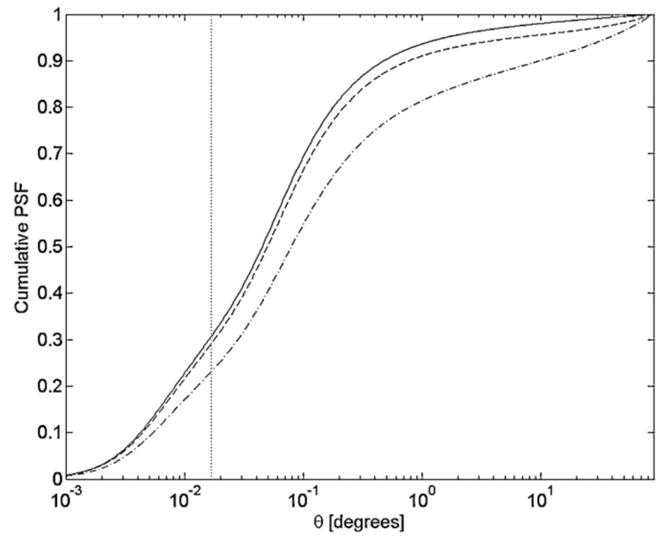

Figure 4. The CIE 1999 total glare function (PSF) integrated from the center (0 degrees) outwards, for the same age/pigmentation conditions as in Figure 2. At 90 degrees the integrated value is 1 by definition, since the PSF is normalized. For angles smaller than 90 degrees, the fraction of light up to that angle in the PSF is indicated. The fraction of light in the central part of the PSF, below 1 minute of arc (dotted line) that determines visual acuity is only about 30%.

function is given. Here the integrated PSF is given, starting from the center and going outwards.

For practical purposes, the CIE 1999 total glare equation is relatively complicated. Therefore, some simplified equations were formulated. The simplest (given as equation 9 in the CIE report [4]) version of a disability glare formula equals the classic Stiles-Holladay equation, in which the constant is multiplied by an age factor. It was called the *age adapted Stiles-Holladay equation*:

$$PSF = [L_{eq}/E_{gl}]_{S-H,agead.} = \left\{1 + [A/70]^4\right\} \cdot 10/\theta^2$$

which has a validity domain that runs from 3° to 30°.

As it is evident that the Stiles-Holladay equation falls short in particular below 1°, the following equation, the *simplified glare equation* (equation 10 in the CIE report [4]), may serve in a more extended angular domain:

$$PSF = [L_{eq}/E_{gl}]_{simpl.} = 10/\theta^3 + \left\{1 + [A/62.5]^4\right\} \cdot 5/\theta^2,$$

which has a validity domain from 0.1° to 30°.

To also cover the very large angle domain, more terms of the total glare equation must be taken into account. This is the *general glare equation* (equation 11 in the CIE report [4]):

$$\begin{aligned} PSF &= [L_{eq}/E_{gl}]_{gen.} \\ &= 10/\theta^3 + [5/\theta^2 + 0.1 \cdot p/\theta] \cdot \left\{1 + [A/62.5]^4\right\} \\ &\quad + 2.5 \cdot 10^{-3} \cdot p, \end{aligned}$$

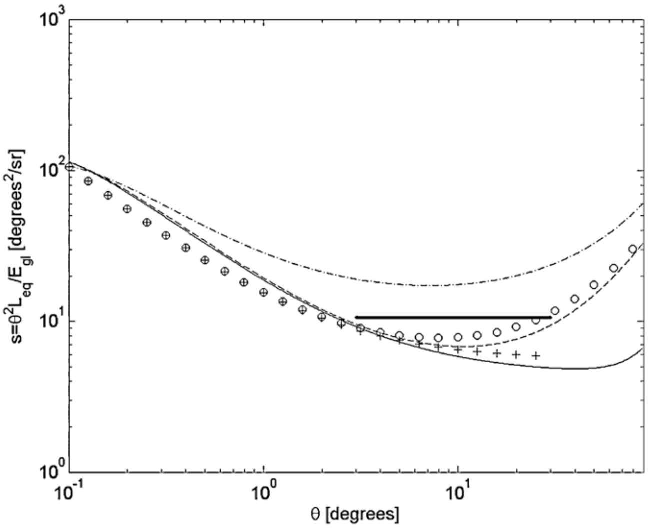

Figure 5. The simplified versions of the total glare equation of a 35-year-old blue-green eyed Caucasian. The age adapted Stiles Holladay equation is shown with the thick line, the simplified glare equation as +, and the general glare equation as o. For clarity also the total glare function is plotted for a 35-year-old negroid (continuous line), a 35-year-old blue-green eyed Caucasian (dashed line) and a 80-year-old blue-green eyed Caucasian (dash-dotted line).

which has a validity domain that stretches from 0.1° all the way up to the very limit of the field of view, somewhere around 100°.

An overview of the simplified versions of the total glare equation is given in Figure 5 for a blue-green eyed 35-year-old Caucasian.

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