Measurement of straylight for glare assessment and driving

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Abstract

This review presents an overview of straylight as a quantification for glare sensitivity, to be used as a criterion for driver licensing. Glare disturbance is an important safety issue while driving. It is a known fact that glare issues in the early stages of cataract development are one reason why people give up driving at night. Glare is caused by the physical process of light scattering in the eye, causing a veil of straylight seen over the road. This veil lessens visibility, potentially to the point of complete blindness. By international agreement, glare must be quantified by measuring straylight, based on the "equivalent luminance" concept. Normal standards have been defined, including the dependence of straylight on age and cataract. Straylight can be measured accurately with the psychophysical 2AFC "compensation comparison" method, including a reliability check. An instrument for straylight measurement, the C-Quant is now commercially available. Straylight is a basic aspect of the eye, on which also other aspects of quality of vision, such as face recognition, contrast sensitivity, etc. depend. Straylight presence is used in ophthalmology as an early indication for cataract surgery. It is to a large degree independent of acuity. This review discusses the practical aspects of straylight measurement and limit values for occupational testing. Normal values for young subjects are around $\log(s) = 0.9$. For demanding professions, a limit elevation of 2× (0.3 log, corresponding to 3 standard deviations) is proposed. For normal driving a limit elevation of 4× is proposed, corresponding to $\log(s) = 1.5$. Cataract surgery is indicated at $\log(s) = 1.4$.

Sammendrag

Denna artikel ger en översikt av bländning och kvantifiering av bländningkänslighet, som kan användas som kriterium för körkortstillstånd. Bländning är en viktig säkerhetsfråga vid bilkörning. Det är ett känt faktum att bländningsproblem i de tidiga stadierna av kataraktutveckling är en orsak till att människor ger upp körning på natten. Bländning orsakas av den fysiska processen ljusspridning i ögat, vilket ger en slöja som ses över vägen. Enligt internationell överenskommelse måste bländning kvantifieras genom mätning av ljusspridningen, baserat på begreppet "ekvivalent luminans". Normala normer har definierats, inklusive beroende av straylight på ålder och katarakt. Ljusspridning kan mätas exakt med den psykofysiska 2AFC "kompensationsjämförelse metod", inklusive en pålitlighetskontroll. Ett instrument för ljusspridningsmätning är C-Quant, finns nu kommersiellt tillgängligt. Ljusspridning är ett grundläggande begrepp, där också andra aspekter av synkvalitet, såsom ansiktsigenkänning, kontrastkänslighet etc. ingår. Ljusspridning används i oftalmologi som en tidig indikation för kataraktoperation. Det är i stor utsträckning oberoende av visus. Denna översyn diskuterar de praktiska aspekterna för mätning ljuspridning och gränsvärden. Normala unga värden är runt log(s) = 0,9. För krävande yrken föreslås ett gränsvärde på 2× (0, 3 log, motsvarande 3 standardavvikelser). För normal körning föreslås en gränshöjning på 4×, motsvarande $\log(s) = 1,5$. Kataraktkirurgi indikeras vid $\log(s) = 1,4$.

Introduction

After the Kongsberg Vision Meeting of November 2016, I went on a lovely drive through the Norwegian countryside. But my joy turned into a frightening experience when I had to drive back in the dark along unlit, yet busy, two-lane (single carriageway) roads. Even during the day, the drive had been a challenge because of a low sun glare blinding me, but the headlights of oncoming traffic at night, on roads of which many were winding, made driving seem an act of foolishness. Many studies have shown the importance of glare for safe driving (Anderson & Holliday, 1995; Gray & Regan, 2007; Lachenmayr, Berger, Buser, & Keller, 1998; Mäntyjärvi & Tuppurainen, 1999; Ranney, Simmons, & Masalonis, 2000; Rubin, Roche, Prasada-Rao, & Fried, 1994; Theeuwes, Alferdinck, & Perel, 2002; 2002; Von Hebenstreit, 1984). Virtually everybody recognizes the above anecdote. Because of this importance, many glare testing devices have been proposed, but none has gained general acceptance. A good overview of the issues with glare testing was given by Aslam in 2007 (Aslam, Haider, & Murray, 2007). Earlier critical discussions of glare testing were done by the groups of Elliott and Rubin (Elliott, Hurst, & Weatherill, 1990; Rubin & Stark, 1995). Dozens of glare testers and/or instruments have come onto the market under all kinds of names, and many more have been proposed, with no one system achieving general acceptance status. Please see the literature for an overview of potential reasons (Aslam et al., 2007; Elliott et al., 1990; Rubin & Stark, 1995; van den Berg et al., 2009). The present review discusses straylight as a precise quantification of glare sensitivity.

From the beginning of the 20th century onwards, the problem of drivers being blinded by glare has generated much scientific work. It became clear early on that the effect of blinding might correspond to the effect of light that is seen to radiate from bright sources, be it low sun or a car headlight. An important step was taken by Cobb, 1911, when he proposed that this *perceived* light could be quantified in the same way as *real* light, i.e. by means of the photometric quantity of luminance (cd/m^2). Since the light only exists as a perception, not as real light, its intensity is called *equivalent* luminance, and is defined as the (real) luminance giving perceptually identical visual effects. In parallel, many studies were done to find the laws underlying the glare effects. Disability glare is defined as the reduction in visibility caused by an intense light at some distance of a visual task. A typical example could be an acuity test in the presence of a bright light next to the chart. However, early researchers already realized that acuity is not a suitable criterion, and used contrast sensitivity tasks (increment thresholds) instead (Holladay, 1926; 1927; le Grand, 1937; Stiles & Crawford, 1937). All these studies led to the consensus that disability glare derives in a one-to-one fashion from the equivalent veiling luminance. Because it was realized that the perceived light results from light scattering, causing a veil of light projected onto the retina, this perceived light was called "straylight". The international standards committee CIE (Commission International d'Éclairage) decided that straylight must be used as the definition of disability glare. The thesis of Vos in 1963 (Vos, 1963) defines an important scientific endpoint of this development. Later Vos became chair of various CIE committees defining glare standards (Vos, 1984; Vos & Van den Berg, 1999; Vos et al., 2002).

It may seem surprising that it took as long as it did for this body of knowledge to become part of practical glare testing. The general principle of glare testing is that a visual task (letter acuity, letter contrast, grating contrast, increment contrast, etc.) is performed in the presence of a bright light at a distance (a point source, an annulus surrounding the task, a double point source at both sides of the task, etc.). Such a test not only depends on glare, but also on the ability to perform the task without the glare source present. A pure glare test requires assessment of the difference between task performance with and without glare. So, glare sensitivity must be estimated as the difference between two measurements. This causes errors to multiply. Apart from the problems listed by Aslam et al., 2007 and others, this makes these classical approaches to glare testing cumbersome. Details about glare sensitivity testing by means of straylight measurement are given below, but recently attempts have been made to assess straylight by using an optical measure for light scattering (Ginis, Pérez, Bueno, & Artal, 2012). This method uses the so-called double pass or DP approach. Since the DP approach is hampered by strong artefacts (van den Berg, 2010; Williams, Brainard, McMahon, & Navarro, 1994) the authors adapted the approach to avoid relevant artefacts. In particular, dp suffers from spurious light scattering phenomena, such as light diffusion in the choroid, and back scatter in the optical media. Both these scatter effects are of little relevance for human vision and must be distinguished from the functional effect of forward scatter in the media. Back scatter from the media shows up in the slit lamp image, and is traditionally used to assess the cataractous status of the intraocular lens. However, quantitative studies have shown that the relationship between the intensity of back scatter (also called "density") recorded by slit lamp has little relation with functional vision (Allen & Vos, 1967; De Waard, IJspeert, Van Den Berg, & De Jong, 1992; Elliott & Hurst, 1989). Indeed, a basic study on the origin of the back scattered light has shown it to result from structures other than forward scattered light (van den Berg & Spekreijse, 1999). The artefact in DP recording of light diffusion in the choroid derives from the (incorrect) assumption that the retina acts as a screen, reflecting the retinal projection without changing it. In fact, it should be recognized that only about 1% of the light is reflected at the retinal layer. A large part of the remaining 99% penetrates into the choroid and re-emerges in diffused form. The 1% properly reflected light rides on top of a wide hill. This forms a background to the proper, recording of 1% of the light, dwarfing much of the paracentral part of the point-spread-function or PSF. Only a few minutes of arc of the steep central peak of the PSF is large enough to be recorded with sufficient precision. This background depends strongly on wavelength — a well-known phenomenon for clinicians using red free light to suppress the choroidal contribution in fundus imaging (van den Berg, 2011).

Straylight assessment as a quantitative measure for glare sensitivity according to the CIE definition will be discussed next. Around 1990, the "direct compensation" method was designed (van den Berg, Franssen, Kruijt, & Coppens, 2013) and accepted as the gold standard (Elliott & Bullimore, 1993; Elliott et al., 1990). Most of the present review is based on the further development of the "compensation comparison" (CC) method (van den Berg et al., 2013). A review on other aspects of vision and driving appeared in the SJOVS journal in 2016 (Thorslund & Strand, 2016).

Straylight measurement is not only used for glare sensitivity assessment. As straylight is part of the functional PSF, it has implications for overall quality of vision. Although straylight has little bearing on acuity, it does affect other aspects of vision, such as face recognition, hazy vision, colour and contrast, spatial orientation, etc. When the eye ages, straylight may be the first problem to develop, and cataract surgeons may use the straylight scores as indication for early cataract surgery (Lapid-Gortzak, van der Meulen, van der Linden, Mourits, & van den Berg, 2014; van der Meulen et al., 2012).

Methods

As explained above, straylight is defined as a perceptual quantity. It is the intensity of the light seen to spread around a bright light source against a dark background (see Figures 1 and 2). This intensity experienced at some distance from the bright source, can be compared to a real intensity. If the straylight has the same visual effect as a real light, it is called "equivalent". The straylight quantity is set equal to the luminance of the comparison light, and is called "equivalent luminance". However, comparing these two types of intensity is not easily done. Viewing a bright light, memorizing the intensity seen at some distance from it, and then comparing that to a subsequently presented light patch is a virtually impossible task. Most studies used an adaptation paradigm instead (Vos, 1984). This involves finding out what (equivalent) background luminance is required for a test object to reach the same threshold value as it does in the presence of the glare source. Although this involves rather elaborate testing, many studies, including a few relatively large population studies, used it up until the 1984 review by Vos, 1984. In later years, the groups of Sjöstrand and Elliott, among others, have continued this line with a simplified approach (Abrahamsson & Sjöstrand, 1986; Elliott, Gilchrist, & Whitaker, 1989; Paulsson & Sjöstrand, 1980; van den Berg et al., 2013).

Figure 1: *These two images illustrate — for a normal eye and for an eye with some media turbidity — what straylight may look like in a traffic situation. Straylight is defined as the light that is seen to spread from a bright light source. It casts a veil of light over other objects. When straylight is strong, as in the lower image, it may cause complete blinding. Straylight is quantitatively assessed by means of the (equivalent) luminance it presents to the eye.*

The CC method makes use of other psychophysical paradigms, which make the measurement more effective and precise. First, the 2-alternative forced choice (2AFC) technique was used with a bi-partite field (Figure 3), to compare the intensity of straylight to that of a comparison light. From e.g. the Nagel anomaloscope for colour vision testing it is well known that such a paradigm is very precise. Second, straylight was evoked by means of a flickering bright annular light surround-

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ing the bipartite test fields (Figure 3). Figure 4 is a graphic representation of how the CC method works. One of the bipartite test fields is dark, and the scattered light is perceived as flickering in that part of the field (purple line). This part of the field must then be compared to the other part, where light of several intensity values is added, flickering in counter-phase (dark blue line). The subject must push one of two buttons to indicate which side of the bipartite field has the stronger flickering. The added light quenches the flickering seen from straylight. If the added light is equal to the straylight, the quenching will be complete (at the value of 10 in figure 4). If the added light is twice the straylight, both parts of the field will be seen to flicker equally strongly. This point of equality can be assessed precisely because of the 2AFC bipartite field paradigm, and can be used to determine the equivalent luminance Leq value of the straylight. From this value the straylight parameter is calculated as $s = \frac{\theta^2 \mathrm{Leq}}{\mathrm{Ebl}}$, with θ being the angle between annulus and bipartite field, and Ebl being a normalization value equal to the illuminance on the eye from the straylight source (van den Berg, 1995). Normally, straylight is given logarithmically as $\log(s)$; compare logMAR.

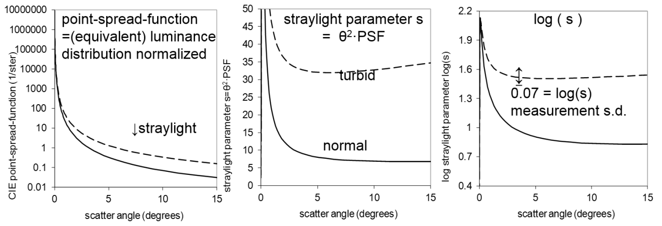

Figure 2: *Straylight is defined as the peripheral part of the (functional) point-spread-function (PSF). The left graph shows the PSF according the CIE disability glare standard (Vos & van den Berg, 1999) for two conditions; the continuous line is for a normal eye, the dashed line is for an eye with 4× increased straylight. The middle graph shows the same curves, but expressed as straylight parameter s, by multiplication by angle squared. The right graph shows the same functions, but now expressed as the logarithm of s. Figure adapted from (van den Berg et al., 2013).*

Straylight can differ widely in the population. Best values are around $\log(s) = 0.7$, and worst values are around $\log(s) = 2.5$. So, one needs the capability to test equivalent luminance values over a wide range. However, 95% of normal subjects are within the range 0.9 to 1.9. Therefore, the instrument has a default range "E" for the $0.9 - 1.9$ interval. For eyes experiencing low amounts of straylight a lower range can be chosen (range "C" running from $0.7 - 1.7$ is advised), and for eyes experiencing high amounts of straylight there are higher ranges ("F" covering 1.2 to 2.2, and "G" covering 1.5 to 2.5).

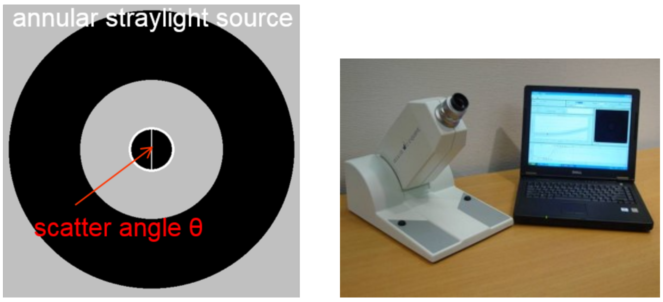

Figure 3: *Left: test field as presented by the C-Quant (right). The measurement involves a bipartite field surrounded by an annulus. Flickering light is presented within the annulus. Light from the annulus is scattered towards the bipartite field and its intensity is measured using the psychophysical CC method (van den Berg et al., 2005). The annulus has inner radius of 5° and outer radius of 10°, which makes for an effective mean radius of 7° (van den Berg, 1995). Please see text for details on the CC method.*

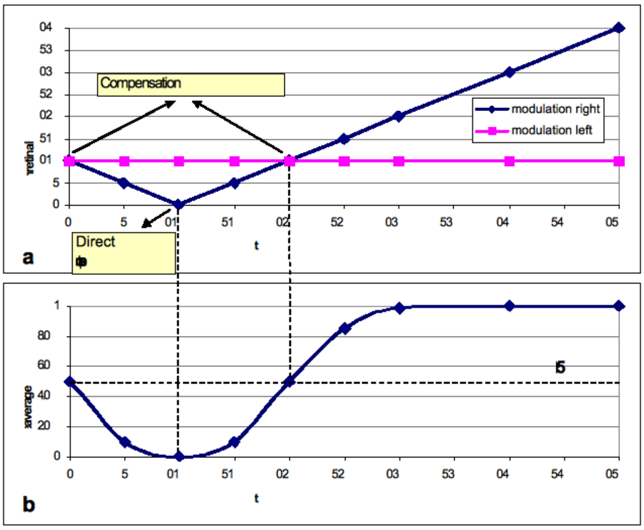

Figure 4: *Principle of the 2AFC bipartite CC test. Upper graph (a): One of the halves of the field receives flicker from light scattering only (pink), the other half contains counterphase flickering light, also called "compensation" (dark blue). If this compensation starts to increase from zero (on the left), the straylight flicker is quenched. In this example quenching is complete if the compensation light is 10. If compensation light is increased further, flicker reappears, and at strength 20 the relevant half of the field will again flicker as strongly as the other half, with straylight only. This point of equality can be used to assess the value of straylight, being half the value needed for equality of flicker in the bipartite field test. The lower graph (b) shows the statistical score of the subject. It shows the probability of the subject indicating the side with compensation as flickering more strongly. At 20, the subject has a 50% chance of choosing either side as flickering more strongly (because they flicker equally).*

Results

Figure 5 shows the result of a demonstration of the test on a volunteer during the Kongsberg Vision Meeting of November 2016. The lower frame gives the individual responses in blue and red, and the fit of the psychometric function in red. The task of the subject is to observe — with the eye close to the instrument — the bipartite field, and use one of two push buttons to indicate which side of the bipartite field is perceived to be flickering more strongly. The test consists of 25 short presentations and the subject must choose or guess within 2 seconds. The whole test takes about 1.5 minutes, but in this case it took a little longer, as it was a demonstration. The pattern of responses in the lower frames of Figure 5 show that the point of equality is rather precisely determined. Using maximum likelihood estimation, from a comparison between the psychometric function and the precise pattern of responses, a best estimate for the point of equality is made, including an "expected standard deviation" or ESD (Coppens, Franssen, Van Rijn, & van den Berg, 2006). The instrument gives a warning if ESD > 0.08 log units, but values up to SD $= 0.12$ are acceptable, depending on the demand of the application (van den Berg, Coppens, & Franssen, 2010; van der Meulen et al., 2012; van de Wouw et al., 2016). When ESD > 0.12, the result should not be used. Reasons for poor ESD can be reduced visual acuity (the limit is about logMAR 1.0), erroneous instruction to the patient or erroneous settings (see below).

Figure 6 shows the proportion of individuals that failed because of poor ESD (> 0.12) in a large European driver study. At age 90 about 20% failed. The reasons for this were not studied, but repeated measurements with better instruction or settings may have partly resolved this. In particular the Range setting may be important. This is illustrated in Figure 5. The lower frames show that the first phase (blue crosses) tests a range of about one log unit (a factor of ten). This is done for reasons of time. The default range setting E catches straylight values of $0.9 < log(s) < 1.9$, which suffices to catch the straylight value for 95% of normal ophthalmological patients. However, differences of up to almost 2 log units (a factor of 100) may exist within the population. In the case of Figure 5, we artificially increased straylight from $\log(s) = 0.83$ to $\log(s) = 1.92$, a factor of 12.3. It is clear that range G, used for the lower picture, would have missed the subject's straylight value shown in the upper picture. In practice, if ESD is found to be poor (i.e. high), the pattern of responses will indicate in which direction the range should be changed. If all responses are "1" (the comparison half-field flickers more strongly than the straylight half-field) the range was too high. If your study involves mainly healthy young eyes, it is advisable to use range C instead of E as default, as shown in the upper part of Figure 5. For eyes with significant media opacities the use of range G is recommended, as shown in the lower part of Figure 5.

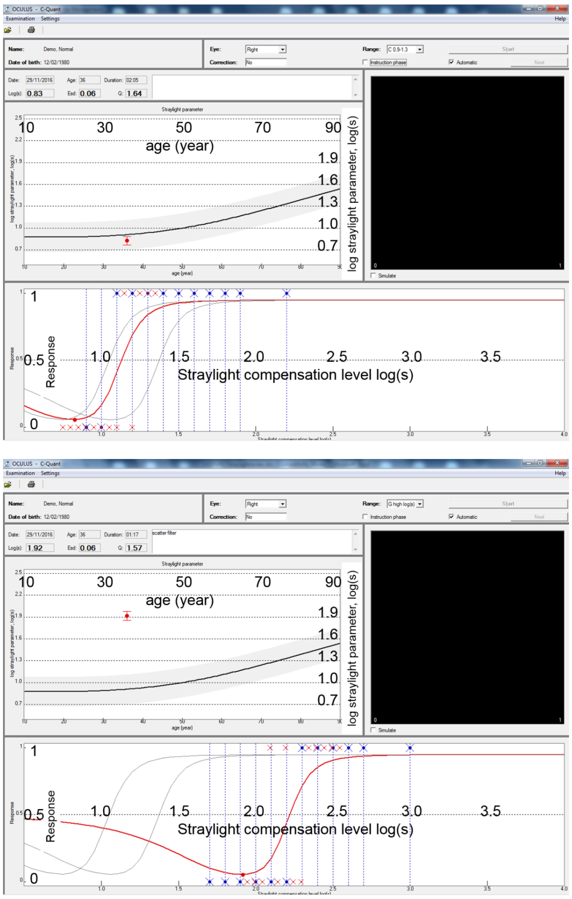

Figure 5: *Example measurements on a healthy subject ($\log(s) = 0.83$). In case of the lower image, with a scattering filter in front of the eye ($\log(s) = 1.92$). The images are screen shots at the end of a measurement, with added lettering for visibility. The upper graph in each screenshot gives the $\log(s)$ result of the subject (red dot) with the ESD value (red error bars), and compares that to age-normal values. The age-normal values are given as mean (black line) and 95% interval (grey area). The lower graph in each screen shot shows the responses of the subject, and the fitted psychometric function. The measurement contains two phases, a coarse phase indicated by blue crosses, and a refinement phase indicated by red crosses. The measurements in the refinement phase are concentrated around the point of equality (the 50% point) as estimated from the first coarse phase. Accuracy as estimated with the SD value (expected standard deviation) is 0.06 in both measurements. The grey lines show the 95% limit positions of the psychometric function for age-normal eyes for the respective age (36 years in this case). The red line shows the psychometric function shifted to coincide with the responses. The fitted position of the psychometric function gives a best estimate of the $\log(s)$ value of the subject (red dot). During a measurement, the area of the black square shows the stimulus presented to the subject.*

Discussion

This review discusses straylight measurement as a quantitatively precise approach towards disability glare assessment according to the international CIE standard. As it has long been recognized that glare constitutes a safety hazard for driving it was deemed necessary to have a scientifically appropriate test (Elliott & Bullimore, 1993; Elliott et al., 1990; Elliott, Hurst, & Weatherill, 1991; Rubin & Stark, 1995). Straylight measurement yields precise predictions for the degree of interference caused by glare (van den Berg et al., 2009). It is a well-known fact that subjects developing a cataract often give up driving at night because of the hazards of being blinded by glare. In a European study it was found that when straylight had increased by a factor of approximately 4 subjects tended to give up driving (van den Berg et al., 2013). Since normal values for the young eye are around $\log(s) = 0.9$, this corresponds to $\log(s) = 1.5$. If this is compared to a value of $\log(s) = 1.4$ for early cataract surgery (Lapid-Gortzak et al., 2014; van den Berg et al., 2013; van der Meulen et al., 2012), it follows that patients are already eligible for cataract surgery before the limit for safe driving is reached. This should be recognized.

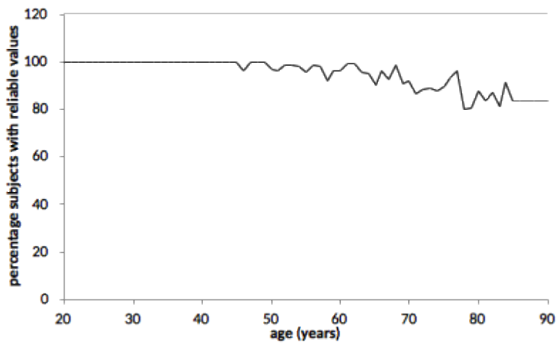

Figure 6: *The percentage of subjects with reliable straylight measurements according to the ESD criterion declines with age from 100% at young age to about 80% at 90 years of age. These are thus far unpublished results from a large European driver study (Van Den Berg et al., 2007; van Rijn et al., 2011). www.glare.eu*

The use of the word "normal" for the increase in straylight with ageing needs a comment. As can be seen in Figure 6, starting from about 40 years of age, straylight increases, doubling by about 65 years of age and tripling by about 77 years of age. Although this may be considered "normal", it is also a real loss of quality of vision and increased glare sensitivity. It would be improper not to take this seriously. This change is not normal if we consider the values of the young eye to be normal. Patients with an active life style, seeking cataract surgery to continue driving should be allowed such treatment even if their straylight values are "age-normal".

For visually demanding professions such as pilots a limit value of $\log(s) = 1.2$ has been proposed (van Bree, van Verre, Devreese, Larminier, & van den Berg, 2011; van den Berg et al., 2013), corresponding to an elevation of glare sensitivity by a factor of 2. Considering that the variation of straylight in the normal population has a standard deviation of about 0.1 log units, the limit value of 1.2 corresponds to an increase of 3 standard deviations compared to normal. So, statistically the value of 1.2 would constitute a highly significant deviation from the normal situation.

Official regulations on occupational glare testing are presently somewhat unclear. On the subject of vision and driving, EU-directive 2009/113/EC states: All drivers: "When there is reason to doubt the applicant's vision is adequate…attention shall be paid, in particular, to…twilight…glare"; and for Group 1 drivers: "if the visual field standard or visual acuity standard cannot be met…there is no other impairment…including glare…and twilight vision". For Group 1 drivers, this could be interpreted as $\log(s) \leq 1.2$ based on the above, but for the other drivers it seems to be left to the discretion of the person doing the testing what cut-off value to use. Based on the results of the European driver study mentioned above, it will be clear that we would suggest $\log(s) = 1.5$ as the cut-off value. Practical

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studies are required.

The EASA and FAA regulations for pilots says: "glare sensitivity is within normal standards". As for Group 1 drivers, this can be interpreted as $\log(s) \leq 1.2$. A study was conducted in a military testing centre in 2007 (van Bree et al., 2011). It found that 33 out of 373 subjects who had had laser refractive surgery scored above this limit. Studies in refractive surgery centres showed somewhat better results (Beerthuizen, Franssen, L., & van den Berg, 2007; Lapid-Gortzak, van der Linden, van der Meulen, Nieuwendaal, & van den Berg, 2010; Rozema et al., 2010; Vignal, Tanzer, Brunstetter, & Schallhorn, 2008). Advancing techniques will, in time, yield more reliable results.

Many studies have shown the importance of glare for safe driving (Anderson & Holliday, 1995; Gray & Regan, 2007; Lachenmayr et al., 1998; Mäntyjärvi & Tuppurainen, 1999; Ranney et al., 2000; Rubin et al., 1994; Theeuwes et al., 2002; Von Hebenstreit, 1984). However, the relationship with actual accidents is not strong, although several clear incidental cases have been reported (Bradley, personal communication). This may be partly due to the limitations of the glare assessment techniques used, as discussed in the introduction, but also partly to avoidance behaviour of people suffering from increased glare hindrance. Most glare studies note that people avoid driving at night if they feel unsafe due to glare sensitivity. Avoidance behaviour may depend on awareness: people who are aware of the danger may respond with avoidance. Also, the awareness may differ for different visual defects. It could be that awareness of the dangers of glare is relatively high.

In conclusion, this review discusses straylight as an international standard for glare sensitivity assessment. For safe driving a limit of about $\log(s) = 1.5$ is proposed, which is $4\times$ the normal value for young eyes. Straylight is also a basic quality parameter of the eye, independent of acuity, and is useful for ophthalmological practice.

Acknowledgement

Proprietary Interest: The Royal Academy owns a patent on straylight measurement and licenses this patent to Oculus for the C-Quant instrument.

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