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NEUROPHTHALMOLOGY

Marked dissociation of photopic and mesopic contrast sensitivity even in normal observers

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Abstract
Aim Although contrast vision is not routinely tested, it is important: for instance, it predicts traffic incidents better than visual acuity. Mesopic contrast sensitivity (CS) testing approximates low-lighting conditions but entails dark adaptation, which can disrupt clinical routine. In receptor-specific diseases, a dissociation of photopic and mesopic sensitivity would be expected, but can photopic CS act as a surrogate measure for mesopic CS, at least for screening purposes?
Methods Photopic and mesopic contrast sensitivities were studied in three groups: 47 normal subjects, 23 subjects with glaucoma, and three subjects with cataract. Twenty-eight of the normal subjects were additionally tested with artificial blur. Photopic contrast sensitivity was assessed with both the Freiburg Acuity and Contrast Test (FrACT) and the Mars Letter Contrast Sensitivity Charts. Mesopic contrast sensitivity, without and with glare, was measured with the Mesoptometer IIb. Coefficients of repeatability and limits of agreement were calculated for all tests.
Results Test–retest limits of agreement were ± 0.17 logCS for Mars, ± 0.21 logCS for FrACT, and ±0.20 logCS / ± 0.14 logCS for Mesoptometer IIb without and with glare, respectively. In terms of inter-test comparison, Mars and FrACT largely agreed, except for ceiling effects in the Mars test. While mesopic and photopic contrast sensitivities correlate significantly (r =0.51, p<0.01), only 27 % of the variance is in common. In particular, subjects with high photopic results may be nearly as likely to have low as well as high mesopic results.
Conclusions The photopic contrast sensitivity tests assessed here cannot serve as surrogate measures for current mesopic contrast sensitivity tests. Low photopic CS predicts low mesopic CS, but with normal photopic CS, mesopic CS can be normal or pathologic.

Keywords Contrast sensitivity · Mesopic vision · Photopic vision · Rods · Cones · Age · Traffic

Introduction

Two obvious parameters characterizing vision are visual acuity (VA) and visual field. Contrast vision is much less often assessed, although it is a better predictor for traffic accidents than visual acuity [1, 2]. In some countries, normal mesopic and contrast vision is legally required for permission to drive, e.g., in Germany [3]. The latest version of the aforementioned regulation is unclear as to whether contrast sensitivity be tested under mesopic or photopic conditions, or both. Contrast testing is technically more demanding than acuity testing, and the methodology is not as standardized. Accurate mesopic testing requires well-defined dark adaptation, whose timing and room requirements can disrupt clinical routine. This experiment was thus designed to answer the practical question whether photopic contrast sensitivity can predict mesopic contrast sensitivity. Apart from specific diseases that differentially target rods versus cones, this seems possible in principle.

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Materials and methods

Subjects

Eighty subjects were recruited from patients and staff of the University Hospital Freiburg. Written informed consent was obtained from all subjects. The study adhered to the tenets of the Declaration of Helsinki and was approved be the local ethics committee. All participants underwent a thorough eye examination comprising habitually corrected visual acuity, intraocular pressure, slit-lamp assessment of the anterior and middle segments, and indirect ophthalmoscopy of the optic nerve head and central retina.

Criteria for exclusion were

- visual acuity worse than 0.3 logMAR (to ensure that visual acuity sufficed for resolution of the optotypes used in our contrast tests)
- retinal disease (except age-related macular drusen or pigment irregularities)
- other eye diseases interfering with contrast sensitivity. Glaucoma or cataract were not excluded; instead, these conditions led to inclusion into specific study groups.

After applying the exclusion criteria, 73 participants remained. One eye per participant was studied. The participants fell into three groups (see also Table 1).

1) Glaucoma group (n=23). We recruited these participants from the Ophthalmology Department of the University of Freiburg while they were being hospitalized for day and night tonometry. The eyes showed glaucomatous optic disc cupping, typical visual field defects, and no signs of other eye disease (apart from mild macular changes, see above). If there was no or little visual field loss, we included them based on structural damage detected by spectral-domain optical coherence tomography measurement of the retinal nerve fiber layer (SD-OCT-RNFL) or the Heidelberg Retina Tomograph (HRT).
2) Cataract group (n=3). Two subjects with cataract were patients scheduled for cataract surgery and were examined both before and 3 months after surgery. Another participant was diagnosed with cataract during a routine eye exam at our hospital (the low count in this group is due to insurmountable logistic difficulties regarding the cataract clinic's workflow).
3) Healthy subjects (n=47). Forty-seven participants with no ocular disease were included in this group. To increase the number of individuals with low contrast vision, we additionally tested some of the normal subjects with a scattering filter placed in front of their eye in order to blur vision and artificially reduce contrast sensitivity.

Scattering filter subgroup (n=28)

Because of the steep slope at the high-spatial frequency end of the contrast sensitivity function, the haze caused by such a filter affects contrast sensitivity more than visual acuity, imitating the experience of many cataract patients [4]. We used clear sheet protectors (Leitz copy safe No. 4734) to create two kinds of filters: one layer of sheet protector for a weak (F1) and three layers for a stronger filter (F3). The layers were mounted in a trial lens frame and attached directly onto the subjects' spectacles or onto a trial glass frame.

Across all groups, we recorded 104 measurement sets of 73 eyes.

Contrast measures and contrast sensitivity

Contrast occurs between two regions in the visual field when their luminances differ (L_{min} for the darker region, and L_{max} for the lighter region). There exist, unfortunately, at least four different definitions of contrast: Michelson contrast $c_{Michelson} = (L_{max}–L_{min})/(L_{max} + L_{min})$, Weber contrast $c_{Weber} = (L_{max}–L_{min})/L_{max}$, the contrast ratio $cRatio=L_{max}/L_{min}$, and the inverse contrast ratio $c_{Aulhorn} = L_{min}/L_{max}$. The Michelson contrast treats the two areas equally, and is useful when the light and dark areas are similar in size, making it the appropriate measure for gratings or checkerboards. For isolated targets on a differently-lit background, the Weber contrast is appropriate. These two measures have a non-linear relationship: for low contrast values, e.g., 1 %, c_{Weber} is twice as large as $c_{Michelson}$, at 100 % they become equal: $c_{Weber}=2\cdot c_{Michelson} / (1 + c_{Michelson})$ [5]. In industry (DIN Norm 58220 part 7), the contrast ratio is preferred, and it can attain seemingly impressive high numbers (1,000 or higher) if the dark areas are dark enough. The inverse contrast ratio, which is named $c_{Aulhorn}$ in honor of Elfriede Aulhorn's pioneering work

Table 1 Details on the study participants. Visual acuity (VA) was tested with habitual correction. Note that VA for cataract patients is pre-operative

	Normal	Glaucoma	Cataract
Number of subjects (total: 73)	47 (23 OD, 24 OS)	23 (12 OD, 11 OS)	3 (2 OD, 1 OS)
Age range [years]	20–61	37–80	63–76
Visual acuity [logMAR]. Mean, SD, and range	−0.12±0.09 (+0.15 to −0.28)	0.00±0.14 (+0.20 to −0.26)	0.09±0.13 (+0.21 to −0.04)

with Harms [6], is used in recommendations by the German ophthalmological professional associations pertaining to contrast [7].

The contrast threshold can be expressed in % of contrast; its inverse is called contrast sensitivity, "CS". We will use here the logarithm of the inverse Weber contrast, as this approximately corresponds to an interval scale (due to the Weber–Fechner law, and analogous to logMAR for acuity). This unit will be called $logCS_{Weber}$, short for log(contrast sensitivity), where contrast is measured according to the Weber definition, or even shorter: logCS.

Contrast sensitivity tests

We employed three different contrast tests, one for mesopic and two for photopic contrast. The contrast in the mesopic range was assessed with the Mesoptometer IIb (Fig. 1, Oculus, Germany, abbreviated as "Mesotest" from here on).

According to the manufacturer, the light surround has a diameter of 3.6°; without glare its luminance is 0.032 cd/m^2, with glare 0.1 cd/m^2. The glare source leads to an illumination of 0.35 lux in the pupillary plane. The central optotype (a Landolt C equivalent to a decimal visual acuity of 0.1) was presented in six possible orientations [skipping left (directed towards the glare source) and right] and had various luminance levels, leading to the contrast levels specified in Table 2.

As an example, requirements for vehicle driving in Germany are: 0.02 logCS to drive a car (recommended, but not routinely tested), 0.1 logCS for driving heavy vehicles and taxis, and 0.2 logCS for bus driving. Subjects unable to recognize even the highest contrast (1:23=0.02 logCS) are considered unfit for night driving according to the recommendations of the German Ophthalmological Society [7]. (Mesopic contrast sensitivity is not routinely tested in subjects applying for a "standard" car driver's license in Germany, only in those failing to meet the VA requirement or when applying for a heavy vehicle, taxi or bus-driving permit).

Contrast in the photopic range was assessed with two different tests. One was the Mars Letter Contrast Sensitivity Test [8], which consists of three versions of charts measuring 0.22 ×0.35 m in size. Letters of the Sloan font are arranged in eight lines with six letters each. Contrast between letters changes by 0.04 logCS; the test thus nominally covers a range between 0.04 and 1.92 logCS. The charts were placed in a holder and lit in a standardized way to achieve the specified chart luminance of 60–120 cd/m^2. The measurement steps followed the Mars manual, and are described under "Procedure" below.

We also employed the Freiburg Acuity and Contrast Test (FrACT) [9–13], available online at <http://michaelbach.de/fract.html>. FrACT displays optotypes (in this study a Landolt C) on a computer screen, using dithering to achieve contrast levels below human thresholds on standard 8-bit visual display units [14]. The threshold is estimated with an adaptive staircase procedure, based on maximum-likelihood calculations ("Best PEST" [15]). Great care was taken to avoid any stray light that could degrade the contrast levels being displayed.

Table 2 Mesotest contrast levels expressed as inverse contrast ratio (left column as output by the Mesotest device) or logCS (right column). These values are specified in the German Traffic regulations [7] and are based on extensive research by Aulhorn and Harms [6]

Mesotest contrast level ($c_{Aulhorn} = L_{min} : L_{max}$)	log contrast sensitivity (logCS)
1:23	0.02
1:5	0.1
1:2.7	0.2
1:2	0.3

Procedure

All testing was monocular with habitual correction. Subjects over the age of 40 who did not have their own near correction were provided a +2 dpt near add to adjust for testing distance when tested with the FrACT and Mars test. Eyes were altered between subjects, and the eye not being tested was covered with an eye patch. In the scattering filter subgroup, the same

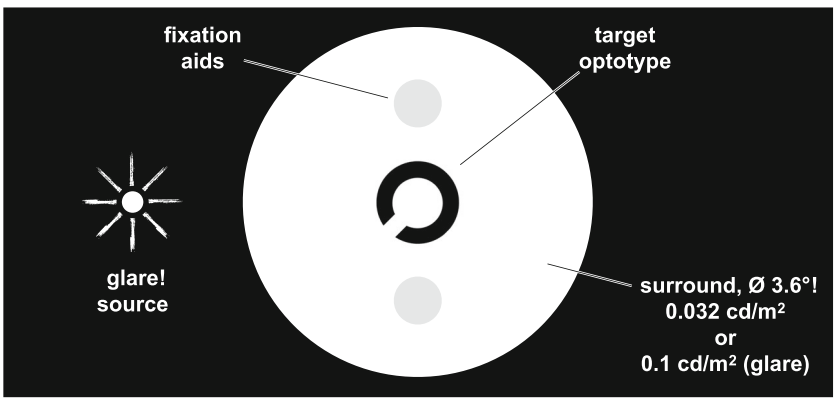

Fig. 1 Mesopic contrast test ("Mesotest"). Within the rubber tubing serving as the light screen, this is the view the participant sees

eye was tested with and without a filter, with half of the group beginning the measurement without, the other half with filter.

Before assessing contrast sensitivity, visual acuity was assessed with FrACT at 2.5 m distance. Each test was performed twice, starting with a binocular warm-up run of the first contrast test, the results of which were not recorded. We encouraged our subjects in all trials to guess and provide a response, even if they felt unable to perceive the optotype.

Five-minute dark adaptation is necessary before mesopic contrast sensitivity can be tested. To save time, the Mesotest measurements (two runs without glare, followed by two runs with glare) were taken consecutively before or after assessing photopic contrast sensitivity. Starting with the highest contrast, subjects were shown up to five Landolt Cs per contrast level and had to identify the gap. Testing proceeded to the next level with lower contrast when three out of five positions had been correctly named, and stopped when the subject failed to meet this criterion. The last successfully completed level determined that subject's score. Subjects unable to recognize even the highest contrast were assigned the value −0.1 logCS to enable us to include their results in our analyses (being aware that negative values are technically not possible).

The order of the photopic tests followed an ABBA scheme. Testing distance was 50 cm (the optotypes' size thus corresponded to a decimal visual acuity of 0.04 ≙ 20/500) in both tests, and subjects were instructed not to move or tilt their head.

For the Mars charts, this testing distance was defined by mounting them in a reading stand. All three forms were used equally in random order. Chart luminance ranged from 70 to 104 cd/m^2 under ceiling illumination with fluorescent tubes (thus within the specified limits). Following the Mars user manual, subjects were instructed to read the letters across and down the chart. Only letters in the Sloan alphabet were accepted as responses. A "C" when an "O" was presented and vice versa was not accepted as correct, unlike as suggested by other authors [16]. Testing stopped once two consecutive errors had been made, the last correctly identified letter determining the subject's log contrast sensitivity. For each earlier mistake, 0.04 logCS were subtracted to obtain the final result.

Testing with FrACT consisted of two runs with 24 optotypes each, the contrast of the optotype varying from trial to trial, homing in on the subject's contrast sensitivity in an adaptive staircase manner. Between each trial, a thin fixation cross was displayed for 200 ms to help locate the optotype when contrast was low. Ceiling illumination was turned off to avoid reflections on the monitor; background luminance on the screen ranged from 75 to 110 cd/m^2. Subjects announced the position of the Landolt C to the examiner operating the response keypad. At the end of each run, the subject's result was presented on the screen and recorded.

Statistical analysis

All statistical analysis was performed using R [17]. Results of all test runs were transformed into "logCS", the logarithm base 10 of the inverse Weber contrast. To assess test–retest reliability and agreement between runs, we calculated differences (diff) between the first and second runs of all tests. Coefficients of repeatability (COR) and the 95 % limits of agreement (LOA) were then computed as suggested by Bland and Altman [18] ($COR = 1.96 \times SD_{diff}$, $LOA = mean_{diff} \pm 1.96 \times SD_{diff}$). These calculations are based on all measurements of all subjects (that is, across all groups) unless otherwise stated. For comparison between the different test types, first and second runs were averaged per test.

Results

Test–retest reliability

We started by assessing our methodology, namely test–retest reliability. Figure 2 shows scatter plots for the photopic tests. Mean contrast sensitivities (±SD) for the different groups of subjects are shown in Table 4. The mean difference between the first and second run of all subjects was 0.02±0.11 (SD) logCS for FrACT (right), resulting in limits of agreement of ±0.22 logCS. For Mars (left), mean difference was 0.00±0.09 (SD) logCS, the limits of agreement being ±0.17 logCS.

In Fig. 2, we noted that the Mars values stopped at a ceiling of around 1.8 logCS (more on this below). When the FrACT values were also clipped to≤1.8 logCS, the mean inter-test difference dropped to 0.02±0.10 (SD) logCS. Limits of agreement were then ±0.20 logCS and thus narrower and closer to the respective Mars values.

Figure 3 shows scatter plots for the two mesopic tests, without (left) and with glare (right). Mean contrast sensitivities (±SD) are shown in Table 3. The mean difference for the no-glare condition was 0.01±0.10 (SD) logCS and 0.01±0.07 (SD) logCS with glare. Limits of agreement were ±0.20 logCS without and ±0.14 logCS with glare respectively. Since there are only five possible discrete result values, many data points are superimposed. The bottom shows an alternate plot where the column heights indicate the counts per condition. The data show accumulation (ceiling) at the top (below 0.02 logCS) and the bottom (0.3 logCS) ends of the tested contrast sensitivities. Note that subjects failing to recognize even the highest contrast (0.02 logCS) were assigned −0.1 logCS. When testing without glare, 43 participants had a mean logCS of less than 0.02, meaning they failed the Mesotest in at least one of the two runs; with glare this applied to 64 participants. Twenty-seven and 50 subjects, respectively, failed in both runs (mean contrast sensitivity −0.1 logCS).

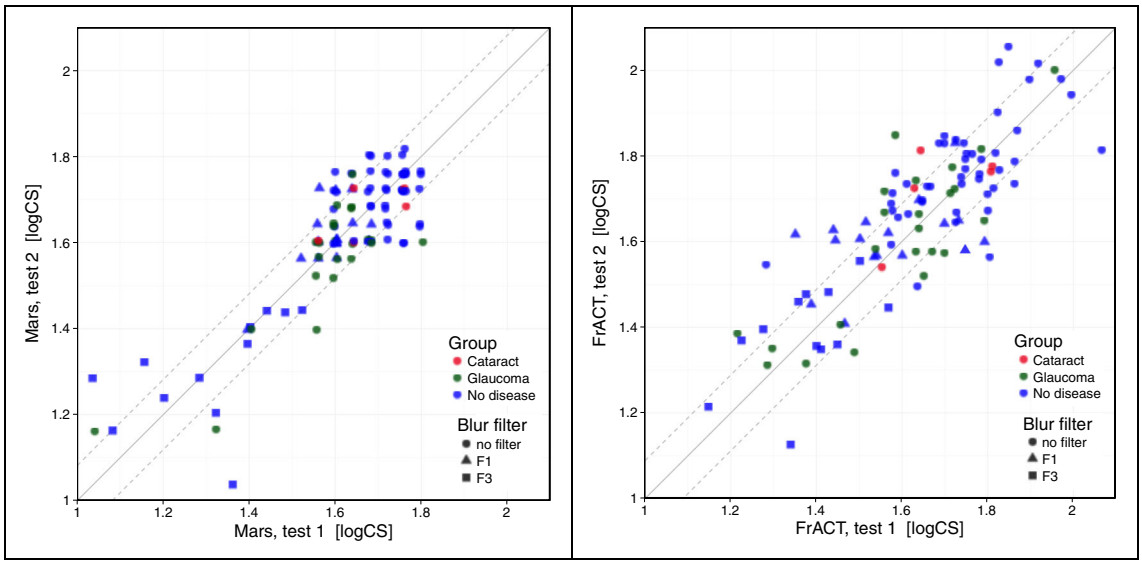

Fig. 2 Photopic tests, test–retest reliability for Mars (*left*) and FrACT (*right*). Results of first run are plotted on the abscissa, of the second on the ordinate. The *dotted lines* represent the limits of agreement

To better judge test–retest reliability of the mesopic vs. the photopic tests, Fig. 4 depicts all test results on a scale encompassing the full range. Taking marked overplotting into account (see Fig. 3), it is apparent that the mesopic and photopic tests are quite similar in their test-retest reliability – the data cluster similarly relative to the identity line. This is borne out numerically (Table 3).

Agreement between the two photopic tests Mars and FrACT

Although this question was secondary to this study's main objective, it revealed interesting aspects as seen in in Fig. 5. The ceiling effect for the Mars charts, already mentioned, is here obvious in the form of missing data points to the right (above 1.8 logCS). Contrast sensitivity ranges from 1.18 to 1.98 logCS when obtained with FrACT and between 1.10 and 1.79 logCS for Mars. Therefore, contrast sensitivity on average is a little higher in FrACT (1.65 logCS vs 1.61 logCS). The mean difference between FrACT and Mars is 0.03±0.10 logCS, and limits of agreement are −0.17 and 0.23 logCS. The slightly higher contrast sensitivity with FrACT may be due to its adaptive bracketing staircase strategy versus the ascending strategy in Mars.

As mentioned above, the limits of agreement for FrACT narrow when the results are clipped to 1.8 logCS (imitating a ceiling as seen in Mars results). We thus concluded that Mars and FrACT values agree within their test–retest limits, and chose FrACT for further analysis since it covers a wider range.

Comparison of photopic and mesopic contrast sensitivity

Having ascertained reliable measures for mesopic and photopic contrast sensitivity, we can now turn to the main point of this paper: does photopic CS correlate with mesopic CS? In Fig. 6, mean FrACT values are plotted against mean Mesotest values of the same eyes.

Mesopic and photopic CSs correlate significantly (r=0.52 / 0.56 (no glare/glare), p <0.0001). However, only 27/32 % of the variance is explained. Eyes with *high mesopic* values (with or without glare) also had high photopic values, and eyes with *low photopic* values also had low mesopic values. However, the reverse does not apply: eyes with low mesopic values had either low, intermediate, or high photopic values, and eyes

Table 3 Test–retest reliability. Mean difference (second minus first run) ± SD between in logCS. The corresponding 95 % limits of agreements (LOA) are given in parentheses

	All subjects	No disease (without scattering filter)	Glaucoma	Cataract (preop)
Mars	0.00±0.09 (−0.17 to +0.16)	−0.01±0.08 (−0.16 to +0.15)	−0.02±0.09 (−0.19 to +0.17)	−0.03±0.06 (−0.15 to +0.09)
FrACT	0.02±0.11 (−0.19 to +0.23)	0.02±0.11 (−0.19 to +0.24)	0.01±0.11 (−0.20 to +0.22)	0.08±0.09 (−0.10 to +0.26)
Mesotest, no glare	0.01±0.10 (−0.19 to +0.21)	0.02±0.12 (−0.20 to +0.25)	−0.02±0.08 (−0.17 to +0.13)	−0.03±0.15 (−0.33 to +0.27)
Mesotest, glare	0.01±0.07 (−0.13 to +0.14)	0.02±0.09 (−0.16 to +0.20)	0.01±0.05 (−0.08 to +0.10)	highest contrast not seen

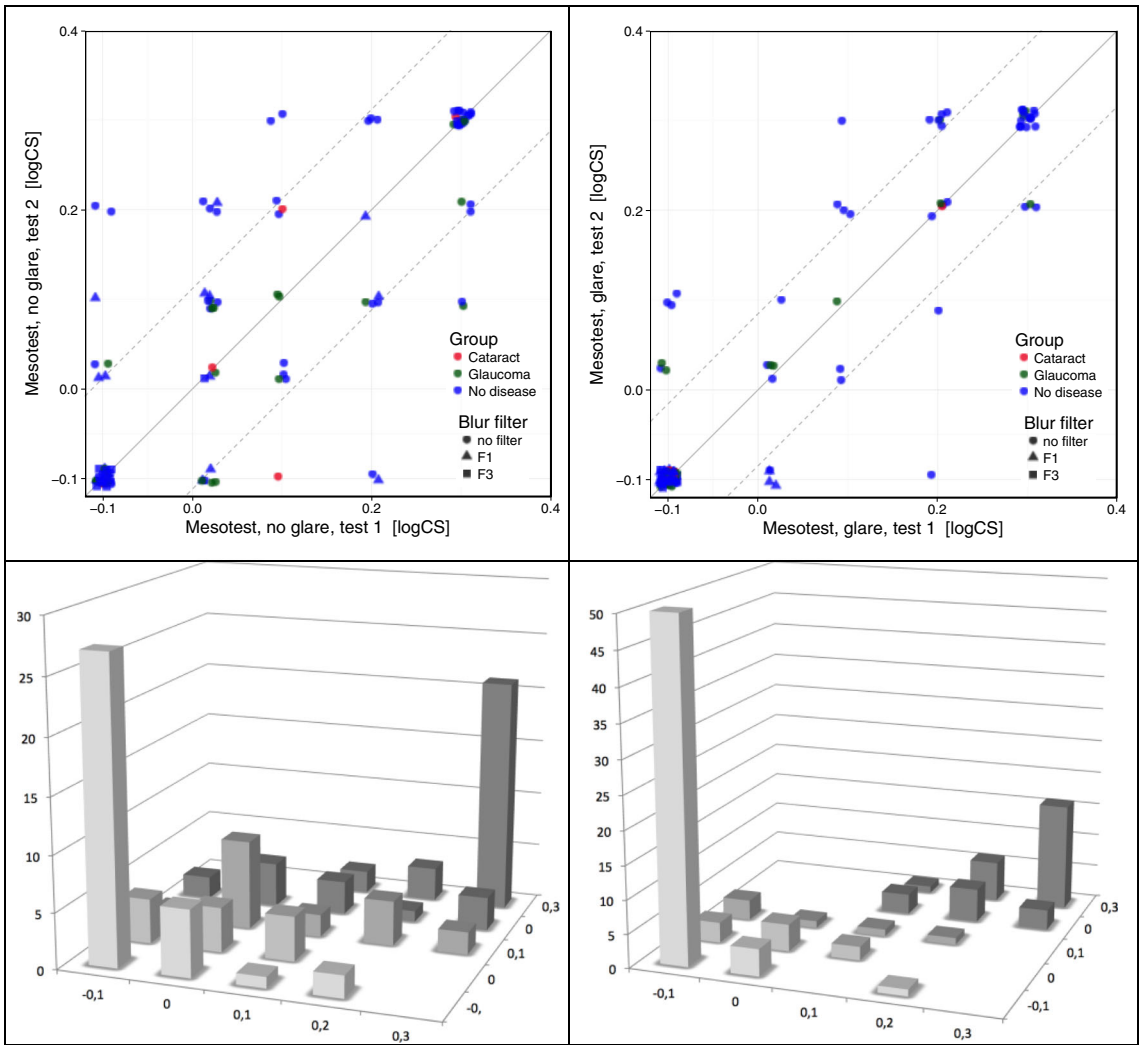

Fig. 3 *Top row*: test–retest reliability for Mesotest without (*left*) and with glare (*right*). Results of the first test run are plotted on the abscissa, of the second on the ordinate; a little jitter is added to reduce overplotting. The *dotted lines* represent the limits of agreement. Subjects unable to correctly identify even the highest contrast (0.02 logCS) were assigned the value −0.1 logCS. Note that this was the case for a considerable number of healthy subjects. *Bottom row*: same data, re-plotted in 3D to reveal the huge amount of overplotting. First-run results are on the *x*-axis, second-run results on the *y*-axis (both in logCS). Third axis (*z*; column heights) depicts counts per condition

with high photopic values had either low, intermediate or high mesopic values.

Comparison among the different groups

Compared to the normal eyes in our study, the glaucoma and cataract eyes had on average lower results in all contrast tests. Results were, unsurprisingly, especially low when scattering filters were placed in front of the eyes (see also Tables 4 and 5 and Figs. 7 and 8). The differences to normal eyes without filter were statistically significant (except for the cataract eyes, probably due to their very low number). Figures 7 and 8 show mean contrast sensitivities (dots) for FrACT and Mesotest compared between normal

Table 4 Mean ± SD scores (logCS) of the different groups of subjects for all tests

	All subjects	No disease, no scattering filter	Glaucoma	Cataract (preop)	Cataract (postop)
N	73	47	23	3	2
Mars	1.61±0.16	1.71±0.05	1.56±0.14	1.64±0.07	1.71±0.04
FrACT	1.65±0.17	1.75±0.12	1.60±0.17	1.65±0.09	1.79±0.01
Mesotest, no glare	0.08±0.15	0.17±0.13	0.05±0.14	0.06±0.08	0.10±0.28
Mesotest, glare	0.04±0.16	0.15±0.15	0.00±0.15	-0.1±0.00	0.05±0.21

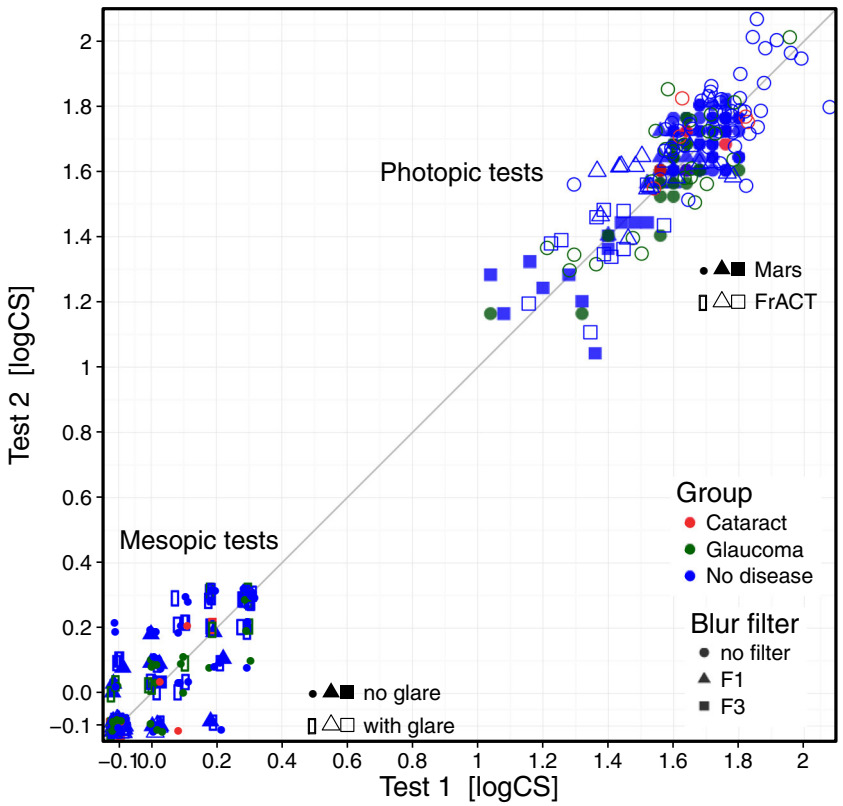

Fig. 4 Similar test–retest reliability of photopic and mesopic tests. Results of the first run are plotted on the abscissa, of the second on the ordinate. *FrACT* = Freiburg Acuity and Contrast Test

subjects without and with scattering filter (Fig. 8) and between groups (Fig. 8).

The differences between normal and diseased eyes (or eyes with scattering filters) were more pronounced in the mesopic

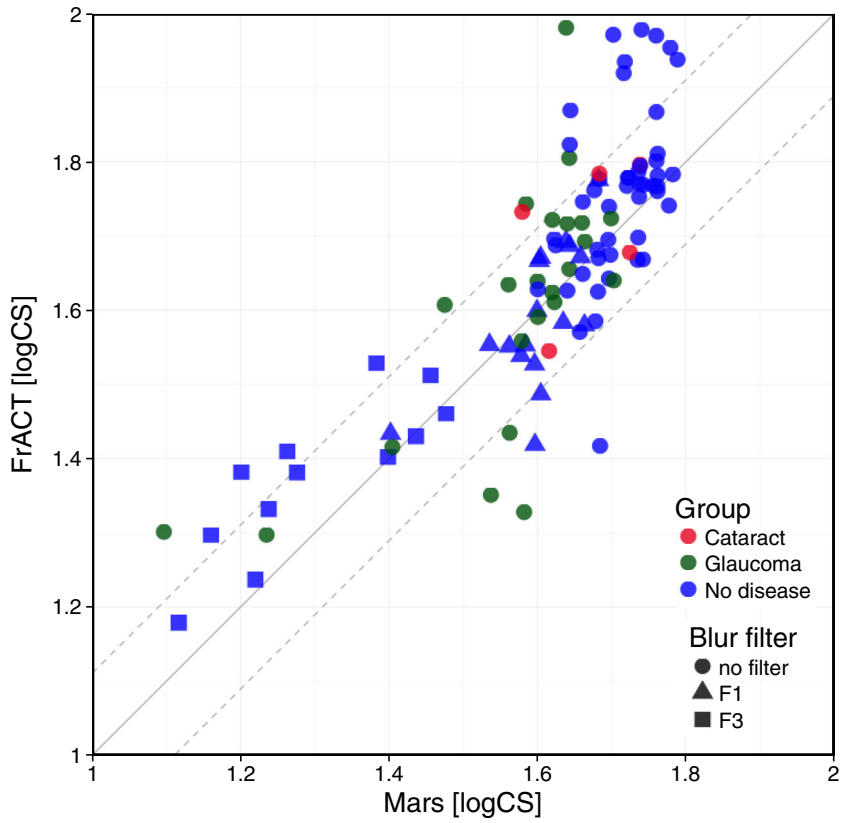

Fig. 5 Comparison of mean contrast sensitivity as obtained by Mars charts (abscissa) and FrACT (ordinate) over the range of one log unit. A ceiling effect is seen in the Mars results at 1.8 logCS

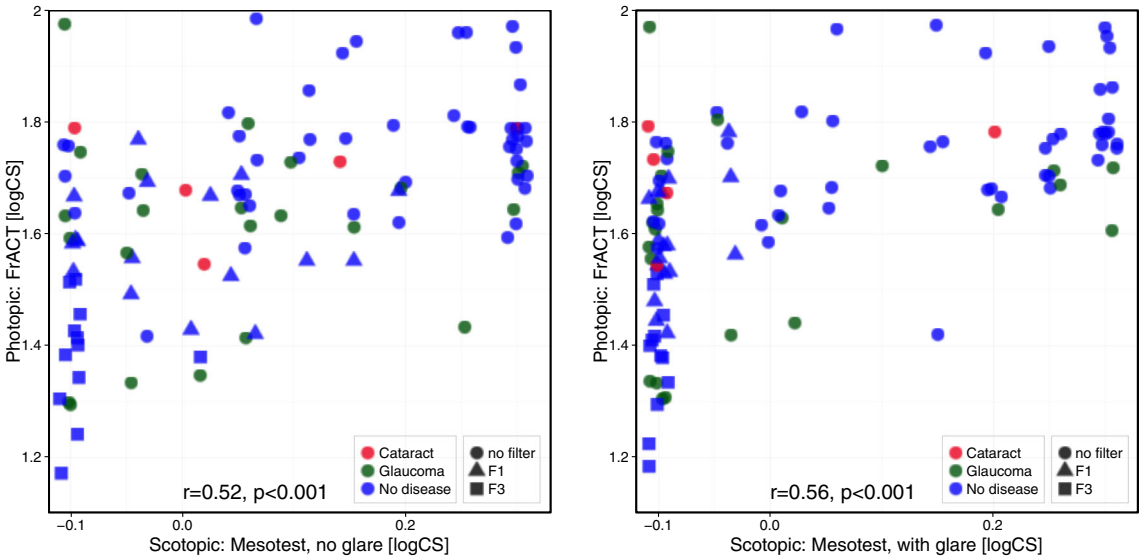

Fig. 6 Comparison of photopic and mesopic contrast sensitivity. Abscissae: mesopic (Mesotest) contrast sensitivities, *left* without, *right* with glare. Ordinates: photopic sensitivity (FrACT). In both graphs there is better correlation in the range of high rather than low mesopic CS

tests. Contrast sensitivity improved after surgery in the few cataract eyes (see also Table 4): mean photopic logCS as obtained with FrACT rose from 1.65±0.09 to 1.71±0.04, and was thus as good as the mean photopic logCS in the normal control group.

Discussion

This study was designed to compare individual photopic with mesopic contrast sensitivity. To validate our tools, we first assessed test–retest reliability and correlation of three contrast sensitivity tests: the Mesoptometer IIb (mesopic) and the Mars Charts as well as the FrACT (both photopic) in 73 individuals with different ocular conditions (glaucoma, cataract, or no abnormality). For the photopic tests, we found 95 % LOAs of≈±0.16, sufficiently lower than the range of around 1.0 to 1.8 logCS (photopic) covered between subjects (Table 3). It also agrees with data from the literature: Haymes et al. [19] give ±0.13 logCS, Dougherty et al. [16] give±0.18 logCS for their young group and±0.20 logCS their elder group. Interestingly, the mean test–retest differences were very low and within the margins of error (Table 3), suggesting that with the present number of repetitions no significant learning occurred (after several tens of trials thresholds improve by 0.1–0.2 log units [20, 21]).

Regarding the Mesotest's test–retest reliability, we found that the mean differences±SD between test and retest and thus limits of agreement did not differ much between photopic and mesopic tests (Table 4). For all subjects, 95 % LOA were ±0.21 logCS for FrACT, ±0.17 logCS for Mars, and ±0.20 and ±0.14 logCS for Mesotest without and with glare. Given the fact that the Mesotest only covers a small range of contrast sensitivity values (0.02 logCS–0.3 logCS), and that the differences in contrast between the Mesotest levels are as low as 0.1 logCS, variability of ±0.20 and ±0.14 logCS between test and retest is high: there is a high risk of falsely labeling a subject as not fit for night driving although he/she is, and vice versa, an observation also made by van Rijn et al. who consider Mesotest repeatability poor, given the small range between fit vs unfit for driving [22].

Table 5 Mean ± SD scores (logCS) of healthy subjects without (first column) and with scattering filter (second column)

	No disease (no scattering filter)	No disease (with scattering filter F1 and F3)
N	47	47
Mars	1.71±0.05	1.48±0.17
FrACT	1.75±0.12	1.50±0.14
Mesotest, no glare	0.17±0.13	-0.04±0.09
Mesotest, glare	0.15±0.15	-0.09±0.02

Global photopic contrast sensitivity outcome

Normal subjects without artificial blur displayed photopic sensitivities a bit above 1.7 logCS (Table 4), well in line with findings from the literature: Haymes et al. [19] tested contrast sensitivity with Mars in a normal control group (n=27) as well as glaucoma patients (n=27). Mean CS was 1.62±0.06 logCS for the control group and thus lower than our result of 1.71± 0.05 logCS, possibly due to their subjects' being older. In their glaucoma group, mean CS was 1.56±0.15 logCS in their

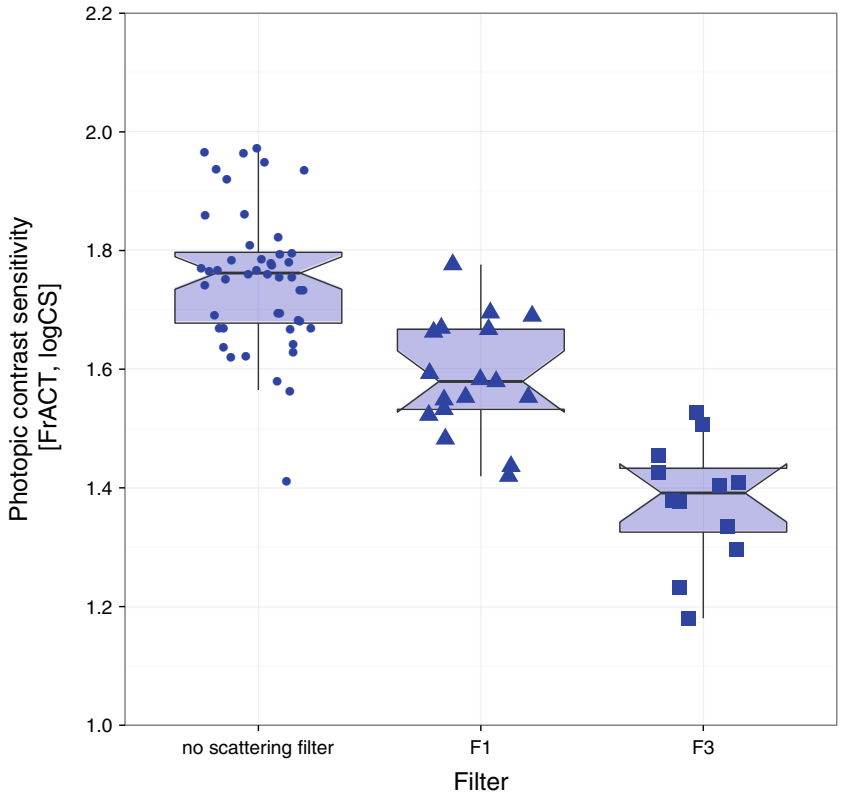

Fig. 7 The effect of the two scattering filters on FrACT results. The *dots* represent mean photopic logCS as obtained with FrACT for the different subgroups of the control group; horizontal jitter is added to reduce overplotting. In the box-and-whisker-plots, the *bottom and top of the boxes* represent the first and third quartiles, the *line* in the box is the median and the *notches* of the boxes represent the 95 % confidence interval of the median. As a simple rule: when the notches of two box plots do not overlap, the medians differ significantly [29]. The *whiskers* denote the range of mean values

study and similar to our finding of 1.56±0.14 logCS. Dougherty et al. [16] found CS assessed with Mars charts to be 1.73±0.07 logCS and 1.75±0.06 logCS for the young (n=20, mean age 24.2) and older (n=17, mean age 57) normal vision group, respectively. This is slightly greater than our finding, but unlike in our study, they accepted C as a correct answer for O and vice versa.

Photopic inter-test comparison (Mars vs FrACT)

When comparing the mean contrast sensitivities obtained with FrACT and Mars, we found a ceiling effect for the Mars Charts: while mean contrast sensitivity reached values as high as 1.98 logCS with FrACT, no subject scored better than 1.79 logCS with the Mars Charts (see also Fig. 5). This ceiling effect might account for the Mars Charts' slightly better reliability [±0.17 logCS vs ± 0.21 logCS (95 % LOA)]. When the FrACT values were clipped to 1.80 logCS, reliability improved (±0.19 logCS 95 % LOA). While the authors do not address it, this ceiling is also quite evident in the data by Haymes et al. 2006 [19]: mean logCS was lower for Mars than for Pelli–Robson in their normal control group (n=47) — 1.62 vs 1.79 logCS — and the corresponding Figs. 2 and 3 reveal no data points above a logCS of 1.7 for Mars, while many subjects score higher with Pelli–Robson charts.

Mesopic test

Comparing our Mesotest results to those of other studies turned out to be somewhat difficult due to the different contrast sensitivity units used: some results are illustrated in steps 1 to 4, corresponding to the Mesotest levels, and it is not always clear how they relate to the contrast steps of Table 2, rather than log contrast sensitivity. Another problem was how to deal with subjects unable to recognize even the highest contrast. In our study; we assigned them the value −0.1 logCS. Other studies either did not encounter the problem of subjects failing to reach the first contrast level, or they do not specify if or how those subjects' results were included in their calculations.

Fifteen of 47 healthy subjects (32 %, without scattering filter) were unable to score values at or above 0.1 logCS in the Mesotest without glare. With glare, 18 of 47 subjects (38 %) failed. Those subjects would not be given permission to drive a taxi, bus, or heavy vehicle in Germany (Table 6). Six of those subjects, or 13 % of all (when tested without glare) and 14 or 30 % (with glare) should not be allowed to drive at night *at all* according to the current recommendations [7].

Comparison of individual photopic and mesopic results

Finally, to address the main question of this study: comparison of one photopic (FrACT) with the mesopic test demonstrated

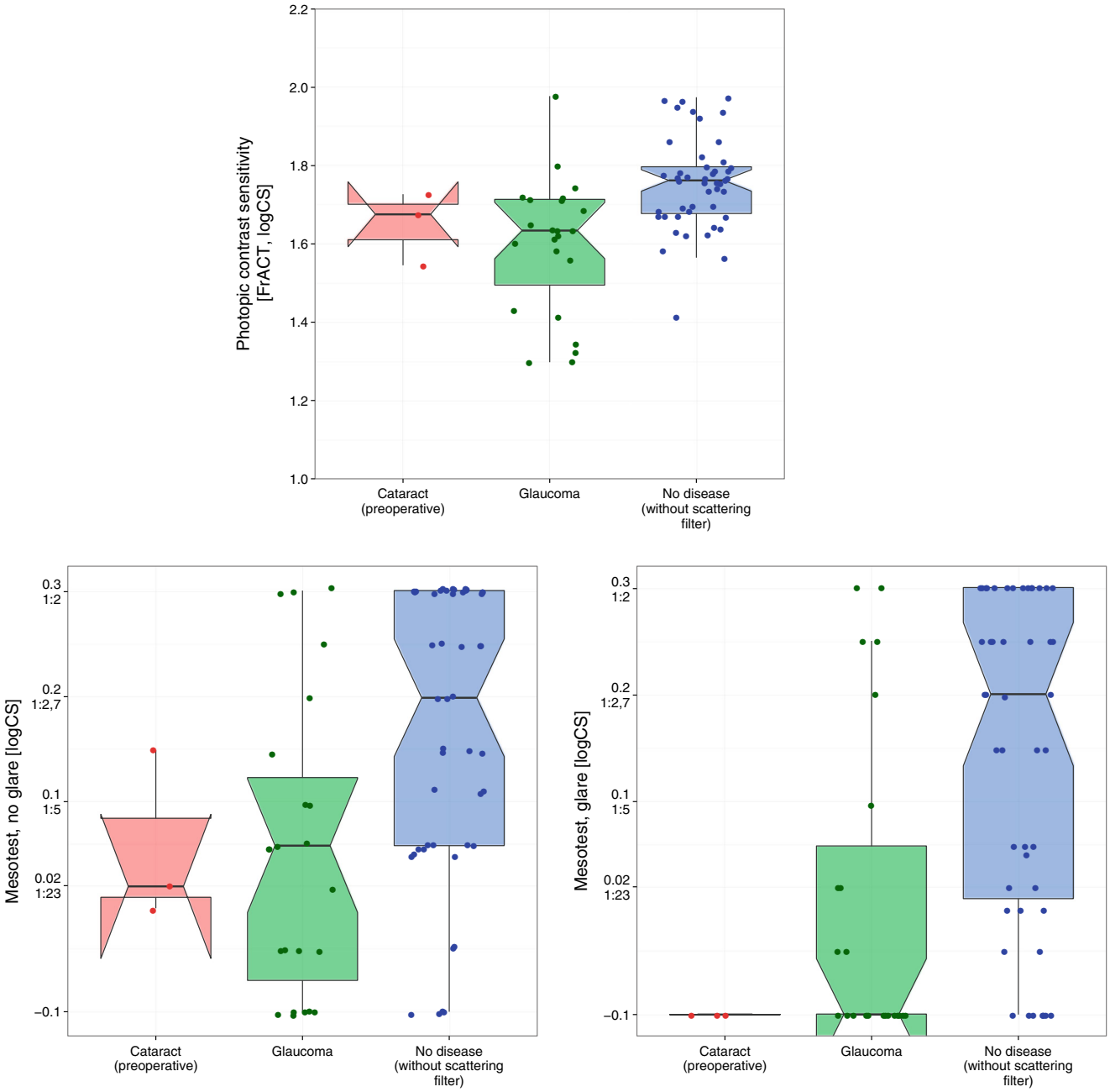

Fig. 8 Differences between groups for FrACT (*top*) and Mesotest without and with glare (*bottom*). The *dots* show mean contrast sensitivities in logCS (see also Table 4). For explanation of box-and-whiskers-plots see Fig. 7

Table 6 German law requirements for night driving: Recommendations of the German Ophthalmological Society. These recommendations used to be stricter (by one contrast level), but were loosened when street illumination improved, as many older drivers would otherwise have been excluded from night driving (DOG, BVA, 2013)

$c_{Aulhorn}$	logCS	required for
1:23	0.02	car driving
1:5	0.1	heavy vehicles and taxis
1:2.7	0.2	bus driving

a limited correlation. Good mesopic results predict good photopic results, but the reverse does not apply: good photopic results do *not* necessarily predict good mesopic results (Fig. 6). Low photopic results seem to predict low mesopic results, but also here, the reverse does not apply: low mesopic results do *not* predict low photopic results. While it is typical for retinal diseases such as retinitis pigmentosa or other rod–cone dystrophies to (initially) have preserved visual function during the day with impairment in mesopic or scotopic lighting conditions [23], we were surprised by the large number of healthy subjects who showed remarkable discrepancies

between photopic and mesopic contrast sensitivity. This observation also applies for our cataract and scattering filter group; two other conditions where there is no photoreceptor damage explaining the discrepancy. Therefore, in practice, the time-saving photopic tests cannot replace the mesopic ones. At the most, we can deduce a corresponding failure in the mesopic test from a very low photopic test score. On the contrary, a good result in a photopic test cannot replace a mesopic test.

Effect of glaucoma, cataract, or artificial haze on photopic and mesopic contrast sensitivity

Compared to our healthy study participants, the glaucoma and cataract patients performed worse in the contrast tests. This indicates once more that, while visual acuity is still good, contrast sensitivity may have already deteriorated to a relevant extent in disorders such as cataract and glaucoma. This difference was more obvious in the mesopic than in the photopic tests. Cataract surgery improved the cataract patients' results.

Possible mechanisms decorrelating photopic and mesopic contrast sensitivity

How can we understand this dissociation of photopic and mesopic CS in normal vision? Testing procedure was rather similar, as was testing distance, and the tests were all done in a brief time interval. But the situation in photopic and mesopic testing also differs markedly: the point of regard shifts from foveal vision to a few degrees perifoveally [24]. Furthermore, optical imaging changes: the pupil enlarges in the mesopic range — probably introducing additional aberrations — and accommodation "tends to shift toward the individual's characteristic resting postures" [25]. Although the optotypes involved are rather large, an addition of one diopter reduces the mesopic contrast sensitivity at 1 cpd by about a factor of two [24]. Even within photopic vision, visual sensitivities are statistically independent when spatial frequency differs by a factor of ≥ 2 [26]. Finally, when considering low correlation, the range encountered plays a major role because the correlation index is normalized by range [27], and the actual range covered by the scotopic test used here is quite low (Fig. 4); had we included pathologic conditions, the photopic CS range would have been larger and the numerical correlation coefficient (Fig. 6) would have been higher. Low correlations ($r<0.4$) were also reported for visual acuity in photopic and mesopic conditions [28].

Conclusion

While good mesopic CS always entails good photopic CS, good photopic CS is associated with both good and bad mesopic CS. Therefore, photopic contrast sensitivity tests cannot serve as a surrogate measure for mesopic contrast sensitivity testing. Only when a low result in the photopic test is obtained can one expect an equally low result in the mesopic test.

Conflict of Interest statement Author MB has received honoraria for custom variants of "FrACT". All other authors certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

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