Doc Ophthalmol (2020) 140:83–93
https://doi.org/10.1007/s10633-019-09715-5

TECHNICAL NOTE

Use of diffusing filters for artificially reducing visual acuity when testing equipment and procedures

Sven P. Heinrich · Isabell Strübin

Received: 17 January 2019 / Accepted: 27 August 2019 / Published online: 5 September 2019

Abstract
Purpose When evaluating ophthalmological devices and procedures, for instance those for visual electrophysiology, it is often desirable to perform tests with reduced acuity. Doing this with individuals with actual visual impairments has a number of disadvantages, such as considerable recruitment efforts, especially when a specific acuity range is targeted, and little control about the actual perceptual characteristics of the impairment, which are normally not fully known. Lenses with positive diopters or blurring filters that are placed in front of the eyes of visually normal observers promise a simple solution to the problem. However, defocus results in considerable spurious resolution, and previous studies suggest that the frequently used Bangerter occluders are not optimal for the purpose. The present study therefore reviews a number of other options and tests a selection of filters with respect to their effect on acuity and contrast sensitivity with the aim of identifying filters that primarily degrade acuity while mostly sparing contrast sensitivity.
Methods First, we screened several filters for potential usefulness. The Freiburg Acuity and Contrast Test was then used to measure visual acuity and contrast sensitivity with a subset of three filters (Luminit LSD 0.5° and 1°, and LEE 420) and, for comparison, with a Bangerter occluder with a nominal acuity grade of 0.1. A qualitative comparison of the filters' effect on the checkerboard-reversal VEP was also performed.
Results With both Luminit filters, variability in acuity across participants was relatively small, and at least with the 0.5° version, contrast sensitivity was relativity little affected. The LEE filter and the Bangerter occluder resulted in more variability and, compared to the effect on acuity, a relatively strong reduction in contrast sensitivity. Comparing the Luminit 0.5° and 1° filters, the reduction of acuity was not proportional to physical stimulus degradation. The effect on VEP responses was consistent with the psychophysical data.
Conclusions The Luminit filters, which have a Gaussian light diffusion profile, appear to be a good choice for artificial reduction of acuity.

Keywords Visual acuity · Contrast sensitivity · Occlusion · Blur · Observer method · Artificial degradation

S. P. Heinrich (✉) · I. Strübin
Eye Center, Medical Center, University of Freiburg, Killianstr. 5, 79106 Freiburg, Germany
e-mail: sven.heinrich@uni-freiburg.de

S. P. Heinrich
Faculty of Medicine, University of Freiburg, Freiburg, Germany

Introduction

For systematically testing the performance of novel equipment and procedures in visual electrophysiology or other fields of ophthalmology or optometry, especially during the development process, it is usually desirable to include not only individuals with normal vision. Rather, it is often important to perform validation tests also with impaired vision. For instance, reduced acuity may cause a diagnostic procedure to yield inaccurate results, a low-vision patient may be unable to comply with the equipment's practical requirements, or a procedure that yields an estimate of visual performance (e.g., visual acuity [1–3]) needs to be quantitatively validated over a large parameter range. For such purposes, it is a frequent approach to artificially degrade vision in normal participants. This facilitates recruiting a homogenous study population with acuity reduced by a similar degree and no other impairments of vision.

There are several approaches to the artificial degradation of vision. Most of them fall into either of two categories, namely "observer method" and "source method" [4]. The source method requires the actual visual stimulus as it is generated by the tested device to be degraded. For instance, the stimulus picture may be blurred by applying mathematical operations to the original stimulus. Most commonly, this involves convolving the image with a blur kernel, which usually represents the point-spread function corresponding to a certain type of visual degradation [e.g., 5–7]. While such a direct modification of the presented stimulus offers a huge flexibility as to the type of simulated impairment, it requires in-depth access to stimulus generation, which is not available with many off-the-shelf devices or it is simply too complex. Sometimes, placing a physical filter directly in front of the stimulus [8, 9] can help if the geometry of the setup permits.

The term "observer method," in contrast, refers to degradation of vision that takes place at or near the eye of the observer. In most cases, this does not require any changes to the device or procedure that is to be evaluated.[1] Frequently, lenses with positive dioptric values are used for this purpose, as these are readily available in many different strengths at every ophthalmic or optometric clinic. This simple approach, however, results in a very specific type of degradation that is not representative of most typical visual impairments found in patients (except for refractive errors). In particular, it results in quite prominent spurious resolution [10], which may also manifest itself in electrophysiological data obtained with grating stimuli [11]. Furthermore, for reproducible results, cycloplegic mydriasis is required [12]. This suggests a need for different optical elements with more benign properties.

In principle, of course, visual degradation could take place at any location in the optical pathway between eye and stimulus. However, any other place than one near the eye or at the stimulus level (or near the stimulus) appears problematic, given that an extra accommodation target is introduced.

Subsequently, the term "filter" will be used for whatever type of object is inserted into the optic pathway to degrade vision, irrespective of its actual optical properties. For simplicity, the problem of filters having a light transmission of less than 100% is ignored. However, if a filter absorbs or reflects a sizable amount of light, this would need to be accounted for.

The aim of the present technical note is to take a closer look at what makes a good means of optical degradation of vision for the purpose of testing equipment, and to report on test measurements with a subset of filters that appeared most useful after a preliminary assessment. Although some of the thoughts that are discussed here will also apply to the source method, the primary focus will be on the observer method.

Criteria for a good filter

If a filter is to imitate a specific visual impairment, such as cataract or amblyopia, the characteristics of the "real" impairment constitute the benchmark for the filter. In contrast, the following considerations are aimed at identifying filters that are useful to create a

[1] This discussion only considers aspects related to the observer's own visual performance. Any function of a device that benefits from a clear optical pathway toward the observer, such as imaging the eye, or video-based tracking of eye movements, might of course be affected by whatever is inserted between the device and the eye.

generic reduced-acuity condition with well-behaved properties.

Generally, the filter's point-spread function (PSF) should have a shape that minimizes spurious resolution. Otherwise, the filter may not result in a unique acuity value. This is best achieved with a Gaussian PSF, which means that dioptric blur (having a PSF that is a homogenous disk) is far from optimal [10].

The filter should be sufficiently homogenous. If it is not, eye movements or small changes in filter position may have a profound effect on stimulus degradation. Furthermore, because the pencil of rays that passes through the filter before entering the eye has a finite size, inhomogeneities result in a superposition of different degradation characteristics. For large observation distances, the size of the pencil of rays at the filter plane is approximately the same as the size of the pupil. Examples of inhomogeneous filters are those that consist of a relatively clear base sheet with an array of scattering structures. A significant fraction of light passes unhinderedly, resulting in a crisp stimulus image with a superimposed veil of scattered light.

Obviously, the degree of stimulus degradation should be within a useful range. In the case of a Gaussian PSF or similar shapes, the full width at half maximum (FWHM) is a commonly used parameter to quantify the PSF which determines the amount of degradation.

When a simple scattering filter is placed in front of the eye, blur width scales linearly with stimulus distance when quantified in absolute measures (e.g., in millimeters on the stimulus monitor). However, blur is independent of distance when quantified in terms of visual angle. Therefore, the filter works equally with any stimulus distance. This would be different with, for instance, dioptric defocus where blur is the result of a discrepancy between focal length and stimulus distance.

For most applications, isotropy is another desirable property of a filter. In other words, the filter's effect should not depend on the orientation of the filter. Some filters on the market are specifically designed to be anisotropic, for instance for use as diffusers in LED strips for room lighting, where the light of individual LEDs should fuse along the length of the strip while emission orthogonal thereto is confined to a narrower angular range.

A qualitative overview

There is not a large market for filters tailored to the specific use case that is discussed here. This means that there is no manufacturer offering specialized products, and one has to use what is available. What comes nearest in purpose are occluders that are used for diagnostic or therapeutic purposes, notably Bangerter occluders. There are also low-vision simulator glasses, such as the "Cambridge Simulation Glasses." These, however, do not only aim at reducing acuity, but also contrast sensitivity. Thus, one has to look outside the ophthalmic/optometric devices industry for potentially useful products. Table 1 lists some of the filters that were assessed qualitatively before a subset was selected for a quantitative assessment. This is clearly just a small selection of what is available, but it illustrates some of the major problems that different types of products are associated with.

Of the filters considered, the Luminit LSD Light Shaping Diffusers (subsequently "Luminit") and the LEE 420 Light Opal Frost Filter (subsequently LEE 420) appeared most useful for the purpose of degrading vision. These were used in a small series of measurements to test performance and to compare them to Bangerter occluders that are frequently used for degrading vision. Both the 0.5° and 1° versions of the Luminit filters were used.

Figure 1 shows micrographs of the surface structure of the Luminit, LEE 420, and Bangerter filters. The Luminit and LEE 420 filters have an irregular structure, with the LEE 420 filter having a finer structure. The Luminit filters are described by the manufacturer as having a pseudorandom non-periodic micro-lens structure [16]. Simply speaking, this means that the surface of the filter consists of irregular convex bumps. There is less documentation available about the LEE 420 filter. The micrograph suggests that the surface is characterized by small scattering/refracting structures that are distributed irregularly across the surface, in contrast to the "softer" structure of the Luminit filters.

Methods

Luminit and LEE filters were mounted in aluminum rings (Fig. 2) in order to fit them into a regular trial frame. The Bangerter occluder was applied to a plano-lens.

Table 1 Details of the considered filters

Product	Manufacturer	Original purpose	Description	Qualitative assessment
Black Pro-Mist 2	Tiffen Filters, Hauppauge, NY, USA	Photographic softening lens	Glass with dense small dark spots	Adds halo, but otherwise no appreciable change in sharpness; see also de Wit [13]
Hoya Fog B	Kenko Tokina Co., Ltd, Tokyo, Japan	Photographic softening lens	Glass with slightly irregular milkish appearance	Adds halo, but otherwise no appreciable change in sharpness; see also de Wit [13]
LEE 452 Sixteenth White Diffusion	LEE Filters, Andover, UK	Photography and cinematography lighting	Sheets from milkish plastic or with scattering/milkish structure imprinted	Adds halo, but otherwise no appreciable change in sharpness; see also de Wit [13]
LEE 450 Three-Eighth White Diffusion				Most light is scattered but halo too large
LEE 251 Quarter White Diffusion				Mostly wide-angle scattering
LEE 420 Light Opal Frost				Potentially useful, slightly irregular, relatively small (but perceivable) fraction of unscattered light; see also de Wit [13]
LEE HT 254 New Hampshire Frost				Not all light scattered, stripe structure; see also de Wit [13]
PET screen protector (no name)	Unknown	Tablet computer anti-reflective screen protector	Frosted plastic sheet	Most (not all) light scattered. Degradation too strong for the present purpose, possibly useful for simulating very low vision
4ProTect	hsw3000, Borken, Germany	Smart phone anti-reflective screen protector	Frosted plastic sheet	
HDPE sheet	Various manufacturers	Freezer bag/sandwich bag	Semi-opaque plastic sheets	Strong anisotropy due to manufacturing process [14, 15]
Luminit LSD Light Shaping Diffuser	Luminit, Torrance, CA, USA	General lighting applications (diffusor for LED lamps)	Plastic sheets with irregular micro-lens structure. Several strengths available (0.5°, 1°, 2°, 5° and higher)	Approximately Gaussian luminance profile [16]
Occlusion according to Bangerter	Various manufacturers (here: Ryser Optik, St. Gallen, Switzerland)	Occlusion therapy (e.g., strabismus)	Plastic sheets with scattering structure imprinted/embossed. Several grades (different nominal acuities) available	Variable effects, nominal grade does not necessarily match actual effect on acuity [17, 18]
Cambridge Simulation Glasses Level 1	University of Cambridge Engineering Design Center	Simulation of visual impairments in inclusive design applications, aims at reducing both acuity and contrast vision	Plastic sheets with weak milkish surface structure, mounted in simple cardboard frame for wearing as glasses. Normative data for acuity reduction available [19]	Some wide-angle scattering (consistent with purpose to reduce contrast vision), some halo, not all light scattered

The qualitative assessment of scatter properties was performed by passing the beam of a laser pointer through the filter and visually inspecting the resulting distribution of light that was projected onto a white surface behind the filter. The manufacturer column shows the designation stated on the product or its packaging and may be the distributor rather than the manufacturer proper

Quantitative psychophysical assessment

Sixteen participants who reported no ophthalmic disorder were included in the study after providing informed consent. The study belonged to a series of experiments that was approved by the local institutional review board and followed the tenets of the Declaration of Helsinki.

All participants were tested with the 1° and 0.5° Luminit diffusers, the LEE 420 filter and a Bangerter

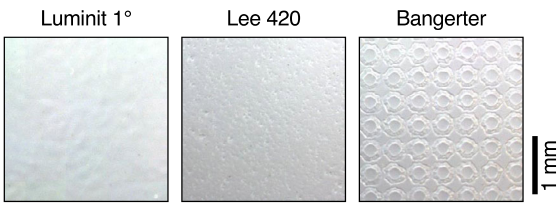

Fig. 1 Micrographs of the filter surfaces. The Luminit 0.5° filter is not depicted. Its surface structure is similar to the Luminit 1° filter, albeit with an even less pronounced structure

Fig. 2 The LEE and Luminit filters were mounted in aluminum rings for insertion into a trial frame

occluder with a nominal target acuity of 0.1 (Ryser Optik, St. Gallen, Switzerland), and also without any filter. The sequence of filters (including the condition without filter) was individually randomized for each participant.

Most participants were members of the department who could provide their up-to-date refractive values. In case of doubt, refraction was determined with an autorefractor (AR-1s, Nidek Co. Ltd., Gamagori, Japan). During the experiment, subjects wore a trial frame with their refraction and, in addition, the respective filter as appropriate for the experimental condition, in front of one eye. The filter was worn for approximately one minute before the start of the respective test run. The experimental procedure thus accounted for the typical scenario in which a blurring filter is being used temporarily for equipment testing without a prolonged period for accustomization to blurred vision. Testing was performed monocularly with a non-translucent occluder placed in front of the other eye.

The Freiburg Acuity and Contrast Test [20, 21] running on a Mac Mini computer was used to measure acuity and contrast sensitivity. Landolt C stimuli were presented in eight possible orientations on a Dell 1707FPc monitor in 5 m distance from the participant with a maximum Weber contrast of 98%. Participants responded by pressing the respective keys on a small keypad. For acuity measurements, optotype size was controlled by an adaptive staircase procedure while the contrast was kept constant at the maximum value. Contrast sensitivity measurements used optotypes with a fixed gap size of 10 arcmin, with the contrast being adjusted via an adaptive staircase procedure.

Qualitative assessment of effects on visual evoked potentials

In a separate group of six participants with normal or corrected-to-normal acuity, we tested the effect of the filters on pattern-reversal visual evoked potentials. Following the principles laid down in the respective ISCEV standards [22], checkerboard stimuli with check sizes of 0.2°, 0.4°, and 0.8° with a contrast of 98% were used. Only one eye was tested, which was randomly selected for each participant. The distance between the eye and monitor was 114 cm, and the refraction was adjusted accordingly with a near addition of + 0.75 D. The total extent of the stimulus was 19° × 15°. Signals were band-passed at 1–100 Hz, amplified 50,000-fold, and sampled at 1 kHz. Artifacts were rejected based on a ± 130 µV threshold criterion. Eighty artifact-free trials per check size were recorded and averaged. For display, a 45-Hz low-pass filter was applied to the traces.

Results

Figures 3 and 4 show logMAR and logCS values for all four filter types and for normal vision for individual participants and as group means, respectively. With normal vision, logMAR was consistently better (smaller) than 0.0, as expected in healthy eyes. logCS was also in the usual range (see, for instance, Hertenstein [21] as a reference for values obtained with FrACT). logMAR with the Luminit 1° filter was 0.21 (CI: 0.17…0.25) higher than with the Luminit 0.5° filter, corresponding to a factor of 1.62 (CI: 1.49…1.78). logCS with the 1° filter could not be reliably measured because most participants could not reliably perform the forced-choice task even at full

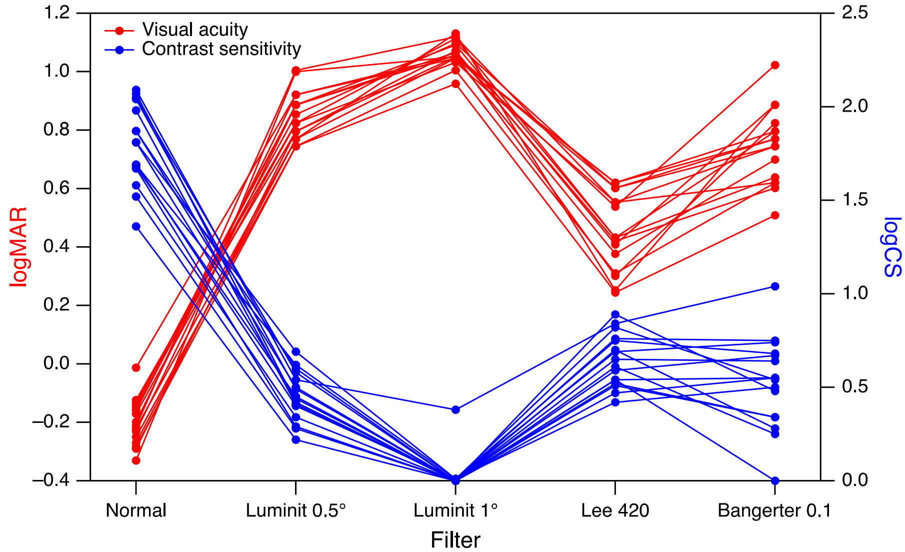

Fig. 3 logMAR (red, left axis; larger values mean worse acuity) and logCS (blue, right axis; larger values mean better sensitivity) values for all five filter conditions. Apparently, the optotype in the contrast sensitivity test was not resolved, resulting in logCS = 0 for all except one participant

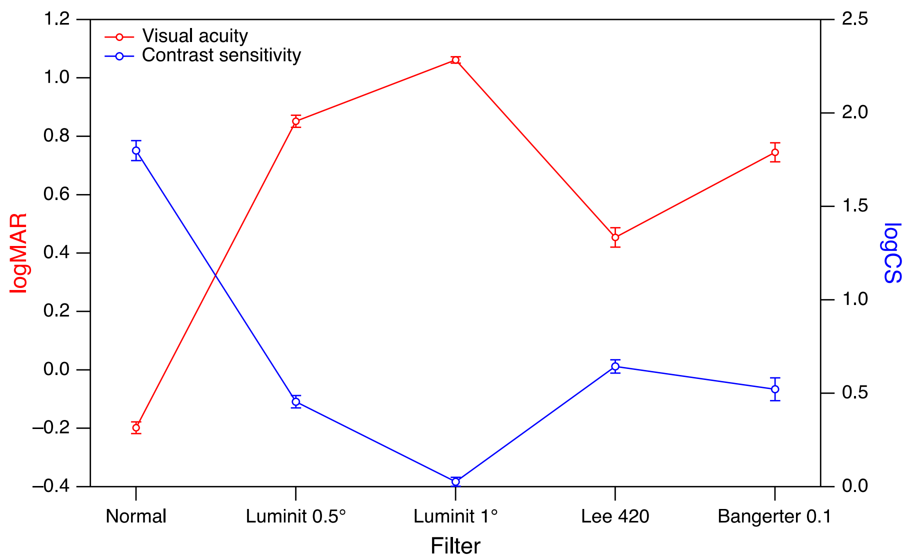

Fig. 4 Average logMAR (red, left axis) and logCS (blue, right axis) values for all five filter conditions

contrast. Hence, the test yielded logCS = 0 for most participants.

In Fig. 5, logMAR and logCS values are presented as the absolute difference relative to normal vision. Comparing logCS to logMAR effects in terms of absolute numbers has only limited meaningfulness. However, the figure illustrates the differential effect of the filters on both measures. As there is an acuity effect on logCS values (see Discussion), not all comparisons can be interpreted straightforwardly. Despite this potential confounder, it is clear that the Luminit 0.5° filter, where the logCS difference is slightly less affected than the logMAR difference, affects vision differently than the LEE 420 filter, which has less effect on logMAR but, relative to the logMAR effect, more effect on logCS.

The variability in image degradation as reflected by the average absolute deviation of logMAR and logCS values, respectively, from average, differed between filters (Fig. 6). In particular, pairwise testing suggests that the Luminit 1° variability is significantly lower than the variability with the other filters (Luminit 1° vs. Luminit 0.5°, $P = 0.004$; Luminit 1° vs. LEE 420, $P = 0.0003$; Luminit 1° vs. Bangerter, $P = 0.002$;

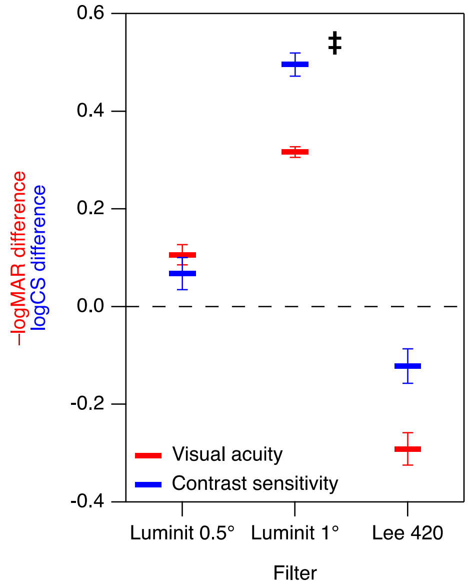

Fig. 5 logMAR and logCS values obtained with Luminit and LEE filters, relative to the respective values obtained with the Bangerter occluder. With the Luminit 0.5° filter, the effect on contrast sensitivity is comparatively small, while the Luminit 1° and LEE 420 filters have a stronger effect on contrast sensitivity than on acuity when compared to the Bangerter occluder. However, see discussion for the effect of the Luminit 1° filter on contrast sensitivity. The symbol ‡ identifies the condition with the Luminit 1° filter, where the optotype for CS measurement was probably not reliably resolved

bootstrap tests, all significant at a family-wise alpha of 0.05 when corrected for the number of independent tests). Several other pairwise tests were significant at a per-test level (normal vs. Luminit 1°, $P = 0.033$; normal vs. LEE 420, $P = 0.020$; Luminit 0.5° vs. LEE 420, $P = 0.017$). logCS variability with the Luminit 1° filter differed from that with normal vision ($P = 0.0002$), LEE 420 ($P = 0.006$), and Bangerter occluders ($P < 0.0001$), all significant when corrected for the number of independent tests. The difference in variability between normal vision and Luminit 0.5° filter was significant at the per-test level ($P = 0.042$).

Unsurprisingly, the filters affected amplitude, temporal parameters and to some degree also the general curve shape of the VEP responses (Fig. 7). Consistent with the acuity reduction (Fig. 4), the Luminit 1° filter produced the strongest reduction of responses, as evident particularly in the absent responses to medium checks.

Discussion

The present study compared logMAR and logCS values associated with the use of several filters that were selected based on a preliminary qualitative assessment, including a Bangerter occluder for

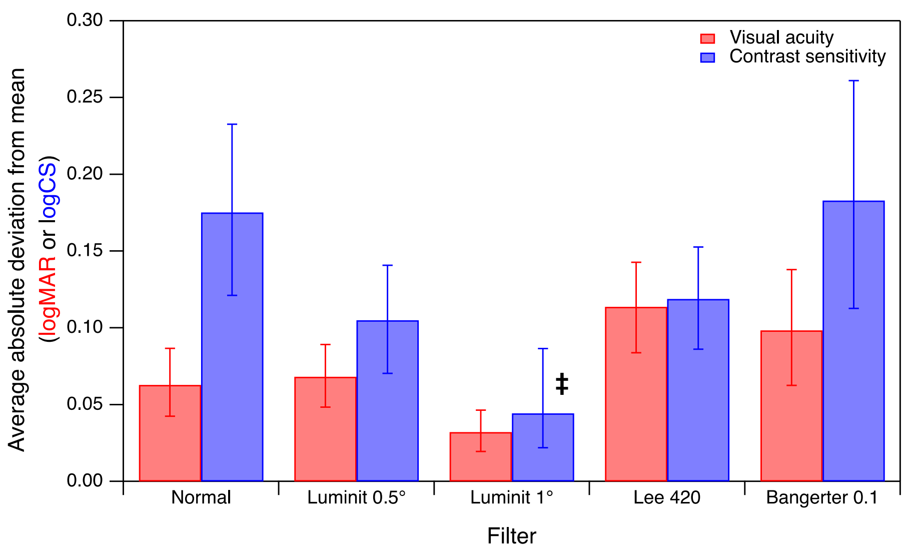

Fig. 6 Interindividual variability of image degradation measured in terms of the average absolute deviation from the mean. In the condition with normal vision, this simply reflects interindividual differences in acuity. With Bangerter occluders, there is a strikingly high interindividual variability in logCS values. The symbol ‡ identifies the condition with the Luminit 1° filter, where the optotype for CS measurement was probably not resolved

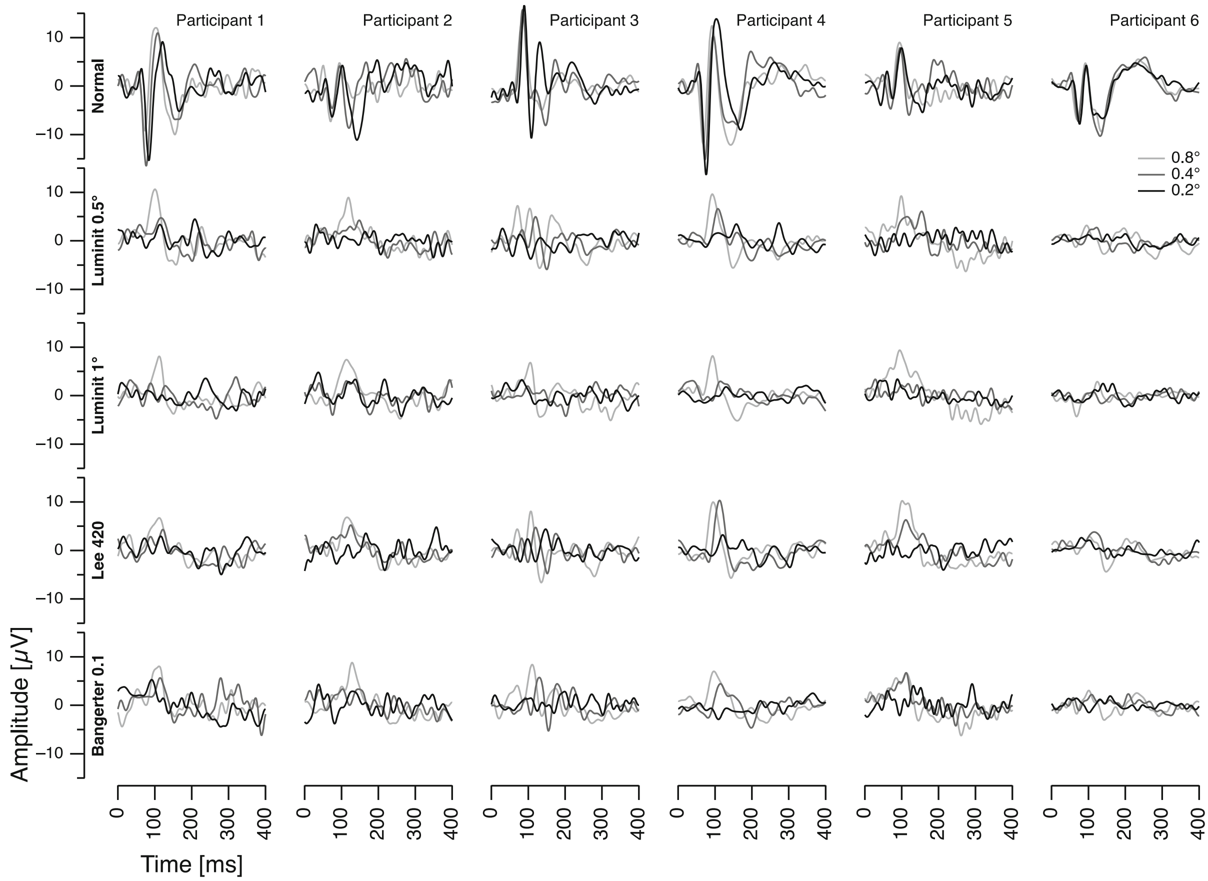

Fig. 7 VEP data obtained from six participants with all five filters. With normal (undegraded) vision, clear responses (N1–P1–N2 structure) are found in all participants with all filters irrespective of the check size. With filters, responses to small checks (0.2°, black traces) are absent, and responses to medium checks (0.4°, medium gray traces) are reduced and delayed. In some cases, particularly with the Luminit 1° filter, the responses to medium checks are completely missing. Responses to large checks (0.8°, light gray traces) are present with all filters, albeit with reduced amplitude and in some cases delayed when compared to the responses with normal vision

reference. The results illustrate that different filters have a differential effect on acuity and contrast sensitivity. While logMAR values can be interpreted quite straightforwardly, the logCS values in the present study require a more cautious interpretation.

The most generic diffusor for simulating reduced contrast sensitivity would be one that affects one part of the light through wide-angle scattering, while leaving the remaining part of the light completely unaffected, i.e., without narrow-angle scattering. Even though the Luminit diffusors have a well-defined limited scatter width with only minimal wide-angle scattering, they result in reduced contrast sensitivity as measured in the present study. This is no surprise, though. Visual acuity is related to the high-frequency cutoff of the contrast sensitivity function (CSF) [23]. Usually, optical devices do not achieve a completely sharp cutoff of the CSF. Rather, they also attenuate the remaining CSF over at least a certain spatial frequency range below the cutoff frequency, which may result in reduced contrast sensitivity values. Obviously, the degree to which this is revealed by a contrast sensitivity test will depend on the test's characteristics. For instance, tests using sinewave gratings with a single spatial frequency are only sensitive to changes of the CSF that affect that spatial frequency.

The logMAR difference between the Luminit 0.5° and Luminit 1° filters is 0.21. This corresponds to a factor of 1.62 (CI: 1.49…1.78). This is somewhat lower than the factor of 2 that would be expected given nominal FWHM scatter angles of 0.5° and 1°. This is presumably because even if both filters degrade the optotypes by the same relative degree when optotype size is scaled according to filter FWHM (resulting in the same physical contrast of the blurred optotypes), recognizability will depend on the observer's actual physiological contrast sensitivity function and thus on spatial frequency or, in other words, on the size of the optotype.

Obviously, the nominal FWHM of the scatter distribution of the Luminit 0.5° and 1° filters (30 arcmin and 60 arcmin, respectively) is much larger than the corresponding (non-logarithmized) minimum angles of resolution obtained in the acuity tests (average across participants, 7.1 arcmin and 11.5 arcmin). Thus, if a specific level of degradation is to be achieved, it cannot be derived directly from the nominal scatter width. This is at least partly explained by the difference between recognition acuity (for instance, tested with Landolt Cs) and resolution acuity [23–25].

The experimental procedure purposefully avoided prolonged exposure to blur induced by the filters, in order to account for typical use scenarios. Previous studies using dioptric blur suggest that any effect of longer adaptation durations would be quite moderate. For instance, Poulere et al. [26] report a logMAR difference of 0.1, and Venkataraman et al. [27] only found adaptation when the adapting blur was limited to the central visual field, but not when it extended to higher eccentricities.

What are the advantages and disadvantages of the different filters?

The data obtained with the *Bangerter 0.1 occluder* showed relatively high variability in both acuity and contrast sensitivity. Although worse than with the Luminit 0.5° filter, contrast sensitivity was less affected than we had originally expected. It should be noted, however, that these findings might be different for different grades of Bangerter occluders, and filter properties may vary between different brands. However, the present data are in a similar range as that obtained by Odell et al. [17] with Bangerter occluders made by a different manufacturer.

Luminit LSD 0.5° and 1° produced the most consistent reduction in acuity, i.e., with less variability across subjects than the other two filters. Relative to the amount of acuity reduction, contrast sensitivity was only moderately affected with the 0.5° filter. With the 1° filter, contrast sensitivity appeared quite markedly reduced because of the size of the contrast test optotype being similar to the size threshold for optotype recognition (acuity-related limit). An advantage of the Luminit filters is the availability of several filter strengths in addition to the two strengths tested here. Judging from the present data on the 0.5° and 1° filters, acuity reduction does not appear to be proportional to the nominal scatter width, but this is probably not a unique problem of the Luminit filters. For special purposes, there are also anisotropic filters (e.g., 1° in one dimension and 40° orthogonal thereto).

The use of the *LEE 420* filter resulted in less acuity reduction than the other filters. However, compared to acuity, contrast sensitivity was more strongly affected. Importantly, variability in acuity data was higher than with the other filters.

The qualitative assessment of the effect of blurring filters on the pattern-reversal VEP shows results that are generally consistent with the psychophysical findings. The pattern of amplitude reduction and peak time increase is compatible with earlier studies including, for instance, those by Sokol and Moskowitz [28] and Bobak et al. [29].

Obviously, testing healthy participants with artificially degraded acuity does not in all cases eliminate the need for patients with real visual impairments, as acuity is not the only parameter that characterizes a visual impairment. For instance, amblyopia [30, 31] is perceptually different than both cataract [32, 33] and refractive errors [7, 10] and requires other optical means to be mimicked in an approximate manner, as attempted with patterned polymethyl methacrylate panes [8, 9]. Nevertheless, a generic artificial reduction of acuity as discussed here provides a means to test equipment and procedures under well-defined conditions. The present findings suggest that the Luminit filters are the most suitable general-purpose filters among the types tested here, given relatively low variability and a moderate effect on contrast sensitivity at least for the 0.5° version. The availability of different filter strengths might be beneficial for some applications.

Acknowledgements We thank Verena Gauggel for their competent assistance with data acquisition, Patrick Weisert for making the holders that allowed for inserting the filters into regular trial frames (Fig. 2), and Gottfried Martin for support with the micrographs of the filters (Fig. 1). We are also grateful to the volunteers who participated in the study. Optrovision, Munich, Germany, a distributor of Luminit diffusers, provided free-of-charge samples.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional research committee (Ethik-Kommission der Albert-Ludwigs-Universität Freiburg, application number 622/14) and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. This article does not contain any studies with animals performed by any of the authors.

Informed consent Informed consent was obtained from all individual participants included in the study.

Data availability Data are available on request from the authors.

References

1. Towle VL, Harter MR (1977) Objective determination of human visual acuity: pattern evoked potentials. Invest Ophthalmol Vis Sci 16:1073–1076
2. Bach M, Maurer JP, Wolf ME (2008) Visual evoked potential-based acuity assessment in normal vision, artificially degraded vision, and in patients. Br J Ophthalmol 92:396–403. https://doi.org/10.1136/bjo.2007.130245
3. Hoffmann MB, Brands J, Behrens-Baumann W, Bach M (2017) VEP-based acuity assessment in low vision. Doc Ophthalmol 135:209–218. https://doi.org/10.1007/s10633-017-9613-y
4. Chan C, Smith G, Jacobs RJ (1985) Simulating refractive errors: source and observer methods. Am J Optom Physiol Opt 62:207–216
5. Ohlendorf A, Tabernero J, Schaeffel F (2011) Neuronal adaptation to simulated and optically-induced astigmatic defocus. Vis Res 51:529–534. https://doi.org/10.1016/j.visres.2011.01.010
6. McAnany JJ, Shahidi M, Applegate RA et al (2011) Contributions of optical and non-optical blur to variation in visual acuity. Optom Vis Sci 88:716–723. https://doi.org/10.1097/OPX.0b013e3182147202
7. Dehnert A, Bach M, Heinrich SP (2011) Subjective visual acuity with simulated defocus. Ophthalmic Physiol Opt 31:625–631. https://doi.org/10.1111/j.1475-1313.2011.00857.x
8. Heinrich SP, Bock CM, Bach M (2016) Imitating the effect of amblyopia on VEP-based acuity estimates. Doc Ophthalmol 133:183–187. https://doi.org/10.1007/s10633-016-9565-7
9. Beusterien ML, Heinrich SP (2018) P300-based acuity estimation in imitated amblyopia. Doc Ophthalmol 136:69–74. https://doi.org/10.1007/s10633-017-9617-7
10. Strasburger H, Bach M, Heinrich SP (2018) Blur unblurred—a mini tutorial. i-Perception 9:2041669518765850. https://doi.org/10.1177/2041669518765850
11. Heinrich SP, Lüth I, Bach M (2015) Event-related potentials allow for optotype-based objective acuity estimation. Invest Ophthalmol Vis Sci 56:2184–2191. https://doi.org/10.1167/iovs.14-16228
12. Jägle H, Zobor D, Brauns T (2010) Accommodation limits induced optical defocus in defocus experiments. Doc Ophthalmol 121:103–109. https://doi.org/10.1007/s10633-010-9237-y
13. de Wit GC, Franssen L, Coppens JE, van den Berg TJTP (2006) Simulating the straylight effects of cataracts. J Cataract Refract Surg 32:294–300. https://doi.org/10.1016/j.jcrs.2006.01.048
14. Stein RS, Rhodes MB (1960) Photographic light scattering by polyethylene films. J Appl Phys 31:1873–1884. https://doi.org/10.1063/1.1735468
15. Ward IM (2012) Structure and properties of oriented polymers, 2nd edn. Springer, Berlin
16. Ang A (n.d.) Predicting scatter of Light Shaping Diffuser® angles using Luminit's proprietary optical model and OpticStudio. Luminit LLC. https://www.luminitco.com/sites/default/files/2017-06/Predicting%20Scatter%20of%20Light%20Shaping%20Diffuser%C2%AE%20Angles%20Using%20Luminit%E2%80%99s%20Proprietary%20Optical%20Model%20and%20OpticStudio.pdf. Accessed 02 Sept 2019
17. Odell NV, Leske DA, Hatt SR et al (2008) The effect of Bangerter filters on optotype acuity, vernier acuity, and contrast sensitivity. J AAPOS 12:555–559. https://doi.org/10.1016/j.jaapos.2008.04.012
18. Pérez GM, Archer SM, Artal P (2010) Optical characterization of Bangerter foils. Invest Ophthalmol Vis Sci 51:609–613. https://doi.org/10.1167/iovs.09-3726
19. Goodman-Deane J, Waller S, Collins A-C, Clarkson PJ (2013) Simulating vision loss. Contemp Ergon Hum Factors 2013:347–354. https://doi.org/10.9774/GLEAF.9780203744581_57
20. Bach M (1996) The Freiburg Visual Acuity Test–automatic measurement of visual acuity. Optom Vis Sci 73:49–53
21. Hertenstein H, Bach M, Gross NJ, Beisse F (2016) Marked dissociation of photopic and mesopic contrast sensitivity even in normal observers. Graefes Arch Clin Exp Ophthalmol 254:373–384. https://doi.org/10.1007/s00417-015-3020-4
22. Odom JV, Bach M, Brigell M et al (2016) ISCEV standard for clinical visual evoked potentials: (2016 update). Doc Ophthalmol 133:1–9. https://doi.org/10.1007/s10633-016-9553-y
23. Chung STL, Legge GE (2016) Comparing the shape of contrast sensitivity functions for normal and low vision. Invest Ophthalmol Vis Sci 57:198–207. https://doi.org/10.1167/iovs.15-18084
24. Heinrich SP, Bach M (2013) Resolution acuity versus recognition acuity with Landolt-style optotypes. Graefes Arch Clin Exp Ophthalmol 251:2235–2241. https://doi.org/10.1007/s00417-013-2404-6
25. Paudel N, Jacobs RJ, Sloan R et al (2017) Effect of simulated refractive error on adult visual acuity for paediatric tests. Ophthalmic Physiol Opt 37:521–530. https://doi.org/10.1111/opo.12387
26. Poulere E, Moschandreas J, Kontadakis GA et al (2013) Effect of blur and subsequent adaptation on visual acuity

using letter and Landolt C charts: differences between emmetropes and myopes. Ophthalmic Physiol Opt 33:130–137. https://doi.org/10.1111/opo.12020
27. Venkataraman AP, Winter S, Unsbo P, Lundström L (2015) Blur adaptation: contrast sensitivity changes and stimulus extent. Vis Res 110:100–106. https://doi.org/10.1016/j.visres.2015.03.009
28. Sokol S, Moskowitz A (1981) Effect of retinal blur on the peak latency of the pattern evoked potential. Vis Res 21:1279–1286
29. Bobak P, Bodis-Wollner I, Guillory S (1987) The effect of blur and contrast on VEP latency: comparison between check and sinusoidal and grating patterns. Electroencephalogr Clin Neurophysiol 68:247–255
30. Sireteanu R, Lagreze W-D, Constantinescu DH (1993) Distortions in two-dimensional visual space perception in strabismic observers. Vis Res 33:677–690. https://doi.org/10.1016/0042-6989(93)90188-3
31. Barrett BT, Pacey IE, Bradley A et al (2003) Nonveridical visual perception in human amblyopia. Invest Ophthalmol Vis Sci 44:1555–1567. https://doi.org/10.1167/iovs.02-0515
32. Elliott DB (1993) Evaluating visual function in cataract. Optom Vis Sci 70:896–902
33. Artal P, Benito A, Pérez GM et al (2011) An objective scatter index based on double-pass retinal images of a point source to classify cataracts. PLoS ONE 6:e16823. https://doi.org/10.1371/journal.pone.0016823