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Article

Quantification of the Dynamic Visual Acuity Space at Real-World Luminances and Contrasts: The VA-CAL Test

Julian Hilmers[1], Torsten Straßer[1,2], Michael Bach[3], Katarina Stingl[2], and Eberhart Zrenner[1,2,4]

[1] Institute for Ophthalmic Research, University of Tuebingen, Tuebingen, Germany
[2] University Eye Hospital Tuebingen, Tuebingen, Germany
[3] Eye Center, Medical Center – Faculty of Medicine, University of Freiburg, Freiburg, Germany
[4] Werner Reichardt Centre for Integrative Neuroscience (CIN), Tuebingen, Germany

Correspondence: Eberhart Zrenner, Institute for Ophthalmic Research, Elfriede-Aulhorn-Str. 7, 72076 Tübingen, Germany; e-mail: ezrenner@uni-tuebingen.de

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Purpose: Best-corrected visual acuity (BCVA) is assessed at a single standardized luminance with maximum optotype contrast, not reflecting the constantly changing daily-life viewing conditions. For a more realistic estimation of visual performance at varying object contrasts (Cs) and ambient luminances (ALs), we developed a new VA test, VA-CAL.

Methods: Landolt-C-rings between 18% and 95% Weber contrast, were presented at 1 m distance (8 Alternative Forced Choice) on a 5.7 degree field in the middle of a frosted glass screen (66 degrees), back-lit by 3060 LEDs (generating ambient luminances between 0–10,000 cd/m^2). Visual acuity (VA) was measured in 14 normally sighted participants twice for 8 conditions of ambient luminance and 6 conditions of contrast using a QUEST staircase procedure.

Results: VA improved continuously up to an ambient luminance of 3000 to 5000 cd/m^2 (best mean VA $\pm$ SEM: -0.47 ± 0.03 logMAR at C = 95%, AL = 3000 cd/m^2), followed by a decline of VA at higher luminances with good test-retest variability. As expected, reduced contrast leads to a lower VA (worst mean VA $\pm$ SEM: -0.03 ± 0.03 logMAR at C = 18%, AL = 0 cd/m^2). A 3D plot of these data shows the VA space (VAS) extending between the contrast and luminance axes, which describes the dynamics of VA continuously changing under varying everyday life conditions.

Conclusions: VA-CAL, an automated device and procedure, allows for simultaneous evaluation of VA at various contrast-luminance combinations, thus providing a more comprehensive assessment of spatial vision problems not seen with standard BCVA tests.

Translational Relevance: The new BCVA test VA-CAL incorporates a range of everyday contrast and ambient luminance conditions for a more realistic description of visual performance.

Introduction

Visual acuity (VA) tests serve as the most important parameter for assessing visual performance in clinical examinations. Currently, clinical VA measurement is based on standards, such as DIN EN ISO 8596, and is performed at a specific ambient luminance (AL) of between 80 and 320 cd/m^2 (recommended = 200 cd/m^2) with maximum optotype contrast.[1] This condition does not necessarily represent daily outdoor environments, where the AL reaches 2000 to 8000 cd/m^2 even on cloudy days[2] and therefore significantly exceeds the defined luminance range of the clinical VA test. Visual perception deals constantly with quickly changing object contrast and variation of AL under which such objects are viewed. Thus, standardized VA testing does not necessarily reflect the actual visual performance in daily life, including outdoor situations, which are especially difficult to master for patients

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with inherited retinal disorders with increased glare-sensitivity like achromatopsia.[3,4] Healthy participants can show an increase in VA up to a luminance of 5000 cd/m^2.[5] Many methods aim to determine VA (e.g. Early Treatment Diabetic Retinopathy Study [ETDRS],[6] the Bailey-Lovie chart,[7] or the Freiburg Visual Acuity and Contrast Test [FrACT]).[8] Glare sensitivity at changing AL is determined with separate devices, like the commonly used mesoptometer, the Ocular Photosensitivity Analyzer,[9] or the Brightness Acuity Tester.[10] Other tests determine contrast sensitivity, like the Pelli Robson chart,[11,12] or the quick contrast sensitivity function method (qCSF),[13] as well as FrACT.[8] However, to the best of our knowledge, there is no automated single test for assessing the visual acuity space (VAS; extending between luminance and contrast axes), which describes the dynamics of VA continuously changing under varying everyday life conditions.

Here, we present a new VA test, VA-CAL, which allows to determine these dynamics of VA depending on the actually viewed objects' contrast under varying everyday luminance conditions, thus detecting abnormalities of spatial vision that go unnoticed in clinical best-corrected visual acuity (BCVA) tests.

Materials and Methods

Participants

VA-CAL was tested in 14 eye-healthy participants (7 women and 7 men) aged between 21 and 29 years (mean ± SD = 25.2 ± 2.8 years) at the Institute for Ophthalmic Research Tuebingen. All of them underwent a second measurement about 6 weeks later. The duration of the test was about 3 hours. BCVA (ETDRS chart), slit-lamp examination, and optical coherence tomography (OCT) was performed in an initial ophthalmic examination at the first visit. The inclusion criteria were a monocular BCVA of 0.1 logMAR or better and no suspected or confirmed eye disease.

Before testing, participants were informed about the aims and purpose of the study, and they gave their written consent to study participation. The protocol was approved by the Institutional Review Board of the medical faculty of the University of Tuebingen (431/2019BO2) and followed the Declaration of Helsinki.

Experimental Design

The VA-CAL setup, depicted in Figure 1, is characterized by a 130 cm × 130 cm (66 degree edge length) semitransparent frosted glass screen, which can be back-lit with luminances of between 0 and 10,000 cd/m^2 using an array of computer-controlled (via DMX RGB(W) Controller 8356; Solarox Holding GmbH, Dessau-Roßlau, Germany) high-power LEDs (Power Flat LED Tapes, 6000K; Solarox Holding GmbH), mounted on a metal plate at a distance of 26 cm. According to the lamp safety standard, a radiation source emitting in the visible spectral range with a luminance of up to 10,000 cd/m^2 does not exceed the exposure limit and poses no danger to the observer.[14] The optotypes are presented in the center of the screen on a magnetically fixed light-tight white circular testing surface (10 cm in diameter) using a projector (Notevision Sharp PGA20X; Sharp K.K., Sakai,

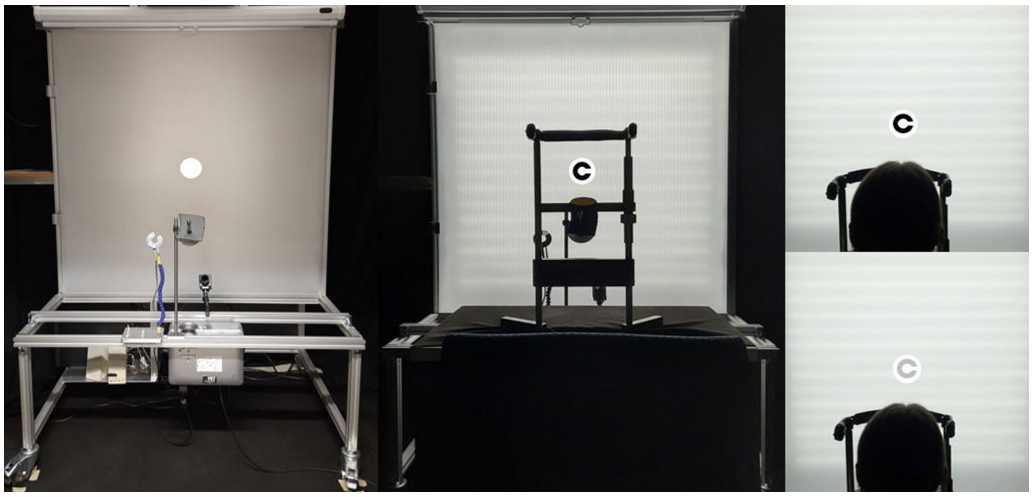

Figure 1. Experimental setup (VA-CAL setup, *center*) backlit by computer-controlled LEDs (*left*) generating different ambient luminances. Landolt C-rings can be presented at different contrasts (*right*). The pictures were modified for better visibility of the projected Landolt C-ring.

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Japan), positioned parallel to the frosted glass screen on an aluminum bar, with the optic lens at 58 cm height. The image is presented on a mirror, fixed at 99 cm height with an angle of 76 degrees. The standard optics of the projector were removed and exchanged for a collecting lens (f = 100 mm) so that the conventional image size (81 cm × 61 cm) of the projector fits the size of the central testing surface. Walls, floor, and ceiling are covered with black fabric. A headrest is positioned at 1 m distance and 1.2 m height. For recording pupil diameter, an infrared camera (DMK 21AU04; The Imaging Source GmbH, Bremen, Germany) is positioned in front of the participant. The investigator sits outside the chamber and controls testing procedure via the main computer (Windows 10 Pro, Intel Core i5-4590 CPU).

Procedure

VA-CAL was programmed with PsychoPy (version 3).[15] The VA threshold for each condition was determined by modulating Landolt C-ring (LCR) sizes from largest to smallest diameter using the QUEST adaptive staircase method.[16] This staircase is based on the respondent's responses and continuously alters the size of the optotype according to the threshold.[17] It measures the threshold using a Weibull psychometric function with threshold at 63.2% correct. The QUEST procedure stops either if the width of 5% to 95% confidence interval of the estimated threshold (gap size of the LCR) falls below 0.03 degrees or if the maximum number of 60 trials has been reached. The threshold was normally reached after 15 to 20 trials. The first stimulus was always presented above the expected threshold with a visual angle of the LCR gap size of 0.042 degree (=VA of 0.4 logMAR).

Table 1 lists the AL and corresponding illuminance values used in VA-CAL. In addition, VA was determined at an AL of close to 0 cd/m^2, with LEDs being switched off. The AL was calibrated beforehand with a luminance meter (LS-100; Konica Minolta Holdings K.K., Chiyoda, Japan). The corresponding LED level was directly controlled by PsychoPy. The illuminance at 1 m distance and 1.2 m height, the participant's eye position, was measured with a luxmeter (Voltcraft MS-1500 digital luxmeter; Conrad Electronic SE, Hirschau, Germany). The chromaticity coordinates (x, y, and z) of the background luminance on the CIE diagram were (0.323, 0.330, and 0.347, respectively), similar to CIE standard illuminant D65.[18] Chromaticity was measured with a digital spectrometer (USB4000-UV-VIS-ES; Ocean Optics Inc., Del Ray Beach, FL, USA) at a distance of 1 m.

The testing surface had the same background luminance as the AL generated by LEDs from 320 cd/m^2 to 5000 cd/m^2. Below this range, the luminance of the testing surface was 100 cd/m^2 and above this range, it was limited to 6800 cd/m^2, the maximum luminance of the projector.

The contrast was calibrated for each luminance level by adjusting the gray value of the optotype in

Table 1. Ambient Luminances, Corresponding Illuminance Levels at the Participant's Eye Position at a Testing Distance of 1 m and Suitable Examples of Daily Life From Literature[2] and Own Measurements

Ambient Luminance in VA-CAL	Corresponding Illuminance at 1 m	Examples[2] of Daily Life With Corresponding Luminance	Own Measurements With Luminance Meter
30 cd/m^2	20 lux	White paper under lamp Text on computer screen	Caucasian facial skin (over cheek bone in interior lighting, office)
320 cd/m^2	260 lux	Wall, ceiling (with interior lighting, office) Computer display	White paper under interior lighting (office) Max. BCVA background (DIN EN ISO 8596)
1000 cd/m^2	770 lux	Daytime road surface	White car (in shadow, sunny day)
3000 cd/m^2	2300 lux	Traffic lights Full moon	Doctors' white coat (in shadow, sunny day)
5000 cd/m^2	3700 lux	Overcast sky (daytime)	Surface of cobblestones (in sunlight)
8000 cd/m^2	6200 lux	Blue sky (daytime)	Caucasian facial skin (over cheek bone in sunlight)
10,000 cd/m^2	7800 lux	Wet (reflective) road	White FFP2 face mask (in sunlight) White porcelain plate on table (in sunlight)

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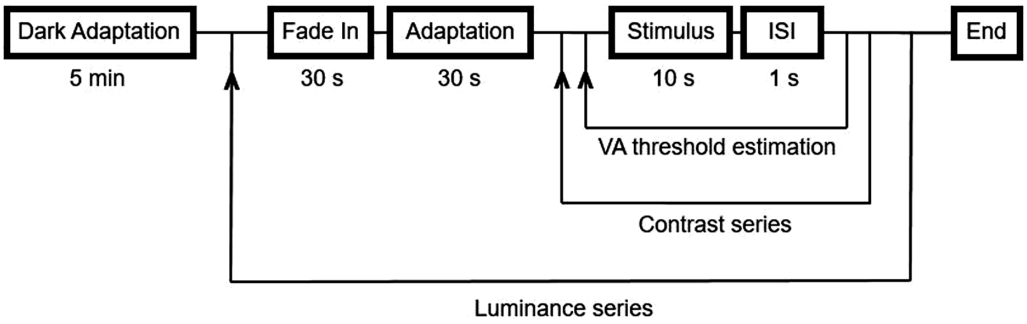

Figure 2. Testing procedure of VA-CAL. After an initial dark adaptation period, the ambient luminance was increased in steps (fade-in) to the next presented luminance level, followed by an adaptation time. Within each ambient luminance, the VA threshold was determined for each contrast using the QUEST adaptive staircase method by adjusting the size of the Landolt C-rings.

PsychoPy so that the luminance of the LCR (L_{min}) and of the testing surface (L_{max}) gave the desired Michelson contrast.[19] For further use and analysis, it was converted into the Weber contrast, best suited for contrast denomination of our particular condition.[19]

In VA-CAL, LCRs were presented in Weber contrasts of 18%, 33%, 46%, 66%, 82%, and 95%. Due to insufficient L_{max} for ALs of 0 cd/m^2 and 30 cd/m^2, the 95% contrast could only be measured from an AL of 320 cd/m^2.

The VA-CAL test was performed monocularly, using the eye with better VA or the dominant eye in cases with equal VA in both eyes, without pupil dilation using refraction of the BCVA of the ETDRS test (no near addition necessary due to young age[20]). The participants' refraction was corrected with the appropriate spherical and cylindrical lenses inserted into a trial frame. The participants had to identify the gap direction of LCR by pressing the corresponding button on a keypad (LogiLink wireless keypad ID0173, 2direct GmbH, Schalksmühle, Germany). The LCR gaps were presented randomly in eight different directions (8 Alternative Forced Choice Method). The participants received auditory feedback if their response was correct (low pitch) or wrong (high pitch). If the gap direction of LCR was not recognizable, they were asked to guess the direction. The participants were instructed to respond as fast as possible within 10 seconds, followed by 1-second interstimulus interval (ISI). No responses were considered as wrong.

Response times of 12 volunteers with normal vision (age = 22–29 years, mean = 25 years) were recorded during the VA measurements with VA-CAL. Response time was defined as the time between the presentation of the optotype and the participants' response by pressing the button on the wireless keypad. Response time measurements were not possible in two participants due to technical problems.

The testing procedure is shown in Figure 2. After 5 minutes dark adaptation, the VA-CAL test started with the lowest AL. Between the presentation of different luminances, there was a fade-in time of 30 seconds in which the luminance was increased in steps until the required level was reached, followed by adaptation time for another 30 seconds (1 min adaptation in AL 0 cd/m^2 and 30 cd/m^2 without fade-in). Subsequently, LCRs were presented at varying contrasts, starting with the highest C (95%) and finishing with the lowest (18%).

A fixation cross subtending 0.23 degrees was displayed in the middle of the testing surface during the entire luminance adaptation phase (fade-in period and adaptation plateau). The contrast value of the cross corresponded to the subsequent first-tested maximum contrast. In addition, the fixation cross was presented during ISI (i.e. between the stimuli), for orientation. During such ISIs, the fixation cross always had the same contrast level as the corresponding contrast series.

Statistical Analysis

All statistical analyses were performed with JMP 15 (SAS Institute, Cary, NC, USA). Mean values and SEM of the logMAR VA were calculated (N = 14, Fig. 3, see Supplementary Table S1 in S1). For testing the normality of the data, we used the Anderson-Darling test. Data of the participants' second visit were used for assessing the test-retest variability (see Supplementary Table S2 in S1).

Luminance and contrast effects on the response time were analyzed with a restricted maximum likelihood method using the participant as random effect, contrast, and luminance as fixed effects. In order to determine the shortest acceptable correct response time, we calculated the 1% level, eliminating outliers due to the "happy trigger effect" (i.e. 99% of all

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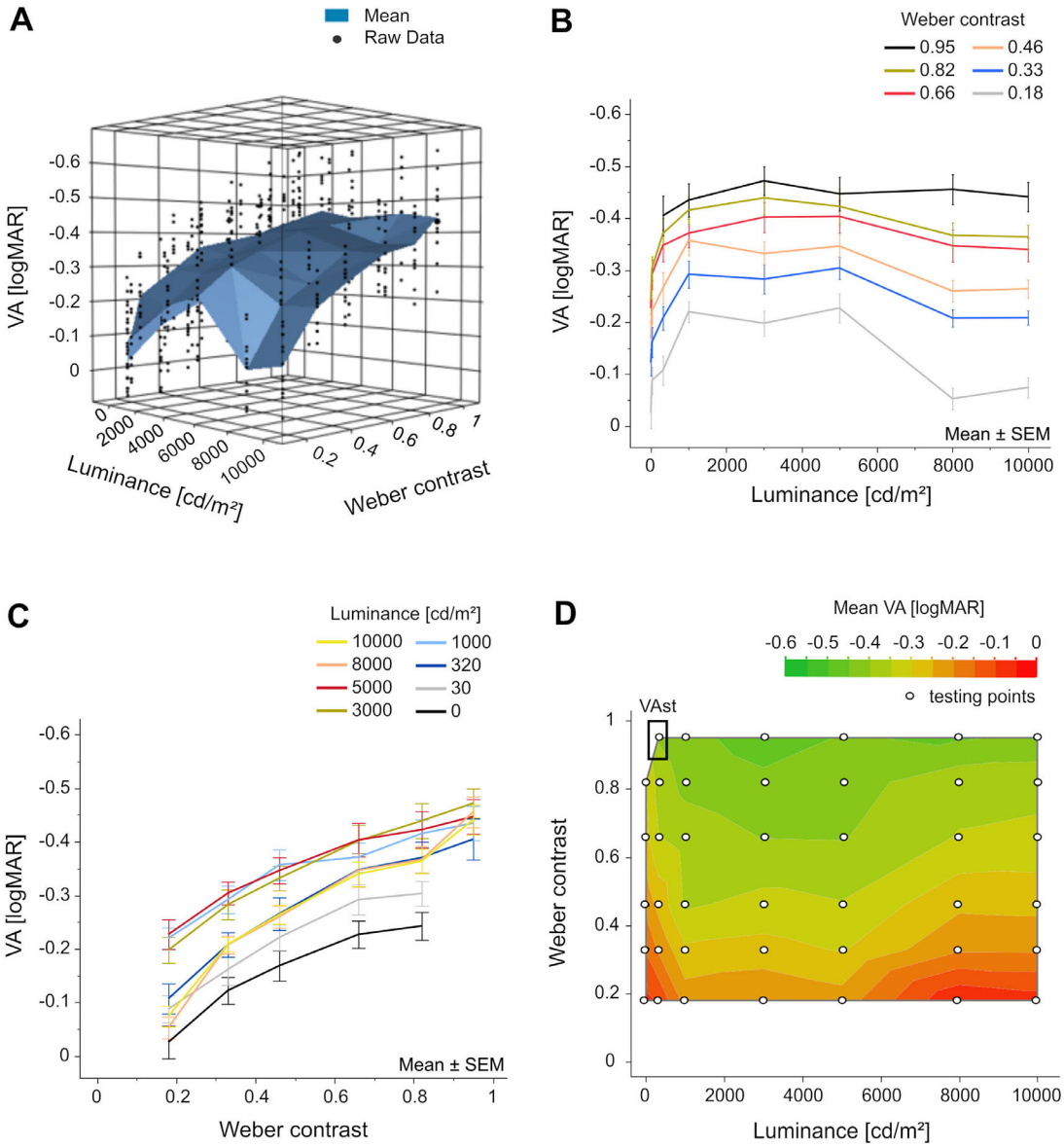

Figure 3. Mean and SEM of the visual acuity threshold of healthy participants for different levels of contrast and ambient luminance. (**A**) Mean values ($N = 14$) are depicted by *blue surface*. *Black dots* symbolize single measurements in each observer. (**B**) Two-dimensional representation with luminance on the abscissa. Different contrasts are represented by different colors. (**C**) Two-dimensional representation with contrast on the abscissa (CS curve). Different luminances are represented by different colors. (**D**) Heat map of averaged VA (logMAR) with Weber contrast and luminance. *Black rectangle* depicts the conditions for standard VA measurement (mean $VA_{st} = -0.41$ logMAR). *White filled circles* show different testing points of VA-CAL.

responses were of longer duration). The last four responses within a test condition were evaluated, ensuring that the response values were close to the VA threshold.

The intraclass correlation coefficient (ICC) for testing the test-retest variability of VA-CAL was calculated according to the formula of Chen et al.[21] by using a linear mixed model, which includes the visit and the participant as random effects, and the contrast and the ambient luminance as well as their interaction as fixed effects. The ICC (2-way random, single measure; ICC[2,1] with agreement definition and 95% confidence interval)[22] for the single testing conditions (C + AL) were determined using IBM SPSS Statistics (version 27). Further, overall paired *t*-test (Bland-Altman-Analysis)[23] was done for checking repeatability of first and second measurement without differentiation between luminance and contrast.

In order to allow for a quick overview of visual performance, VA differences in six different regions of interest (RSI; Table 2) were calculated in relation to the individual maximum VA. Therefore, these VA

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Table 2. Region of Interests (RSI) and Corresponding Conditions for Investigation of VA Differences to the Participants' Personal Maximum VA Within These RSI

Region of Interest	Conditions
1 (high contrast, low luminance)	Weber contrasts ≥50% (66%, 82%, and 95%) Luminances 0, 30, and 320 cd/m^2
2 (low contrast, low luminance)	Weber contrasts <50% (18%, 33%, and 46%) Luminances 0, 30, and 320 cd/m^2
3 (high contrast, medium luminance)	Weber contrasts ≥50% (66%, 82%, and 95%) Luminances 320, 1000, and 3000 cd/m^2
4 (low contrast, medium luminance)	Weber contrasts <50% (18%, 33%, and 46%) Luminances 320, 1000, and 3000 cd/m^2
5 (high contrast, high luminance)	Weber contrasts ≥50% (66%, 82%, and 95%) Luminances 3000, 5000, 8000, and 10,000 cd/m^2
6 (low contrast, high luminance)	Weber contrasts <50% (18%, 33%, and 46%) Luminances 3000, 5000, 8000, and 10,000 cd/m^2

differences of each participant at any testing conditions were first calculated and then averaged by the number of participants ($N = 14$; see Supplementary Table S3 in S1). VA differences of the corresponding conditions of each RSI were averaged. A paired-samples *t*-test was conducted to determine a difference between maximum VA (VA_{max}) and the standard BCVA (VA_{st}) achieved at the testing condition comparable to the clinically measured BCVA according to DIN EN ISO 8596 (at AL = 320 cd/m^2, C = 95%).

The pupil diameter ($N = 12$) was analyzed with ImageJ (version 1.8.0)[24] by marking the corresponding area on images taken at the end of the luminance adaptation time and was measured by using a previously determined pixel to millimeter ratio (1 pixel = 0.286 mm). Pupil measurement of two participants was not possible due to technical problems.

Results

The VA measured with the ETDRS chart in each participant ranged from 0 to −0.3 logMAR (mean ± SEM = −0.19 ± 0.03 logMAR). Spherical refractive errors of the participants ranged from + 2.0 to −3.5 diopter, with cylinders of up to −1.75.

In Figure 3A, the mean VA (blue) averaged from the data of 14 participants (black dots, see Supplementary Table S1 in S2) is shown within the 3D space describing VA under different conditions of luminance and contrast as a VAS. Figure 3D depicts this data as a heat map in which mean VA is presented in different colors. Figure 3B and C show the same data but depicted as VA depending on luminance and contrast respectively in 2D presentation. A figure depicting the data on a log-log scale is shown in the supplement (S1); we prefer linear scales in order to better discern abnormalities in the clinically critical higher luminance range. Data were normally distributed ($P = 0.059$). As expected, lowering the contrast leads to a reduction of VA in all participants. The VA declined at AL 320 cd/m^2 with a reduction of contrast from −0.41 logMAR (mean ± 0.04 SEM logMAR; 95% C) to −0.11 logMAR (mean ± 0.03 SEM logMAR; 18% C). Interestingly, the shape of the contrast sensitivity curve was not affected by the different luminance conditions (Fig. 3C), but is only shifted along the VA axis. However, the VA of the participants improved from the lowest AL of 0 cd/m^2 (mean ± SEM = −0.24 ± 0.03 logMAR at C = 82%) over an AL of 320 cd/m^2 (=VA_{st}; mean ± SEM: −0.41 ± 0.03 logMAR at C = 95%) up to its maximum at an AL of 3000 to 5000 cd/m^2 (contrast dependent; best VA mean ± SEM = −0.47 ± 0.03 logMAR at C = 95% and AL = 3000 cd/m^2). With higher ALs up to 10,000 cd/m^2, VA remained relatively stable at 95% contrast. At lower contrasts, VA decreased again up to an AL of 10,000 cd/m^2, near to the VA value reached with AL 320 cd/m^2 (see Fig. 3).

Figure 4 depicts the ICCs of 14 participants for each testing condition. The ICCs ranged from 0.43 (at AL = 30 cd/m^2 and C = 82%) to 0.94 (at AL = 3000 cd/m^2 and C = 95%). Especially at ALs above 1000 cd/m^2 and high contrast, there was very good test-retest variability. Smaller ICCs occurred especially at both low AL and low contrast. In all conditions, a good

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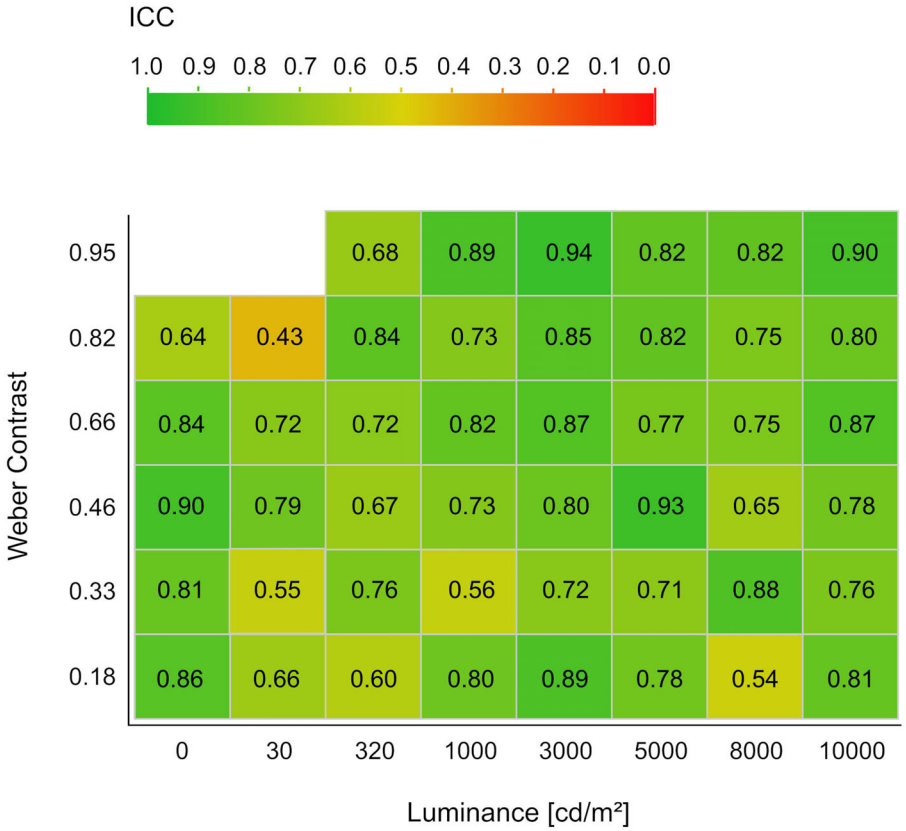

Figure 4. Intraclass correlation (ICC) for each test condition. Colors represent the ICC, ranging from *green* (very good to good repeatability; range = 1.0–0.6), over *yellow* (medium; range = 0.6–0.4) to *red* (ICC <0.4).[25]

or very good ICC was reached. The overall ICC was 0.63, which is considered as good reliability,[25] proving good agreement and repeatability of the VA-CAL test. Paired *t*-test between the first and second measurements resulted in a mean difference of −0.008 logMAR (SD = 0.003, 95% confidence interval [CI] = 0.0024 to −0.0141, $P = 0.0056$, correlation = 0.86).

Figure 5 shows the averaged VA differences to the maximum VA for each RSI (see Table 2 for luminance and contrast conditions). Green indicates no or only a small difference, yellow a moderate difference, and purple a large difference between VA for the respective combination of AL and contrast and the individual maximum VA. Standard BCVA (VA_{st}, white rectangle) denotes the mean VA obtained at the standard condition of our setup (320 cd/m^2 luminance and 95% contrast) comparable to the clinical VA measurement norms (DIN EN ISO 8596; luminance [80–320 cd/m^2] + contrast [>90%]). Overall, participants show the best visual performance at high contrasts, combined with a medium or high luminance (RSI 3 and 5). VA most notably decreased at low luminance levels at both contrast levels (RSI 1), as well as at lower contrasts in all luminance RSIs (RSI 2, 4, and 6). VA_{st} and VA_{max} are illustrated by white rectangles. The VA_{max} (mean ± SEM = −0.50 ± 0.03 logMAR) was reached at an AL of between 320 and 10,000 cd/m^2 (median = 4000 cd/m^2; Q(25) = 3000 cd/m^2, Q(75) = 8500 cd/m^2). Mean VA_{max} exceeds VA_{st} (mean ± SEM = −0.41 ± 0.04 logMAR) of −0.09 logMAR. There was a statistically significant difference between VA_{max} and VA_{st} ($t(13) = 5.40$, $P = 0.0001$).

The 1% level for the shortest acceptable response time (eliminating outliers) was 611 ms for correct responses. The response time was highly significantly increased by lower contrast ($P < 0.0001$), but not by luminance ($P = 0.048$). Near the threshold, correct responses ($n = 1161$; mean ± SEM = 1.71 seconds ± 0.02) were increased in average compared to overall response time ($n = 6118$; mean ± SEM = 1.51 seconds ± 0.01).

Unsurprisingly, the initial pupil diameter at AL 0 cd/m^2 (mean ± SEM = 5.61 ± 0.34 mm) decreased with increasing luminance before remaining stable at about 3000 cd/m^2 (mean ± SEM = 2.57 ± 0.07 mm; see Supplementary Fig. S2 in S1).

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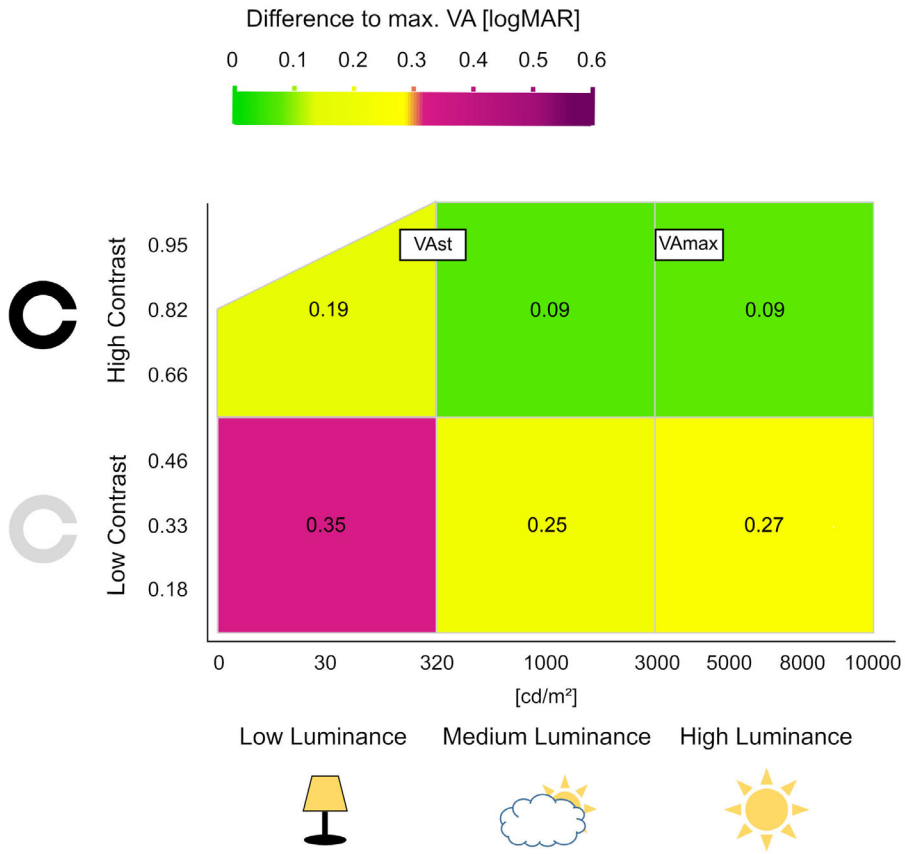

Figure 5. Mean difference in logMAR between the maximum VA and the VA of the respective condition of all participants ($N = 14$). The difference of each VA value for the various conditions to the best VA (mean $VA_{max} = -0.50$ logMAR at C = 95%, median AL = 4000 cd/m^2) was calculated. Each RSI includes certain conditions (contrasts and ambient luminance; see Table 2). These VA differences are averaged accordingly and are written in one representing value in the middle of each RSI. The VA difference is symbolized by different colors (*green* = no/low difference, *yellow* = moderate difference, and *purple* = high difference). The various luminance and contrast levels are clarified by the corresponding symbols. VA_{st} (mean = −0.41 logMAR at C = 95%, AL = 320 cd/m^2) and VA_{max} are shown in white rectangles. Due to technical limitations, VA at 95% contrast could only be determined above AL of 320 cd/m^2.

Discussion

This study demonstrates that the 2D dependence of VA on object contrast and ambient light can be easily assessed. Only testing standard VA (luminance of between 80 and 320 cd/m^2 and maximum optotype contrast)[1] and contrast vision in clinical practice separately do not allow for assessing the full dynamic range of luminance and contrast conditions in everyday indoor and outdoor conditions and thus will miss areas of glare effects. Everyday luminance by far exceeds the standard BCVA condition when the sky is overcast (2000–8000 cd/m^2), and especially when the sky is blue (5000–30,000 cd/m^2).[2] Our measurements on a sunny day (blue sky) have shown that people are confronted with targets, which have much higher luminance (e.g. a white car = 20,000 cd/m^2, a white paper = 13,000 cd/m^2, or a white street sign = 19,000 cd/m^2).

Our study confirms that humans with normal vision reach their VA_{max} at a luminance of 3000 to 5000 cd/m^2, in line with previous observations,[5] with an average improvement of −0.09 logMAR compared to VA_{st}, which approximately corresponds to one line of the ETDRS chart.[6] Thus, clinically determined BCVA underestimates the visual performance of healthy participants.[5] Other studies also found a reduction of VA with decreasing luminance in eye-healthy participants,[26] which is consistent with the lower VA values reached at 0 or 30 cd/m^2 compared to higher ambient luminances in our study. They also figured out that VA for each luminance gradually worsens with decreasing contrast. However, only 0.075 to 75 cd/m^2 were applied as luminance range in the latter study and not to 10,000 cd/m^2 as in our study.

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The VA improvement was contrast-independent at higher AL levels, whereas the VA decreased with lower contrasts, as previously reported.[27–29] AL levels above 5000 cd/m^2 led to a slight drop in VA at higher contrasts and a larger drop in VA at lower contrasts. This is caused by scattered light, lowering retinal contrast, and reducing the contrast sensitivity.[30] Higher contrast seem to be more stable against glare,[31] which is confirmed by our results. It should be noted that the atmospheric Rayleigh scattering depends on wavelength, showing an inversely proportional relationship, increasing for short wavelengths compared to long ones.[32] Because there are different wavelengths during the day, there may be increased scattering during the bluish incident light in comparison to other times of the day.

A pupil constriction in relation to increasing luminance is part of the adaptation mechanism of the human eye[33] and, therefore, as in clinical assessment, VA-CAL allowed for natural pupil function. Because we observed the minimum pupil diameter in the VA-CAL test at about 3000 cd/m^2 and above, we neglected the possible effects of retinal illuminance versus luminance, as we were interested in conditions of daily life. However, whereas with dilated pupils more light falls on the retina, reducing diffraction but degrading resolution due to aberrations, small pupils result in a decrease in optical aberrations coupled with a decrease in light scattering; diffraction in turn leads to an increase in light scattering.[34] If pupil size falls below the optimal pupil size for diffraction-limited visual acuity (2.5 mm),[35] diffraction, which is directly proportional to wavelength, is expected to decrease, resulting in reduced VA at subsequent higher luminances. Because the pupil size in our study assumes values only slightly below this optimal size on average (minimum 2.26 mm at 10,000 cd/m^2), VA probably does not drop considerably any further.

Commercial glare tests mostly use point light sources that are not relevant in most daily activities at daylight. Thus, a large luminance background, as used here, describes more closely daily living situations of object viewing. In VA-CAL, adaptation glare[2] is prevented by fade-in time. Absolute glare (>10,000 cd/m^2)[2] also does not occur in VA-CAL. Clinical test devices, like the mesoptometer, usually examine glare sensitivity in the mesopic luminance range with or without stray light.[5,36] In contrast, VA-CAL measures the VA depending on the luminance throughout the photopic range, which better reflects everyday visual conditions.

Sharp presentation of the optotypes, often limited by the monitor resolution, was perfectly guaranteed in the VA-CAL study down to the smallest sizes. Moreover, although charts, such as the Precision Vision Super Vision Test, extends down to visual acuity values of −0.6 logMAR, most of the common charts, like the ETDRS chart we used to check visual acuity in the initial examination, typically end at a value of −0.3 logMAR, often leaving higher visual acuities undetected.[37]

Auditory feedback, like in VA-CAL, serves as a positive motivational effect in these test procedures and is recommended and does not affect the results.[38] Additionally, the presentation of large, above-threshold optotypes at the beginning of each VA measurement (e.g. 0.4 logMAR in VA-CAL), is recommended[39] and the associated correct responses also may contribute to motivation, similar to "easy trials" in FrACT.[8,37]

The test duration in our experimental setup of about 3 hours limits motivation and concentration and is therefore certainly not suited for clinical application. Nevertheless, the overall mean difference (Bland-Altman analysis) between the first and second measurements, although significant, was less than half a letter. Such variations are therefore not clinically relevant as found also with other visual acuity tests with higher values (e.g. FrACT).[40–42] Within the present study, the basic goal was to understand the entire numerical space of VA, contrasts, and luminances first before committing to a smaller space of specific VA measurement conditions for practical purposes.

For clinical application, we are presently developing an abbreviated test version with 16 pairs of Cs and ALs. Based on our extended results, we are using for short version luminance levels of 30, 320, 3000, and 5000 cd/m^2, representing 2 lower and 2 higher luminances common in daily life, which allows quite well to quantitatively describe visual function under conditions of glare in glare-sensitive patients. Further, the improvement of VA pathologies can be detected in the most interesting range from 30 to 5000 cd/m^2, where VA increases in normal observers but decreases in achromatopsia. As in healthy participants, VA values for 82% and 95% contrast were very similar for all luminance levels, we recommend for the short version contrasts of 80%, 50%, and 20%, representing high, middle, and low contrasts. The reduction to such values reduces the test duration to about 25 minutes in total but still allows for an analysis of the most important conditions for discovering pathology that would go unnoticed at regular clinical VA testing.

We found a wide range of normal BCVA (approximately 5 lines; see Fig. 3D) across the continuum of different contrasts and ambient luminances under conditions of daily life. As photoaversion occurs in many optical and neuronal pathologies, it seems

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worthwhile to measure VA within a broader range of contrasts and luminances to adequately assess the everyday visual performance of such patients in order to avoid over- or underestimations of their actual eyesight in daily activities. This is especially important in people suffering from glare or night vision problems, like achromatopsia,[3,4,43] or other conditions causing impaired vision, like VA loss at low ambient luminances caused by age-related macular degeneration,[44] early cataract,[45,46] early or advanced keratoconus,[47] or post-refractive surgery, where standard clinical BCVA will miss such conditions strongly debilitating such patients in daily life. Another application is quantification of photophobia, observed in psychiatric diseases and inherited retinal dystrophies.[48,49] The VA-CAL test can well describe photophobia-related VA loss in these patients. It can be expected that BCVA in a patient with an inherited retinal disease with standard BCVA of 0.7 logMAR falls at higher ambient luminances and lower contrasts into a range defined as legal blindness. A possible overestimation of visual performance abilities of these patients, measured under standard conditions, can be avoided by the VA-CAL test. In addition, improvement of visual performance after treatments, probably missed by testing standard BVCA, can be detected and quantified in the VAS assessed by VA-CAL at the higher luminance conditions of everyday life. Defining regions of interest, representing natural conditions, is a suited way for a fast judgment concerning the range of VA values during daily living tasks, where the contrast of viewed objects and ambient light levels are continuously changing. However, as VA is the main parameter determined at different levels of contrast and luminance, a clear and well measurable "space of visual performance" for these parameters can be determined by the VA-CAL test.

In conclusion, our approach to understand and measure the dynamic interactions and correlations among contrast sensitivity, AL, and VA in a combined manner along all three axes was not pursued previously. VA-CAL has been established as a reliable computer-controlled method for assessing VA under widely differing conditions of contrast and ambient luminance common in daily life. In the study population, VA improved initially with increasing ambient luminance, which by far exceeds the defined luminance range of actual clinical VA measurements. The 3D presentation of the VA data results in a VAS extending between the contrast and ambient luminance axes. It illustrates the dynamics of visual performance under varying everyday life conditions and can be useful to detect abnormalities in retinal disorders in glare sensitive patients that would go unnoticed in standard tests of BCVA.

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