RESEARCH ARTICLE

Evaluating the Consistency of Online Circular Contrast Perimetry Across Different Computer Monitors: A Cross-sectional Study

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Abstract

Aim and background: The aim of this study is to evaluate the agreement between perimetric findings of a novel 24°, 52-loci online circular contrast perimetry (OCCP) application on three different computer monitors to determine its stability of testing across varying displays.

Materials and methods: Sixty-one participants (19 healthy controls, 42 with glaucoma) underwent SAP testing followed by OCCP testing on three uncalibrated computer monitors in randomized order: a large-screen (24-inch) desktop personal computer (DPC) (Dell, Texas, US), a 17-inch laptop (LPC) (Dell), and a 14-inch MacBook Pro (MP) (Apple, California, US).

Results: Agreement of mean deviation (MD), pattern standard deviation (PSD), and visual field index (VFI)/visual index (VI) values between MP, DPC, and LPC OCCP were strong, with intraclass correlations and Deming's coefficients ranging from 0.96 to 1.00 and 0.93 to 1.03, respectively. When OCCP tests were compared to SAP, ICCs and Deming's coefficients were less strong, ranging from 0.89 to 0.95 and 0.72 to 0.89. Bland-Altman analyses revealed higher biases (2.90 to 3.59 dB) and wider limits of agreement when comparing OCCP to SAP than when comparing OCCP on different monitors. Bland-Altman bias of contrast sensitivities for each 24-2 testing location revealed stronger relationships between OCCP tests on different monitors (–0.82 to 0.78) than between OCCP and SAP tests (–1.53 to 1.32).

Conclusion: OCCP demonstrates strong levels of test-retest agreement when performed on computer monitors of varying display and moderate to strong levels of correlation to SAP perimetric indices.

Clinical significance: With further enhancements, OCCP could potentially be used on different personal computers, which could help address current challenges in glaucoma care, such as limited access to traditional perimetric testing. This has the potential to expand the scope of glaucoma detection and monitoring, particularly in remote and underserved areas of our community.

Keywords: Computer monitor, Cross-sectional study, Glaucoma, Perimetry, Visual field test.

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Introduction

Glaucoma ranks among the leading causes of irreversible vision loss globally, with significant impact on the quality of life of those affected. Early detection remains a challenge, leading to delayed treatment and preventable vision loss.[1–3] Timely intervention is therefore essential for effective glaucoma management, with visual field testing in the form of perimetry facilitating glaucoma diagnosis, severity assessment, and disease progression monitoring.[4,5] Until recently, perimetry was limited to specialized calibrated machines, like those used for standard automated perimetry (SAP), in ophthalmology and optometry practices under the guidance of rigorously trained staff.[6,7]

Although widely used in practice, accessing office-based machine perimetry in highly specialized clinical settings can be costly and inefficient for both patients and healthcare systems alike.[8] Current clinical guidelines recommend patients undergo a minimum of three visual field tests during the initial 2 years of glaucoma diagnosis in order to accurately determine the rate of disease progression and optimize therapy.[9] Yet, most public ophthalmology services are already overburdened with high patient volumes, resulting in growing appointment backlogs and lengthy wait times, with no further scope to accommodate the visual field testing frequency necessary to quantify glaucomatous visual field loss.[8,10,11]

Attempts to resolve these challenges have led to the development of digitized perimetric options that can be operated remotely. Portable and common hardware devices, such as computers,[12] tablets,[13–15] virtual reality headsets,[16,17] and smartphones,[18] offer

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practical alternatives to clinic-based evaluations. These technologies facilitate more frequent monitoring, reduced healthcare costs, and lessen the strain on overloaded glaucoma services.[19] In addition to benefiting developed nations, digital perimetry holds promise for expanding ophthalmological care in developing countries, where an estimated 90% of the global vision loss burden is present.[20,21] Online circular contrast perimetry (OCCP) (Eyeonic Pty Ltd., Melbourne, Australia) is one such validated application that enables visual field assessment from any personal computer (PC) or tablet device, without the need for extra hardware.

Initially, an age-standardized normative data set was established for 24-2 and 10-2 OCCP testing through the acquisition of adequately consistent test results from normal participant cohorts.[22,23] Patients demonstrated a preference for using OCCP over SAP,[24] and the validity of OCCP in identifying glaucomatous visual field changes has already been demonstrated in a cohort of 220 people, with similar sensitivity and specificity to SAP.[25] The repeatability of OCCP was found to be comparable to SAP in a cohort of 36 patients monitored every 6 weeks over 18 weeks.[26] However, these existing studies tested the OCCP application on monitors with the same diagonal screen size of 24 inches and a resolution of 1920 × 1080 pixels, with prior screen calibration using a SpyderX screen photometer (Datacolor, Lucerne, Switzerland) to maintain a consistent range of luminance output.[22–26] Therefore, to determine the feasibility of at-home use, it is necessary to explore the consistency of OCCP testing across different computer monitors of different sizes and display characteristics without external calibration processes and compare its accuracy to SAP. This study aimed to evaluate OCCP testing on three different computer monitors to determine the stability of testing on devices with varying displays and to establish the accuracy of testing on different devices compared to SAP.

Materials and Methods

Methods

This was a single-center, cross-sectional, observational study performed in 2023. Prior to conducting the study, ethical approval was granted by the Royal Australian and New Zealand College of Ophthalmology Human Research Ethics Committee. The study adhered to the tenets of the Declaration of Helsinki with local site governance. Written informed consent was obtained from all participants prior to their participation.

Participants

Participants consisted of sixty-one patients (29 female) aged 20–82 years (mean 62.39) recruited from patients attending a subspecialist glaucoma clinic in Melbourne for routine review appointments.

Study eligibility criteria included the ability to read and understand fluent English, provision of informed written consent, best-corrected visual acuity ≤0.7 logarithm of the minimum angle of resolution (logMAR), optical coherence tomography (OCT) image of satisfactory quality, and reliable test results for SAP and OCCP. The reliability of both OCCP and SAP tests was assessed using traditional parameters as follows: false negative (FN) <33%, false positive (FP) <15%, and fixation losses (FL) <20%. FL was assessed with the Heijl and Krakau method.[27] Visual field tests were further assessed for eyelid or rim artifacts, inattention, improper fixation, and fatigue or learning effects, with tests found to have any of the above being excluded from the study.[28] Segmentation errors on OCT scans or a signal strength below 8 out of 10 also necessitated rejection.

Exclusion criteria were ocular pathology unrelated to glaucoma, including visually significant cataracts (defined by the Lens Opacities Classification System III greater than Grade 2[29]), nonglaucomatous optic neuropathy, and pathology of the retina or macula; <18 or greater than 95 years of age; secondary causes of glaucoma; angle and papillary abnormalities; ametropia greater than ±5 diopters; large peripapillary atrophy; neurological conditions or medications that might affect visual field results (e.g., pilocarpine, chloroquine, vigabatrin); ocular surgery within the last 3 months; and media opacities that hinder clear image scans.

Assessment of Clinical Parameters

The study's principal investigator (consultant ophthalmologist and author SS) conducted a thorough ophthalmic assessment of all participants to determine any factors that might warrant study exclusion. Baseline data collected included the following clinical parameters: best-corrected visual acuity, refractive correction for distance, Cirrus OCT of the macula and optic nerve head (Carl Zeiss Meditec Inc., Dublin, CA), central corneal thickness (CCT) measured with the PachMate handheld pachymeter, and intraocular pressure (IOP) assessed with the Goldmann applanation tonometer (Haag-Streit International, Bern, Switzerland).

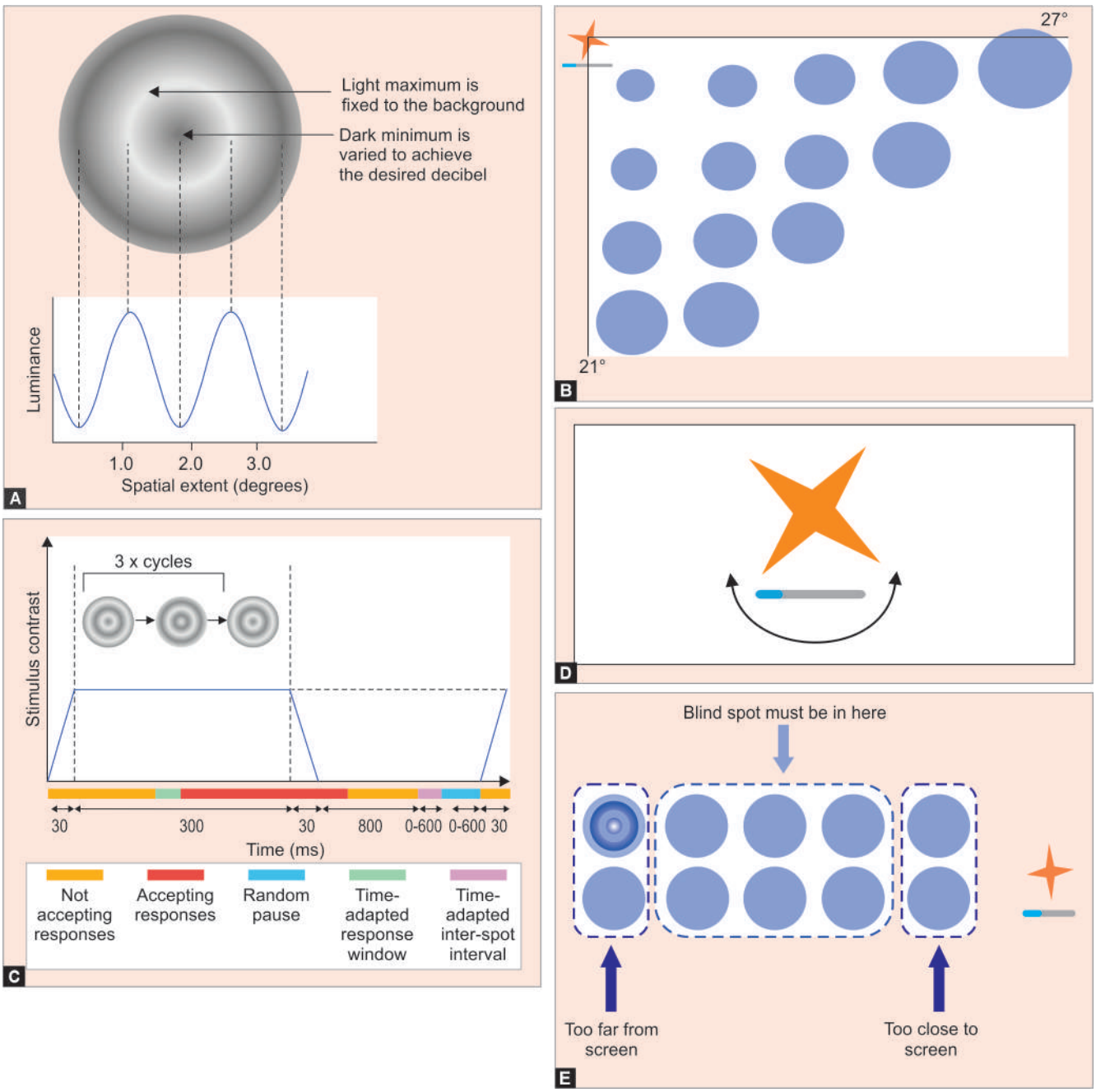
Control subjects were defined as having normal optic nerve head (ONH) appearance, retinal nerve fiber layer (RNFL) thickness, and standard automated perimetry (SAP) results, without additional ocular pathologies. Glaucoma subjects were defined as those with distinctive disk and VF changes. Eyes were defined as glaucomatous according to criteria outlined by the American Academy of Ophthalmology.[30]

Online Circular Contrast Perimetry Application

OCCP offers web-based perimetry accessible without additional hardware on any electronic device. As described in previous papers,[22–26] the 24-2 protocol evaluates 52 loci spanning a peripheral visual field of 24° by presenting users with circular flickering targets characterized by alternating concentric light and dark rings. Each target stimulus measures 3.5° of visual angle with a spatial separation of 6° (Fig. 1). The size of the targets increases with increasing eccentricity to maintain a consistent size of viewing angle on a flat screen and to allow similar normal sensitivity thresholds across different loci.

While OCCP targets are similar to those used in Pulsar perimetry (Haag-Streit International), they maintain consistent contrast with respect to the maximum and minimum luminance peaks and troughs throughout their spatial extent, with a slight reduction at the peripheral edges to reduce light scatter and prevent unintended ganglion cell activation.[31,32] OCCP targets are also smaller in size compared to those used in Pulsar perimetry (3.5 vs 5°).[31,32] Simple trigonometry is used to modify the placement of test loci on the screen relative to fixation to account for viewing on a flat plane.

Targets are composed of concentric sinusoidal contrast rings (Fig. 1). These targets alternate with their inverse image on flicker (with bright peaks replacing dark troughs and vice versa). Each target undergoes an 8.3 hertz (Hz) flicker that lasts 360 milliseconds across three counterphase flicker cycles. This is slower than the traditional 24-2 frequency doubling perimeter (FDP) (Welch Allyn, Skaneateles, NY, and Carl Zeiss Meditec, Dublin, Calif.), where targets exhibit sinusoidal contrast with a spatial frequency of 0.5 cycles per degree flickered at a rate of 18 Hz.[33,34] The contrast is ramped up and down in a linear fashion over 30 milliseconds at the beginning



Figs 1A to E: Online circular contrast perimetry test settings. (A) Flickering test target; (B) Map of lower right quadrant in 24-2 perimetry loci testing with a magnification factor to peripheral loci that grows with eccentricity. The fixation target moves to all four corners of the screen for maximization of the sampling area at a comfortable viewing distance; (C) Sequence of target presentation: targets appear for three counterphase flicker cycles lasting 360 ms; contrast is graded at the start and end of target presentation; ms: millisecond. Figure adapted from Alawa et al.[18]; (D) Fixation target: spinning golden star; (E) Blind spot localization optimizes the user's viewing distance; (B and E) The dark gray homogeneous circles are a diagrammatic representation of where test targets may appear and are not present during the live test

and end of each target presentation to avoid saccades and temporal transients (Fig. 1).[35,36] In the JavaScript code, the window requestAnimationFrame object with a timestamp callback allows for synchronization of target presentations with the display's refresh cycle, improving timing consistency. This minimizes variability due to hardware-specific temporal properties, such as pixel response times or display overdrive algorithms.

In comparison to traditional FDP, where background luminance represents the average of light and dark target bands, OCCP sets light rings to match the background screen color (light gray) and varies only the dark ring intensity to achieve the desired target contrast, similar to using a luminance pedestal flicker for stimulus decrements. This minimizes the number of grayscale levels incorporated into the background design and stimulus to maintain consistency across display parameters. Importantly, the assumption in FDP—that the background is the mean of the light and dark bands—may not hold true on modern screens and tablets without extensive precalibration. OCCP's approach avoids this assumption,

thereby increasing the consistency of display parameters with different gamma corrections.[37]

Three key mechanisms are used in combination to maintain accurate viewing distance and head positioning. First, the web application calculates and then informs the user of the correct viewing distance by detecting the screen size in pixels of the device used. For instance, a 24-inch screen results in a viewing distance of 40 cm. Second, at the start of the test, the user's blind spot is identified by testing small (0.5°) targets on a 4 × 10° grid overlying the estimated blind spot, which is located approximately 15° temporal and 0.5° inferior to fixation (Fig. 1). If the blind spot is detected too far from the fixation point, instructions to shift closer to the screen are given; on the other hand, if the blind spot is detected too near to fixation, the user is instructed to shift backward to maintain an appropriate visual angle for screen viewing. If the blind spot is not located within the initial grid, it is searched for further laterally to account for the possibility that the user is sitting even farther back from the monitor screen than anticipated. Third, the computer's webcam continuously tracks head position during the test with a refresh rate of 1 second using machine learning (ML) for facial detection (not recognition). Any deviations of facial position monitoring beyond 15% in four planes are permitted, while those exceeding this threshold are detected, causing the test to pause. Testing resumes once the participant's head position is corrected *via* verbal instruction. When used together, the three mechanisms maintain head position within an error rate of <1%.[38]

Fixation loss is assessed using the Heijl and Krakau method, where a smaller 0.5°, higher-contrast target is presented periodically within the predetermined blind spot, compared to the standard 3.5° target used during the test. The process of fixation assessment functions independently of the head position monitoring described above, which occurs using face detection *via* the webcam. To allow for the maximization of sampling area regardless of monitor screen size, the fixation target moves throughout the test (Fig. 1). The fixation target begins at one corner (top left or top right) and then moves toward each other corner of the screen (top left, top right, bottom right, bottom left), sampling each quadrant of the visual field at a time. Accordingly, when the fixation target is at the top right screen corner, the test samples the inferior left quadrant, and when fixation moves to the top left of the screen, the test samples the inferior right quadrant. To compensate for the blind spot being off-screen for half of the test, the frequency of fixation loss tests performed when the blind spot is on-screen is doubled.

The relative luminance for each 256-bit grayscale level was calculated in accordance with the Web Content Accessibility Guidelines standards for relative luminance calculation, with test output ranging from pure white (255, 255, 255), indicating 100% relative luminance, to black (0, 0, 0), signifying 0%.[39]

The app has been designed to provide consistency of testing despite screen brightness variations. The background color is set to a light gray tone, and users are instructed to increase their screen brightness to 75% before commencing the test. This corresponds to a relative luminance of 220 cd/m^2; however, absolute luminance will vary between screens. This background was selected so that the effects of pupil size, background lighting, and lens yellowing on retinal illumination can be minimized.[24]

The contrast of targets was then determined with the Michelson formula, which compares the peaks and troughs of the target rings[40]:

$$\text{Contrast} = (RL_1 - RL_2) / (RL_1 + RL_2)$$

Where RL_1 represents the light band maximum and RL_2 the dark band minimum relative luminance. Contrast was then converted into relative decibels using a method similar to that employed in FDP[33]:

$$\text{Decibel (dB)} = -20 \log(\text{contrast sensitivity})$$

The dynamic range for target intensity ranges from 0 to 36 dB; this range is similar to those found in other perimetric devices, such as HFA, and adequately assesses human threshold estimates throughout the field.[15]

Throughout the test, users were instructed to keep their gaze on a continuously spinning fixation point (golden star) and click the mouse upon seeing a target in their peripheral vision (Fig. 1). A distinct sound was generated upon the user's click and varied depending on whether the click occurred within or outside the accepted response window. An affirmative, comforting sound is generated each time the user clicks at the appropriate moment. Clicks occurring outside the response window produce a sound resembling the noise generated when an error happens during a computer game, indicating a false positive (FP) response. False negative (FN) responses were determined in accordance with methods utilized in SAP, where participants failed to produce a response even when stimuli of higher contrast were presented in areas of normal threshold sensitivity.[41]

OCCP employs a Bayes predictor of threshold, using a priori probability density functions with a 4/2 dB staircase.[42] This is used in conjunction with an iterative maximum posterior probability algorithm, which runs in real time to evaluate when testing at each point can stop. Two reversals are necessary at primary test points, after which only a single reversal is necessary for termination at each point. To account for interuser response rate variability, the sequence of presenting stimuli was adjusted based on the user's previous responses to ensure that testing proceeded at a suitable pace for every user.[43] The interstimulus interval utilized in OCCP ranges from 800 milliseconds to 2 seconds (Fig. 1). An in-built random delay was introduced between stimuli to prevent rhythmic responses.

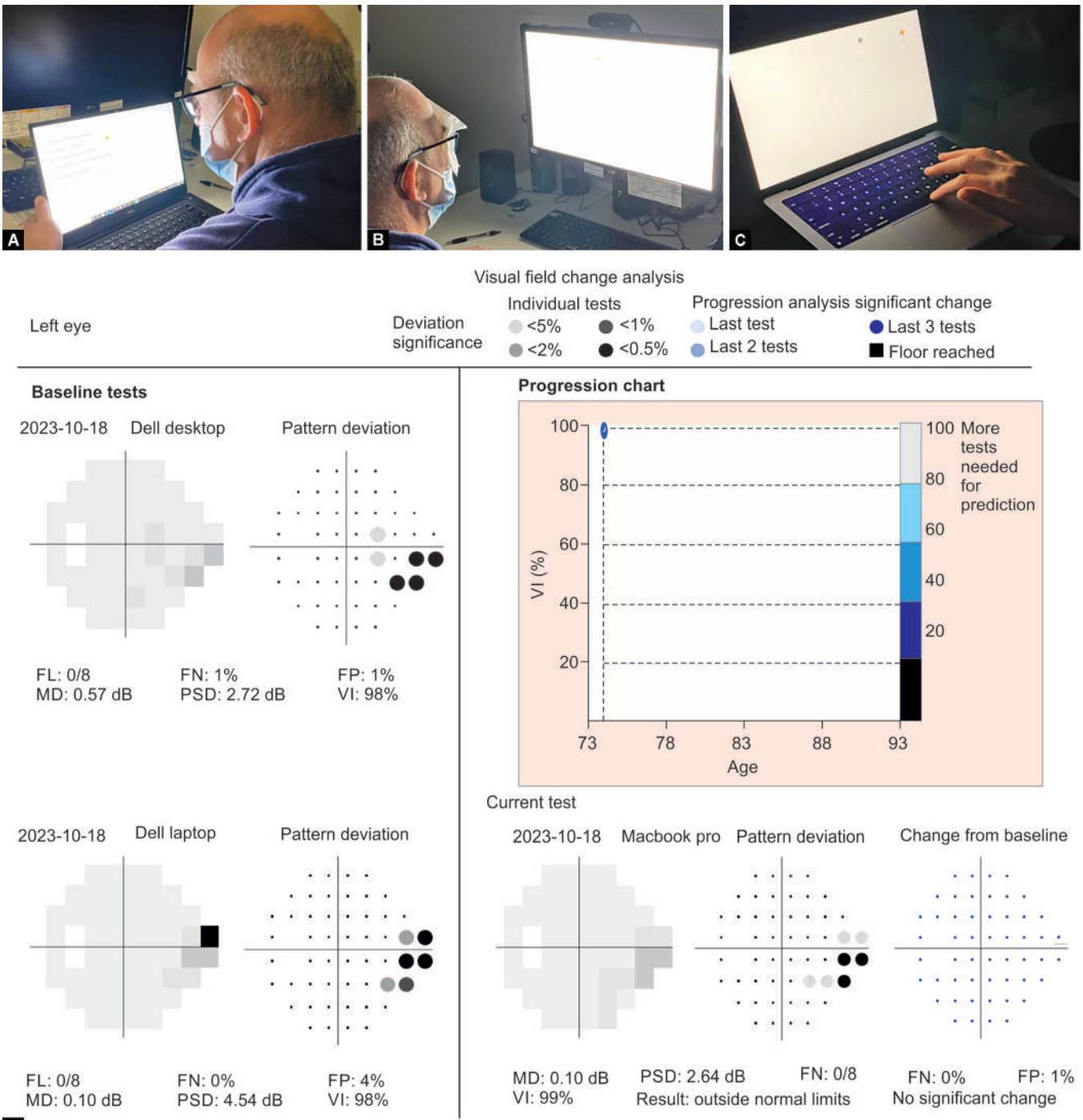
Testing Procedure

Participants completed visual field testing with SAP using the HFA Swedish Interactive Threshold Algorithm (SITA) standard 24-2 test (Zeiss) using one eye selected by simple randomization.[44] Subsequently, participants were led to another dedicated testing room on-site to undergo OCCP testing using the same eye on three separate computers, with the order of use randomized. Before undertaking both perimetric assessments, participants were thoroughly briefed by a trained orthoptist, and the entire testing process was rigorously monitored to ensure absolute adherence to study protocol. Environmental conditions were standardized for testing consistency, with background noise kept to a minimum and room lighting darkened so that the computer monitors were the brightest light source. The screens of all three participating monitors—a large-screen (24-inch) desktop personal computer (DPC) (Dell, Texas, US), a 17-inch laptop (LPC) (Dell), and a 14-inch MacBook Pro (MP) (Apple, California, US)—were wiped clean before testing. Participants wore refractive correction with a near adjustment as required for presbyopia.

Participants were positioned comfortably at a desk facing the first of three computer monitors, with the order of testing determined by simple randomization for each patient (Fig. 2). The orthoptist then guided participants in the registration process

for an account, under which all test results and patient details were securely stored. The web-based application calculated the appropriate viewing distance for the participant, and the orthoptist directed the participant to sit at the correct viewing distance for each monitor and optimized the seating height. The testing process was repeated for the next two monitors, with a 5-minute break between each test. Contrasting with the protocol of previous papers validating the OCCP, no external screen calibration processes were undertaken. Screen brightness was set to 75% luminance, following instructions from the app for optimal testing conditions.

While variability in absolute screen brightness, gamma, and color is unavoidable across different devices, the OCCP parameters are chosen to be minimally affected by such variations. Key design features of the OCCP, such as spatial frequency, background color, target size, and rate of flicker, have also been optimized to maximize consistency and account for possible variations in



Figs 2A to D: Testing computers and testing output. (A) Laptop personal computer; (B) Large-screen (24-inch) desktop personal computer; (C) MacBook (Apple); (D) Output from OCCP testing on three separate computers

testing environments and display outputs.[24] The test also relies on the relative contrast between the light and dark bands of the target rather than on absolute luminance values, ensuring that any changes in overall screen luminance affect both components in a similar direction.

OCCP testing output generated on each separate computer is shown in Figure 2. Main perimetric outputs include mean sensitivity per point (MSPP), mean deviation (MD), pattern standard deviation (PSD), and visual index (VI); VI is calculated on a weighted mean system similar to visual field index (VFI).

Main Outcome Measures

Global perimetric indices, including mean deviation (MD), pattern standard deviation (PSD), visual field index (VFI)/visual index (VI), and mean sensitivity per point (MSPP), comprised the study's main outcome measures. Secondary outcome measures included reliability indices (false-positive (FP), false-negative (FN), and fixation loss (FL) rates) and testing duration. Outcome measures were calculated based on data sourced from an established normative dataset and determined in accordance with methods utilized in SAP.[22]

Statistical Analysis

Statistical analysis was performed using Real Statistics in Excel 2016 (Microsoft 365) and the Statistical Package for the Social Sciences (SPSS, Inc., Chicago, IL, US). Statistical significance was set at $p < 0.05$ with Bonferroni correction. The Shapiro–Wilk statistic was used to evaluate data normality, and paired differences between normal controls and glaucomatous eyes were assessed using either the independent *t*-test or the Mann–Whitney *U* test for nonparametric data.

Given the fundamental perimetric differences between OCCP and SAP, direct sensitivity comparisons of decibels were not possible. Instead, to compare MSPP across devices, thresholds from each were translated to log CS, with CS being the reciprocal of the contrast threshold.[33] For SAP, contrast is defined as (peak-background luminance)/background luminance, which is equivalent to Weber contrast for luminance increments. Decibels are reported as $25 + 10 \times \log CS$ for white-on-white perimetry using Goldmann size III stimuli.

Primary outcome measurements (MD, VI, and PSD) obtained through OCCP testing were assessed for their intertest reliability using intraclass coefficients (ICCs), which were defined as poor (<0.5), moderate (0.5–0.75), good (0.75–0.9), or excellent (≥0.90).[45] The strength of associations between each test's global indices was further evaluated using Deming regression analysis, with Deming's regression intercept and coefficient reported with 95% confidence intervals.[46] A significant difference was inferred if the Deming coefficient's 95% confidence interval did not contain 1.

Bland-Altman analyses were used to evaluate the 95% limits of agreement and bias between the three tests' MD values and the pointwise sensitivities at each 24-2 testing location. OCCP indices were then compared to values obtained via SAP testing using the same statistical methods listed above.

Sample size was determined based on the 95% confidence interval of test-retest agreement, which ranged from 0.51 to 0.98.26 With an alpha of 0.05 and a type II error rate of 0.1, using the lower limit of the confidence interval range yielded a sample size of 36. Given the uncertainty of test-retest variability across different screens, as well as potential test reliability issues, this was increased to 60.

Results

Sixty-one participants (61 eyes) were enrolled in the study. Table 1 represents the baseline demographic characteristics of participants, with a mean age of 62.39 ± 3.26 years. Altogether, five participants were excluded from the cohort: two participants failed to meet inclusion reliability criteria, and one participant's OCCP test data failed to save. Another two participants were also excluded for being unable to complete OCCP testing on all computer monitors due to time constraints.

Figure 3 displays the reliability indices for SAP compared to OCCP and for OCCP tests performed on the different computer monitors. No statistically significant changes were found between the SAP and OCCP FP and FL rates. However, FN rates were significantly lower for OCCP testing across all computer monitors compared to SAP. Similarly, OCCP test duration was also shorter across all computer monitors compared to SAP.

When comparing reliability indices for OCCP tests performed on the different computer monitors (DPC, MP, and LPC), no statistically significant changes were observed for FN and FL rates. However, FP rates were significantly higher for LPC use compared to DPC and MP use ($p = 0.004$).

Table 2 presents the regression and intraclass coefficients, Bland-Altman bias, and corresponding limits of agreement for MD, PSD, and VI/VFI when comparing the OCCP tests on different computers and SAP. ICCs evaluating the agreement of MD, PSD, and VI/VFI values between MP, DPC, and LPC OCCP use were excellent. When MP, DPC, and LPC MD values were compared to SAP values, agreement was excellent for MD and VI/VFI values. MP vs SAP PSD values were excellent (ICC = 0.92), while DPC vs SAP and LPC vs SAP values were good (ICC = 0.89).

Bland-Altman plots for the MD values of OCCP tests from different monitors are displayed in Figure 4. For OCCP MD, MP vs DPC had a test bias of −0.56 (LoA −3.44 to 2.31); DPC vs LPC data had a test bias of −0.69 (LoA −2.87 to 1.48); and LPC vs MP had a test bias of −0.11 (LoA −2.57 to 2.36), indicating very strong relationships. Figure 4 presents the Bland-Altman plots of MD for OCCP tests on each monitor compared to SAP, respectively. These showed a test bias ranging from 2.90 to 3.05 and wider limits of agreement than when comparing OCCP tests performed on different monitors to OCCP MD values.

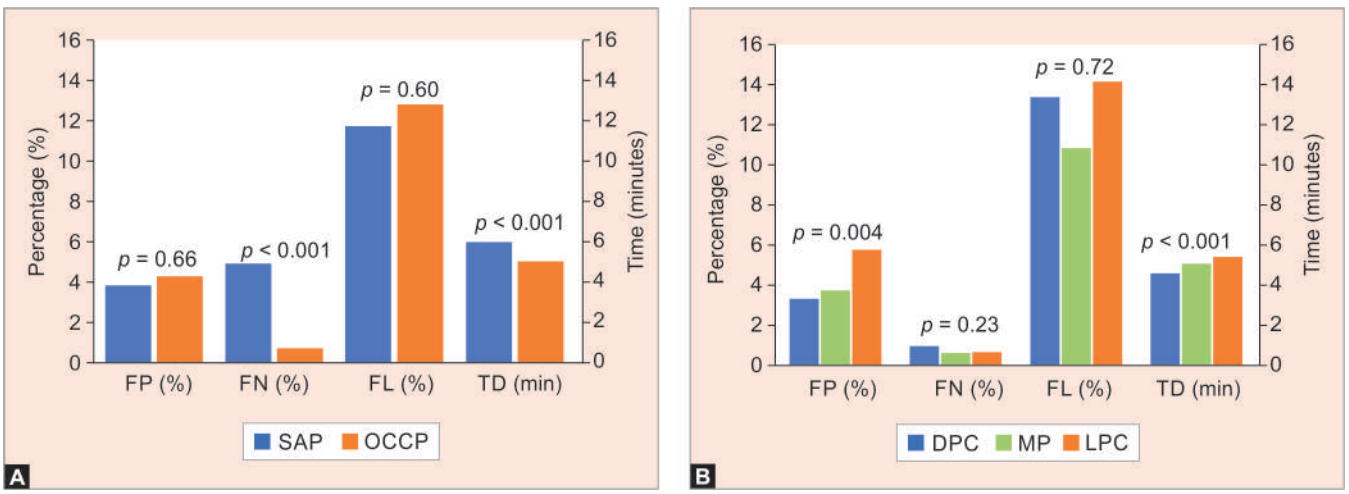
Figure 5 displays heatmaps illustrating the Bland-Altman bias ± 1.96 × standard deviation to give the 95% LoAs for MSPP in CS at each 24-2 testing location (left eye orientation) when comparing OCCP on different computer monitors and SAP. When DPC and MP pointwise sensitivities were compared, Bland-Altman bias ranged from −0.38 to 0.78, and 95% LoA ranged from (−2.33, 2.51) (widest interval) to (−1.73, 1.77) (narrowest interval). Bland-Altman bias for LPC vs MP testing loci ranged from −0.29 to 0.30, with 95% LoA ranging from (−1.84, 2.44) to (−1.33, 1.15). When LPC and DPC tests were compared, Bland-Altman bias ranged from −0.82 to 0.22, and 95% LoA ranged from (−3.39, 1.75) to (−1.11, 1.55).

Figure 5 shows the Bland-Altman bias ± 95% LoA for each 24-2 testing location when OCCP data were compared to SAP. Bland-Altman bias for MP vs SAP testing loci ranged from −1.48 to 1.23, and 95% LoA ranged from (−8.77, 7.81) to (−2.38, 2.38). When DPC and SAP pointwise sensitivities were compared, Bland-Altman bias ranged from −1.49 to 1.17, and 95% LoA ranged from (−8.93, 6.95) to (−1.86, 2.58). When LPC and SAP tests were compared, Bland-Altman bias ranged from −1.53 to 1.32, and 95% LoA ranged from (−8.80, 5.74) to (−1.90, 2.08).

Table 1: Clinical and perimetric characteristics

Variables		*Control group*	*Glaucoma group*	*p-value*
Total		19	41	–
Gender (F/M)		10/9	19/23	0.60
Number of eyes (R/L)		12/7	15/27	0.05
Abnormal ONH (% eyes)		0	100	–
Age (year)		60.66 ± 7.13	63.16 ± 3.82	0.48
log MAR visual acuity		0.00 ± 0.27	0.11 ± 0.06	0.002
Corrected IOP (mm Hg)		17.21± 1.90	13.93 ± 1.95	0.027
CCT (µm)		540.32 ± 17.99	549.23 ± 12.21	0.43
Spherical equivalent (D)		0.46 ± 1.20	–1.38 ± 1.07	0.76
OCT RNFL	MT (µm)	86.05 ± 5.42	68.95 ± 4.53	<0.001
	ST (µm)	99.05 ± 5.95	78.40 ± 6.82	<0.001
	IT (µm)	108.84 ± 9.87	75.43 ± 6.12	<0.001
	VCDR	0.616 ± 0.06	0.69 ± 0.06	0.17
OCT GCC	MT (µm)	75.79 ± 4.72	65.23 ± 4.23	0.002
	ST (µm)	76.68 ± 5.76	66.25 ± 5.76	0.024
	IT (µm)	73.16 ± 5.70	64.38 ± 4.58	0.019
SAP	MD	–1.49 ± 0.72	–9.18 ± 2.50	<0.001
	PSD	2.20 ± 0.98	6.83 ± 1.29	<0.001
	VFI	97.99 ± 1.07	74.80 ± 7.45	<0.001
OCCP DPC	MD	1.33 ± 0.42	–5.19 ± 2.22	<0.001
	PSD	1.47 ± 0.68	5.38 ± 1.04	<0.001
	VI	99.53 ± 0.49	83.38 ± 6.32	<0.001
OCCP MP	MD	1.09 ± 0.48	–5.92 ± 2.15	<0.001
	PSD	1.54 ± 0.34	5.65 ± 1.02	<0.001
	VFI	99.26 ± 0.60	82.53 ± 6.05	<0.001
OCCP LPC	MD	0.91 ± 0.45	–6.00 ± 2.26	<0.001
	PSD	1.96 ± 0.75	5.58 ± 0.97	<0.001
	VFI	99.32 ± 0.53	82.45 ± 6.27	<0.001
OCCP average	MD	1.11 ± 0.38	–5.70 ± 2.19	<0.001
	PSD	1.66 ± 0.45	5.38 ± 1.04	<0.001
	VFI	99.37 ± 0.40	83.38 ± 6.32	<0.001

CCT, central corneal thickness; D, diopters; DPC, desktop personal computer; GCC, ganglion cell complex inner plexiform layer; IOP, intraocular pressure; IT, inferior thickness; LPC, laptop personal computer; MAR, minimal angle of resolution; MD, mean deviation; MP, MacBook Pro laptop; MT, mean thickness; OCCP, online circular contrast perimetry; OCT, optical coherence tomography; ONH, optic nerve head; PSD, pattern standard deviation; RNFL, retinal nerve fiber layer; SAP, standard automated perimetry; SD, standard deviation; ST, superior thickness; VCDR, vertical cup-disc ratio; VFI, visual field index; Values are presented as mean ± standard deviation unless otherwise specified



Figs 3A and B: Reliability indices. (A) OCCP averaged over all tests (MacBook Pro laptop (MP), desktop personal computer (DPC), laptop personal computer (LPC)) compared to SAP; (B) Comparison among OCCP on MP, DPC, and LPC; FP, false positive; FN, false negative; FL, fixation loss; TD, test duration

Table 2: Comparison of OCCP on three different computer monitors to SAP

Test	*Deming's regression intercept (95% CI)*	*Deming's regression coefficient (95% CI)*	*ICC (95% CI)*	*Bland Altman Bias (dB)*	*Bland Altman 95% LoA (dB)*
Mean deviation					
MP vs DPC	–0.59 (–0.93, –0.24)	0.99 (0.93, 1.06)	0.98 (0.97, 0.99)	–0.56	(–3.44, 2.31)
LPC vs MP	0.02 (–0.30, 0.34)	1.03 (0.99, 1.08)	0.99 (0.98, 0.99)	–0.11	(–2.57, 2.36)
LPC vs DPC	–0.62 (–0.89, –0.34)	1.03 (0.98, 1.08)	0.99 (0.97, 0.99)	–0.69	(–2.87, 1.48)
MP vs SAP	2.09 (1.24, 2.93)	0.89 (0.69, 1.02)	0.94 (0.90, 0.96)	3.05	(–3.40, 9.50)
DPC vs SAP	2.69 (1.86, 3.51)	0.86 (0.70, 1.03)	0.95 (0.91, 0.97)	3.59	(–2.45, 9.63)
LPC vs SAP	2.14 (1.34, 2.94)	0.89 (0.73, 1.04)	0.94 (0.90, 0.96)	2.90	(–3.63, 9.42)
Pattern standard deviation					
MP vs DPC	0.26 (–0.18, 0.69)	0.98 (0.90, 1.07)	0.96 (0.94, 0.98)	0.19	(–2.27, 2.65)
LPC vs MP	0.32 (–0.10, 0.74)	0.95 (0.87, 1.03)	0.97 (0.94, 0.98)	0.16	(–2.37, 2.69)
LPC vs DPC	0.58 (0.14, 1.01)	0.93 (0.86, 1.01)	0.96 (0.94, 0.98)	0.30	(–2.00, 2.60)
MP vs SAP	0.22 (–0.26, 0.70)	0.77 (0.70, 0.85)	0.92 (0.86, 0.95)	–1.08	(–5.26, 3.11)
DPC vs SAP	–0.01 (–0.62, 0.60)	0.77 (0.67, 0.88)	0.89 (0.82, 0.94)	–1.21	(–5.75, 3.32)
LPC vs SAP	0.57 (–0.01, 1.16)	0.72 (0.62, 0.82)	0.89 (0.82, 0.94)	–0.91	(–5.29, 3.46)
Visual field index vs visual index					
MP vs DPC	1.85 (–9.15, 12.84)	0.97 (0.86, 1.09)	0.99 (0.98, 0.99)	–0.72	(–8.75, 7.32)
LPC vs MP	–2.67 (–11.07, 5.73)	1.03 (0.94, 1.12)	0.99 (0.98, 0.99)	–0.03	(–6.89, 6.82)
LPC vs DPC	–0.78 (–5.30, 3.74)	1.00 (0.95, 1.05)	1.00 (0.99, 1.00)	–0.77	(–5.67, 4.13)
MP vs SAP	24.83 (5.58, 44.07)	0.77 (0.56, 0.98)	0.92 (0.87, 0.95)	4.00	(–28.26, 36.26)
DPC vs SAP	23.49 (1.20, 45.78)	0.79 (0.55, 1.04)	0.93 (0.88, 0.96)	6.26	(–14.27, 26.79)
LPC vs SAP	22.87 (1.79, 43.94)	0.79 (0.56, 1.02)	0.92 (0.87, 0.95)	5.49	(–15.67, 26.65)

CI, confidence interval; dB, decibels; DPC, desktop personal computer; ICC, intraclass correlation coefficient; LPC, laptop personal computer; LoA, 95% limits of agreement; MP, MacBook Pro laptop

Discussion

The adaptability of a web-based perimetric application to different electronic devices with varying display characteristics is crucial for expanding glaucoma monitoring in both clinical and at-home settings. However, this capability has rarely been assessed in the current literature on screen-based perimetry. Most studies have used devices with standardized screen sizes and extensive photometric calibration to ensure uniform luminance.[12–18] To achieve accurate perimetric results, key display parameters such as brightness, contrast, and gamma must be appropriately adjusted.[47,48] Additionally, spatial nonuniformity in digital displays can further complicate screen calibration and impact test reliability.[47] While screen-based perimetry technology is widely accessible, its reliance on rigorous calibration and controlled screen sizes means that only a limited number of individuals can effectively utilize it. This reliance reduces accessibility and cost-effectiveness, hindering broader implementation.[12,47,48]

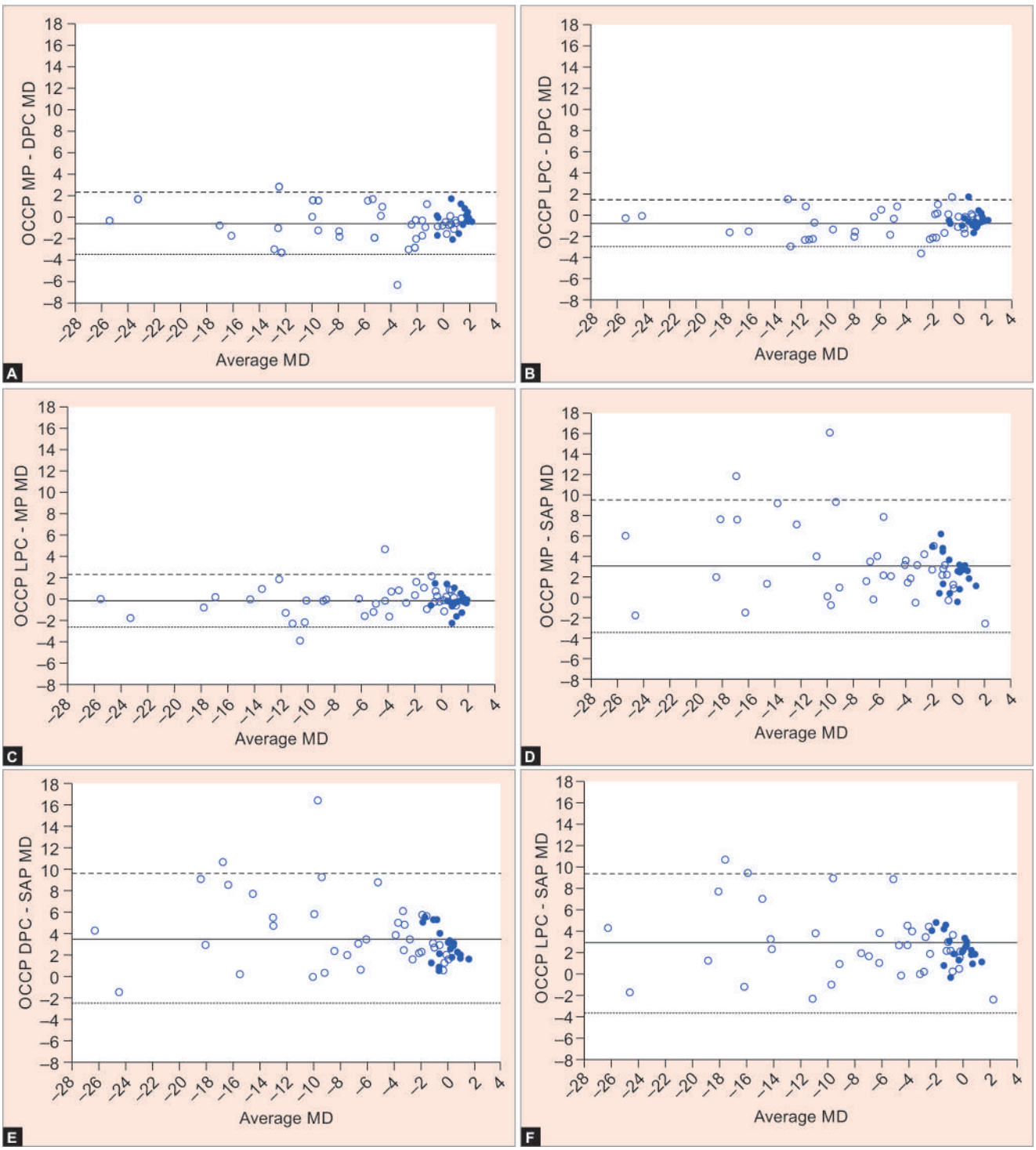
This is the first study to investigate the reliability of OCCP testing across different computer monitors without prior external screen calibration. There was strong agreement between the global perimetric indices tested, with ICCs for MD, PSD, and VFI ranging from 0.96 to 1.00 when DPC, MP, and LPC results were compared, indicating excellent reliability of OCCP testing. We also observed close agreement between OCCP and SAP indices, with a Deming's coefficient ranging from 0.72 to 0.89. ICCs were good for DPC vs SAP and LPC vs SAP PSD values and excellent for all MD and VI/VFI tests. These findings are comparable to results from previous studies evaluating OCCP on a single device type as a diagnostic screening tool for glaucoma.[22–25]

Testing biases ranging from 2.90 to 3.59 dB were observed between SAP and OCCP MD values, along with wider 95% LoA on Bland–Altman plots. The comparison of point-wise sensitivities revealed varying strengths of correlation, with Bland–Altman bias ranging from −0.82 to 0.78 when OCCP tests were compared and −1.53 to 1.32 when OCCP and SAP tests were compared for each 24-2 testing locus.

Several factors may explain the differences between SAP and OCCP. Personal device-based testing with OCCP introduces additional variables in visual field assessment, including variations in screen size, brightness, and color tone, increased head positioning flexibility, and the need for the fixation target to move. Online perimetry also presents a range of unfamiliar elements to both patients and staff, including navigating online login processes, following new instructions, identifying the blind spot, responding to facial monitoring system cues, and using a mouse or spacebar instead of the perimetry clicker; these variations can increase testing difficulty for users.

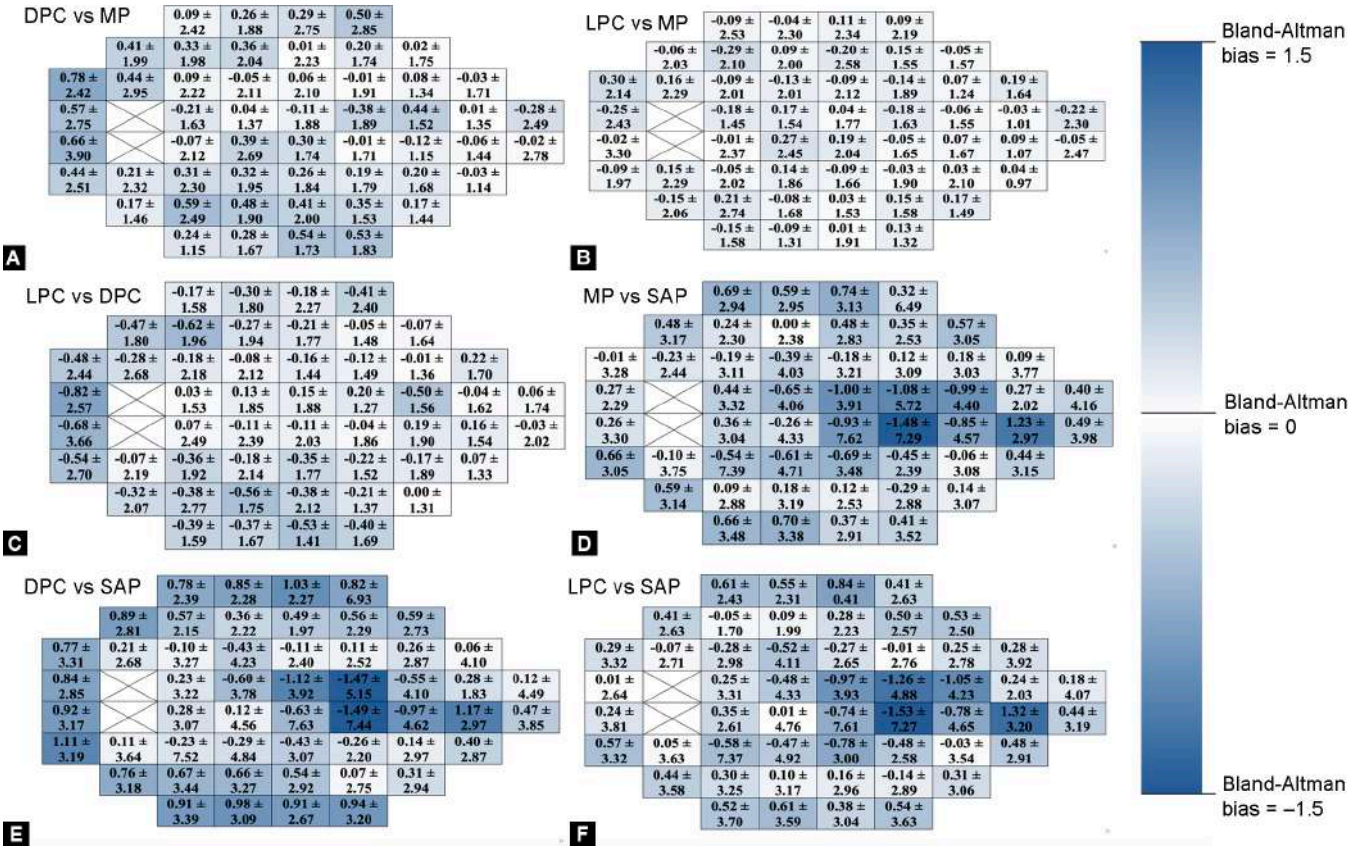
OCCP uses a large, flickering target, unlike SAP's standard white-on-white perimetry. Fundamental differences in target type and size, test setup, and test algorithm likely account for the wider 95% limits of agreement, in contrast to the narrower limits observed when comparing different computer monitors using OCCP. Additionally, since randomization only occurred between OCCP test variants while SAP was always performed first, some systematic differences between OCCP and SAP may be due to test order.

It is not uncommon for different perimetry devices to have varying perimetric sensitivities while still maintaining test–retest consistency and the ability to detect disease.[15] Based on this study's



Figs 4A to F: Bland-Altman plots (A–F) of MD values for online circular contrast perimetry (OCCP) and standard automated perimetry (SAP) tests. MacBook Pro laptop (MP) vs desktop personal computer (DPC) OCCP MD values are shown by (A) Laptop personal computer (LPC) vs DPC OCCP MD values are shown by (B) LPC vs MP OCCP MD values are shown by (C) MP OCCP vs SAP MD values are shown by (D) DPC OCCP vs SAP MD values are shown by (E) LPC OCCP vs SAP MD values are shown by (F). The continuous horizontal line represents the mean difference (bias) between tests; dashed and dotted horizontal lines represent the 95% limits of agreement (bias ± 1.96 SD). Black-colored circles represent controls, and white-colored circles represent glaucomatous eyes

outcomes, further modifications to OCCP's code are planned to improve accuracy and agreement with SAP. The data from this study will also be used to refine the normative range, ensuring the test remains reliable across monitors of different sizes. Ongoing testing, along with software improvements and user interface adjustments, is expected to enhance OCCP's usability and diagnostic accuracy.



Figs 5A to F: Heatmaps representing Bland-Altman bias and 95% limits of agreement for pointwise sensitivities across each 24-2 test location (left eye orientation) for online circular contrast perimetry (OCCP) and standard automated perimetry (SAP) tests. (A) Desktop personal computer (DPC) vs MacBook Pro laptop (MP); (B) Laptop personal computer (LPC) vs MP; (C) LPC vs DPC; (D) MP vs SAP; (E) DPC vs SAP; (F) LPC vs SAP. Pointwise sensitivities are represented as bias ± 1.96 × standard deviation

Several components of OCCP's software design may explain its reliability in testing across different computer displays. First, OCCP testing uses a flickering test target, with the chance of detection determined by the difference between its light and dark peaks and troughs. This differs from the approach used by most conventional perimetry machines and offers greater resilience to disparities in screen display and luminance. A study by Tahir et al. corroborates this observation, revealing that variance in background luminance across a device's screen had minimal impact on specified contrast levels.[48] Second, OCCP has an interactive screen calibration process that guides users to adjust their environment and device for optimal testing conditions. Variance in screen size is automatically detected by the application, which then sets an appropriate viewing distance—this is verified using a combination of blind spot localization and machine-learning-based webcam monitoring technology that identifies head position. The web application can also detect poorly calibrated monitors based on the first few test responses and adjust spot presentation accordingly to ensure consistent testing.

OCCP had significantly lower FN responses compared to SAP in both participant groups, which aligns with prior studies. Conversely, no statistically significant differences were observed between FP and FL rates. When reliability indices for OCCP tests performed on different computer monitors were compared, FP rates were significantly higher for LPC use compared to DPC and MP use ($p = 0.004$). Confounding factors such as differences in computer monitor interface and the participant's familiarity with the devices used may have contributed to this observation. It is important to note that direct comparisons of FP, FN, and FL results between OCCP and SAP tests in this study may be biased due to the nature of these testing parameters. FP rates depend heavily on test-specific factors such as the interval between stimuli, adaptation in the response window, and whether responses made within the first 200 milliseconds of stimulus presentation are counted as FPs.[49] For instance, shorter intervals can increase false positive results when assessed using traditional measurement techniques and thresholds.[50] False negative rates are determined by presenting suprathreshold stimuli at testing locations where threshold sensitivity has been measured.[50] As such, this depends greatly on how much brighter the stimulus is compared to the estimated threshold and whether testing includes any location with a threshold estimate or only those away from scotoma boundaries. Furthermore, the OCCP testing strategy uses a moving fixation target to maximize the sampling area regardless of screen size, causing the blind spot to be off-screen for half of the test duration. To address this, the frequency of fixation loss tests is doubled when the blind spot is on-screen. This distinct approach to blind spot testing could potentially impact the comparability of fixation loss rates between OCCP and SAP. Moreover, the constraints of conventional reliability criteria in VF assessment are well-recognized in the literature.[40,51–55] For instance, the patient's own visual function may influence reliability parameters during the test, with FN rates correlating strongly with increased disease severity rather than patient inattention.[41] In light of this, poor visual

acuity (LogMAR >0.7) warranted exclusion from the study to reduce the potential confounding effects of vision loss on testing results. Despite these potential shortcomings, we maintain the importance of using conventional metrics when evaluating new technology, consistent with our previous studies.[22–26]

In the future, the global provision of glaucoma care is expected to be enhanced by the widespread adoption of online and portable VF testing. This advancement is poised to offer advantages such as increased patient satisfaction, reduced healthcare costs, and alleviation of service strain.[56] In contrast to other digital perimetry devices, such as virtual reality headsets, OCCP requires no additional hardware and can be readily used on any widely accessible and easily replaceable computer or tablet. Its adaptability to at-home testing allows for more frequent perimetric assessment and earlier disease detection, particularly in the face of lengthy wait times and increased costs, which have contributed to significantly lower rates of VF testing in clinical practice compared to recommended guidelines.[57,58]

Significant logistical challenges remain if OCCP is to be successfully implemented reliably in a home environment. This study was conducted in-clinic under rigorous orthoptist supervision and controlled conditions, including the standardization of various environmental factors such as background noise, ambient lighting, and chair height. Such conditions do not emulate those found in a home environment, where distractions, suboptimal lighting, and the presence of other household members may compromise the integrity of testing results. Logistical issues may be further exacerbated in aging populations and individuals with physical disabilities or cognitive impairments, all of which can make navigating a digital interface more difficult. Personal device-based testing also introduces additional considerations compared to clinic-based perimetry, including a user's ability to log into an account online, respond to verbal cues, and follow pretest instructions, especially when no supervision is present. Encouragingly, a prior survey exploring OCCP user experience found no age-based differences in levels of concentration or discomfort, suggesting its user-friendliness for elderly patients.[24] However, further studies should explore OCCP usability in other population groups excluded from this study, such as individuals with reduced visual acuity and other disabilities that may pose obstacles to successfully performing machine-based perimetry.

The feasibility of OCCP testing at home will need to be explored in future studies, with corresponding solutions implemented to address potential challenges. Comprehensive patient education may play a key role in mitigating variability concerns and has previously been found to be feasible in studies evaluating remote perimetric technologies.[59] Modifications to the OCCP software could also help reduce interdevice variability, such as expanding pretest instructions and increasing the number of language options beyond the 18 currently available. Furthermore, as the software continues to scale and data collection expands across diverse populations, ongoing optimization of OCCP's normative database will enhance testing accuracy, ensuring that results are reliable and tailored to the specific context of use and the ethnic backgrounds of users worldwide.

Higher testing variability expected with the shift to home-based perimetry should also be considered in light of the increased testing frequency enabled by such modalities.[58] Prior studies suggest that despite greater variability and decreased compliance in at-home glaucoma monitoring, more frequent testing was ultimately more predictive of visual field progression than higher-quality but less frequent in-clinic assessments.[60,61] Faster testing durations may further facilitate this increased frequency, with OCCP consistently demonstrating shorter test times compared to SAP across our studies.[24–26] Shorter test durations also improve patient satisfaction and enhance compliance with VF testing. In this way, home-based perimetry may help identify patients requiring further follow-up in a timely manner, improving workflow efficiency and reducing healthcare system strain. However, further data is needed to fully understand the role of home-based perimetry in glaucoma care.[10,59,61]

This study has several limitations. Firstly, our entire participant population was recruited from patients attending a single-center ophthalmology practice for routine VF testing. This could introduce selection bias, as the characteristics of the recruited participants may not fully represent the general population. Future studies may benefit from a multisite approach, incorporating additional study centers or increasing randomization to enhance the generalizability of findings.

Data reliability may also be influenced by confounding variables such as user-related fatigue and fluctuations in concentration, particularly when participants complete multiple VF tests within a short timeframe. These factors are known to disproportionately affect patients with glaucoma compared to controls, potentially biasing results in favor of fields completed earlier in the testing sequence.[55,62] Conversely, test repeatability has been associated with improvements in perimetric outcomes and reliability scores due to the learning effect.[63,64] As a result, participants may have become more comfortable with the OCCP test after repeated attempts, leading to faster and more accurate performance. However, any potential impact on perimetric results is likely minimal, as we sought to mitigate biases by incorporating short breaks between tests and randomizing the testing order across devices.

Moreover, it is important to acknowledge the limitations of comparing OCCP outcomes to SAP. SAP is known to exhibit several undesirable test properties, most notably a substantial increase in test variability in areas of vision loss.[65] As such, achieving high agreement between OCCP and SAP may not always be the most meaningful metric for evaluating the clinical strengths of OCCP. Instead, prioritizing the optimization of OCCP's consistency across different monitors may be a more valuable objective, ensuring its reliability and usability in diverse testing environments.

Finally, while this study provides valuable insights into the agreeability of OCCP outcomes across different monitors, it is important to acknowledge that these results may not be fully generalizable to all monitors. The study utilized three distinct computers, representing a sample from a broader population of devices but not encompassing the entire spectrum of models in use. Each monitor configuration can vary in characteristics such as display technology, color calibration, and aging effects,[47] which could influence OCCP outcomes differently. These factors should be considered when interpreting the study's findings, and future research could explore the agreement of OCCP perimetric indices and sensitivity thresholds across a broader range of devices. This would allow for a more comprehensive understanding of its performance across diverse hardware configurations and contribute to refining progression analysis in the future.

Conclusion

In summary, OCCP demonstrates strong levels of agreement when tested on computer monitors of varying screen sizes and display characteristics, with differing levels of correlation to SAP perimetric sensitivities. Future studies will investigate the effectiveness of OCCP as a home-monitoring tool for glaucoma, focusing on its performance in an unsupervised setting and its feasibility for at-home use.

Clinical Significance

With ongoing refinement, OCCP's minimal hardware requirements and enhanced user experience could support the feasibility of online perimetry across multiple devices, expanding the scope of glaucoma detection and monitoring both in-clinic and at home. By improving access to visual field testing and enabling earlier disease detection, OCCP has the potential to address the growing healthcare demands of chronic eye diseases and improve patient outcomes.

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