Contrast Sensitivity in Primary Open-Angle and Pseudoexfoliation Glaucoma: Comparable Levels and Different Association Patterns

Umay Güvenç[1], Ahmet Kaderli[2], Basak Memis[2], Gülizar Soyugelen[1], Sema Tamer Kaderli[2], Sabahattin Sül[2]

ABSTRACT

Purpose: To compare contrast sensitivity (CS) in patients with primary open-angle glaucoma (POAG) and pseudoexfoliation glaucoma (PXG), and to investigate clinical, structural, and microvascular factors associated with CS.

Materials and Methods: This retrospective cross-sectional study included 41 patients (21 POAG, 20 PXG), matched for glaucoma stage. All participants underwent visual acuity (VA) assessment, intraocular pressure (IOP) measurement, visual field (VF) testing, optical coherence tomography (OCT), optical coherence tomography angiography (OCTA), and CS testing using the CSV-1000 system. Correlation, analysis of covariance, and multivariable regression analyses were performed. Benjamini–Hochberg false discovery rate correction was applied to correlation analyses.

Results: No significant differences were observed between the POAG and PXG groups with respect to IOP, VF indices, or OCT/OCTA parameters. CS values were comparable between POAG and PXG across all spatial frequencies, with no significant intergroup differences detected after adjustment for potential confounders (all $p>0.05$). VA emerged as the strongest independent predictor of CS across all models (all $p<0.01$), while higher IOP was associated with lower CS only at the lowest spatial frequency ($p=0.046$). CS showed stronger associations with VF parameters in POAG, whereas in PXG, CS was more closely related to OCTA-derived microvascular parameters.

Conclusion: POAG and PXG patients with similar glaucoma stage demonstrated comparable CS levels across spatial frequencies. However, the clinical factors associated with CS showed different association patterns between subtypes, with stronger associations with VF parameters in POAG and microvascular measures in PXG. CS may provide complementary functional information beyond conventional glaucoma assessments.

Keywords: contrast sensitivity, open angle glaucoma, optical coherence tomography angiography, pseudoexfoliative glaucoma, visual fields.

INTRODUCTION

Contrast sensitivity (CS) is a sensitive indicator of visual function and may reveal functional impairment in glaucoma even when best-corrected visual acuity (VA) remains relatively preserved.[1] Unlike VA, which measures the ability to discern high-contrast details, CS assesses the ability to detect subtle luminance variations relevant to tasks such as reading and night driving.[2]

Standard glaucoma assessments, including visual field (VF) testing and optical coherence tomography (OCT), provide essential structural and functional information; however, they may not fully capture deficits in real-world visual performance, particularly those related to CS.[3] Previous

1 Ankara Training and Research Hospital, Ophthalmology, Ankara, Türkiye

2 Muğla Sıtkı Koçman University, Ophthalmology, Muğla, Türkiye

Received: 19.02.2026
Accepted: 12.07.2026
TJ-CEO 2026; 21: 51-63
DOI: 10.37844/TJ-CEO.2026.21.7

Corresponding author:
Umay Güvenç
Email: umay.guvenc@gmail.com

Copyright © 2026 The author(s). This is an open-access article under the terms of the Creative Commons Attribution License (CC BY) which permits unrestricted use, distribution, and reproduction in any medium or format, provided the original work is properly cited.

studies have demonstrated that CS impairment can occur early in the disease course and is closely associated with patient-reported visual difficulties, even in the absence of marked VA loss.[4]

The relationship between CS and glaucoma is well documented, yet comparative analyses across glaucoma subtypes remain limited.[2, 5, 6] Primary open-angle glaucoma (POAG) and pseudoexfoliation glaucoma (PXG) differ in their clinical course and underlying mechanisms, raising the question of whether patterns of CS impairment and their associated clinical correlates may also differ.

Therefore, the present study aimed to evaluate contrast sensitivity in patients with POAG and PXG matched for disease stage, and to investigate the clinical, structural, and microvascular factors associated with CS impairment in these glaucoma subtypes.

MATERIAL AND METHODS

Study Design and Participants

This retrospective cross-sectional study included patients with POAG and PXG who were followed at a tertiary referral glaucoma clinic. POAG was diagnosed based on characteristic optic nerve head changes (rim thinning or notching), corresponding peripapillary retinal nerve fiber layer (RNFL) thinning beyond the 95% confidence interval on optical coherence tomography (OCT), and compatible visual field (VF) defects on Humphrey 24-2 SITA Standard testing. PXG was diagnosed by the presence of pseudoexfoliative material on slit-lamp examination in addition to the same structural and functional criteria. One eye per participant was randomly selected to avoid inter-eye correlation.

Inclusion criteria were: age ≥18 years, reliable VF tests (fixation loss <20%, false positives/negatives <15%), and high-quality OCT/OCT angiography (OCTA) scans (signal strength >6/10). Exclusion criteria included media opacities affecting CS (including cataract and posterior capsule opacification), ocular surface disease defined as requiring additional topical medication or diagnosed based on Schirmer testing, previous ocular surgery (except cataract), other optic neuropathies, inflammatory or neurological eye conditions, and high refractive errors (myopia > –6.00 D, hyperopia > +4.00 D). Glaucoma severity was classified as early, moderate, or advanced based on the Hodapp-Parrish-Anderson system.[7]

Ethics Approval and Informed Consent

Ethical approval was obtained from the local Institutional Ethics Committee, and the study was conducted in accordance with the Declaration of Helsinki. Given the retrospective design, written informed consent was waived by the ethics committee.

Ophthalmological Examinations

All participants underwent comprehensive ophthalmic evaluation, including best-corrected VA (BCVA, logMAR), intraocular pressure (IOP) via Goldmann applanation tonometry, and gonioscopy to assess the anterior chamber angle.

Spectral-domain OCT (Spectralis HRA+OCT, Heidelberg Engineering, Germany) was used to measure macular ganglion cell complex (GCC) and peripapillary RNFL thickness. OCTA scans (AngioVue RTVue-XR, Optovue Inc., USA) with 4.5 × 4.5 mm² disc-centered views assessed peripapillary and inside-disc vessel density (VD). Functional assessment included standard automated perimetry using the Humphrey Field Analyzer 24-2C (Carl Zeiss Meditec, Dublin, CA, USA), recording mean deviation (MD), pattern standard deviation (PSD), and Visual Field Index (VFI).

CS Measurement

CS was assessed using the CSV-1000 system (VectorVision Inc., Greenville, OH, USA) under photopic conditions at a testing distance of 2.5 m (8 feet). Measurements were obtained at spatial frequencies of 3, 6, 9, and 12 cycles per degree with appropriate refractive correction. Participants were encouraged to blink regularly during testing to maintain tear film stability.

Statistical Analysis

Statistical analyses were performed using IBM SPSS Statistics (version 22.0; IBM Corp., Armonk, NY, USA). Statistical significance was defined as $p < 0.05$. Data distribution and variance homogeneity were assessed using the Kolmogorov–Smirnov and Levene's tests, respectively. Between-group comparisons were conducted using the Mann–Whitney U test for continuous variables and chi-

square or Fisher's exact tests for categorical variables, as appropriate. Effect sizes (r) for Mann–Whitney U comparisons were calculated using the formula $r = Z/\sqrt{N}$ and interpreted according to Cohen's criteria.

Analysis of covariance (ANCOVA) was performed to adjust contrast sensitivity comparisons for potential confounders, including age, lens status, glaucoma stage, VA, RNFL and GCC thickness, MD, and VFI. Multiple linear regression analysis was used to identify independent predictors of contrast sensitivity. Multicollinearity was assessed using variance inflation factor (VIF) values, with a threshold of >3 indicating potential collinearity. Spearman correlation analysis was used to examine associations between contrast sensitivity and clinical, structural, and functional parameters. Given the large number of comparisons, Benjamini–Hochberg false discovery rate (FDR) correction was applied to all Spearman correlation analyses, and results surviving FDR correction are indicated in the corresponding tables.

RESULTS

The study included 41 patients (21 POAG, 20 PXG) with a mean age of 63.6 ± 14.0 years; 51.2% were female. Right eyes comprised 43.9% of cases (Tables 1 and 2).

Patients with PXG were significantly older than those with POAG (p=0.019), whereas VFI values were slightly higher in the POAG group (p=0.049). No significant intergroup differences were observed with respect to VA, IOP, VF-MD or PSD, RNFL, GCC, or OCT angiography–derived vessel density parameters (all p>0.05) (Table 1).

Contrast sensitivity values measured across spatial frequencies ranging from 3 to 12 cycles per degree were comparable between the POAG and PXG groups at all frequencies, with uniformly small effect sizes (r<0.1 for all comparisons) (Table 1).

Categorical variables are summarized in Table 2. Most patients were phakic (70.7%) and had early-stage glaucoma (53.7%). There were no significant differences between the groups regarding sex distribution, laterality, or lens status (all p>0.05) (Table 2).

Correlation analyses revealed strong inverse associations between VA and CS at all spatial frequencies in both groups (all p<0.05, FDR-corrected). VF parameters demonstrated moderate associations with CS in the POAG group. After FDR correction, MD associations with CS remained significant at higher spatial frequencies (B6–D12cpd), as did VFI and PSD at the highest spatial frequency (D12cpd). Associations between IOP and CS in the POAG group did not survive FDR correction. In the PXG group, no significant associations were observed between VF parameters and CS at any spatial frequency (Table 3).

The inverse associations between VA (logMAR) and CS across all four spatial frequencies in the overall cohort are illustrated in Figure 1. Spearman correlation coefficients ranged from r=−0.55 at A3cpd to r=−0.70 at D12cpd (all p<0.001), with stronger associations observed at higher spatial frequencies.

Structural parameters showed limited associations with CS overall. GCC thickness showed a nominally significant positive correlation with CS at the highest spatial frequency (D12cpd) in both the POAG (ρ=0.462, p=0.034) and PXG (ρ=0.455, p=0.044) groups; neither association survived FDR correction. No significant associations were observed between RNFL thickness and CS in either group at any spatial frequency (Table 4).

In the PXG group, CS showed consistent positive associations with multiple OCTA-derived microvascular parameters across spatial frequencies, all of which survived FDR correction, including whole image, inside disc, peripapillary, and inferior hemisphere vessel density metrics. Superior hemisphere vessel density was significantly associated with CS at B6–D12cpd in the PXG group after FDR correction, though this association did not survive FDR correction at A3cpd. In contrast, no significant associations between OCTA parameters and CS were observed in the POAG group (Table 4).

To compare CS between glaucoma subtypes while controlling for potential confounders, ANCOVA was performed with age, lens status, glaucoma stage, VA, RNFL and GCC thickness, MD, and VFI included as covariates. No significant difference in CS was detected between POAG and PXG at any spatial frequency (all p>0.05; $\eta^2 p<0.1$), indicating that the two groups had comparable CS levels after adjustment. VA was a significant covariate across all spatial frequencies (all p<0.01), confirming that VA independently contributes to CS variance regardless

Table 1. *Comparison of numerical clinical, structural, and functional parameters between glaucoma groups*

Variable	Overall (n = 41) mean ± SD, median (IQR)	POAG (n = 21) median (IQR)	PXG (n = 20) median (IQR)	p-value	Effect size (r)
Age (years)	63.56 ± 14.0, 69 (15)	63 (19)	72 (14)	**0.019**	0.365
VA (logMAR)	0.17 ± 0.24, 0.10 (0.22)	0.10 (0.20)	0.10 (0.30)	0.857	0.027
IOP (mmHg)	17.56 ± 8.87, 15 (12)	16 (14)	14 (9)	0.095	0.261
Visual field parameters					
MD (dB)	–3.45 ± 6.49, –3.37 (6)	–3.12 (6)	–3.57 (5)	0.602	0.081
PSD (dB)	3.22 ± 3.05, 2.42 (2)	2.42 (2)	2.40 (2)	0.192	0.204
VFI (%)	90.46 ± 15.59, 96 (8)	96 (7)	93 (9)	**0.049**	0.307
OCT measurements					
GCC (µm)	82.93 ± 12.78, 86 (20)	85 (20)	87 (21)	0.324	0.153
RNFL (µm)	82.34 ± 12.93, 85 (20)	85 (19)	82 (20)	0.057	0.297
Vessel density					
Whole image VD (%)	50.37 ± 6.03, 52.80 (10.70)	52.5 (11)	52.9 (9)	0.262	0.175
Peripapillary VD (%)	52.06 ± 7.08, 54 (11)	53.7 (10)	54.2 (12)	0.144	0.228
Superior hemisphere VD (%)	53.29 ± 7.02, 55.00 (3.40)	54.9 (3)	55.5 (4)	0.055	0.303
Inferior hemisphere VD (%)	50.63 ± 7.52, 51.30 (11.40)	50.7 (12)	52.2 (11)	0.379	0.137
Contrast sensitivity					
A3cpd	1.22 ± 0.28, 1.21 (0.34)	1.19 (0.32)	1.22 (0.35)	0.717	0.057
B6cpd	1.32 ± 0.38, 1.38 (0.64)	1.35 (0.62)	1.40 (0.65)	0.648	0.071
C9cpd	0.96 ± 0.32, 0.94 (0.64)	0.94 (0.63)	0.95 (0.66)	0.861	0.027
D12cpd	0.56 ± 0.32, 0.64 (0.64)	0.61 (0.63)	0.65 (0.67)	0.758	0.048

Abbreviations: VA, visual acuity; IOP, intraocular pressure; MD, mean deviation; PSD, pattern standard deviation; VFI, visual field index; GCC, ganglion cell complex; RNFL, retinal nerve fiber layer; VD, vessel density; A3–D12cpd, spatial frequencies (3–12 cycles/degree); POAG, primary open-angle glaucoma; PXG, pseudoexfoliative glaucoma; SD, standard deviation; IQR, interquartile range. Group comparisons were performed using the Mann–Whitney U test. Effect size was reported as $r = |Z| / \sqrt{N}$, where Z is the standardized Mann–Whitney U statistic and N is the total sample size. Statistically significant p-values are shown in bold.

of glaucoma subtype. GCC thickness showed a borderline association at the highest spatial frequency (D12cpd; p=0.055). Age was included in all models and did not reach statistical significance at any spatial frequency, indicating that the age difference between groups did not confound the main findings (Table 5).

Multiple linear regression analyses were also performed to determine whether glaucoma subtype independently predicted CS across spatial frequencies (A3cpd–D12cpd), adjusting for demographic, structural, and functional variables. All models were statistically significant ($p<0.05$) and demonstrated moderate explanatory power (adjusted $R^2=0.312–0.358$). Glaucoma subtype was not an independent predictor of CS at any spatial frequency (all $p>0.05$). VA emerged as the strongest independent predictor of CS across all models (all $p<0.01$), while higher IOP was associated with reduced CS at the lowest spatial frequency (A3cpd; p=0.046). GCC thickness showed a borderline association with CS at the highest spatial frequency (D12cpd; p=0.066), whereas RNFL thickness, VFI, glaucoma stage, age, sex, and lens status were not independently associated with CS. Variance inflation factor analysis revealed moderate collinearity for RNFL and GCC (VIF > 3), but low collinearity for VA (VIF = 1.362), supporting its independent influence on CS (Table 6).

DISCUSSION

Table 2. *Demographic and Clinical Characteristics of Study Population*

Variable	Overall (n=41, %)	POAG (n = 21, %)	PXG (n = 20, %)	χ^2	p-value
Gender					
- Female	21 (51.2%)	12 (57.1%)	9 (45.0%)	0.605	0.437
- Male	20 (48.8%)	9 (42.9%)	11 (55.0%)		
Laterality					
- Right Eye	18 (43.9%)	9 (42.9%)	9 (45.0%)	0.019	0.890
- Left Eye	23 (56.1%)	12 (57.1%)	11 (55.0%)		
Lens Status					
- Phakic	29 (70.7%)	17 (81.0%)	12 (60.0%)	2.172	0.141
- Pseudophakic	12 (29.3%)	4 (19.0%)	8 (40.0%)		
Glaucoma Stage					
- Early	22 (53.7%)	13 (61.9%)	9 (45.0%)	5.306	0.070
- Moderate	9 (22.0%)	6 (28.6%)	3 (15.0%)		
- Advanced	10 (24.4%)	2 (9.5%)	8 (40.0%)		

Abbreviations: POAG: primary open-angle glaucoma; PXG: pseudoexfoliative glaucoma. Data are presented as n (%).Chi-square (χ^2) analyses were performed between POAG and PXG groups.

Table 3. *Correlation analysis of contrast sensitivity with visual function parameters in glaucoma groups*

Parameter	CS Frequency	POAG (ρ, p)	PXG (ρ, p)
Visual acuity (logMAR)	A3cpd	**-0.534, 0.013*†**	**-0.607, 0.006*†**
	B6cpd	**-0.655, <0.001*†**	**-0.617, 0.005*†**
	C9cpd	**-0.671, <0.001*†**	**-0.699, <0.001*†**
	D12cpd	**-0.673, <0.001*†**	**-0.736, <0.001*†**
Intraocular Pressure (mmHg)	A3cpd	-0.481, 0.027*	-0.276, 0.209
	B6cpd	-0.178, 0.438	-0.210, 0.375
	C9cpd	-0.154, 0.503	-0.188, 0.424
	D12cpd	-0.120, 0.601	-0.143, 0.537
Visual Field-Mean Deviation (dB)	A3cpd	0.350, 0.120	0.201, 0.396
	B6cpd	**0.537, 0.012*†**	0.228, 0.334
	C9cpd	**0.556, 0.009*†**	0.432, 0.057
	D12cpd	**0.647, 0.002*†**	0.404, 0.077
Visual Field Index (%)	A3cpd	0.330, 0.145	0.076, 0.750
	B6cpd	0.447, 0.042*	0.256, 0.275
	C9cpd	0.459, 0.036*	0.250, 0.288
	D12cpd	**0.543, 0.011*†**	0.146, 0.540
Visual Field-Pattern Standard Deviation (dB)	A3cpd	-0.278, 0.223	0.240, 0.309
	B6cpd	-0.286, 0.209	0.051, 0.832
	C9cpd	-0.461, 0.035*	-0.026, 0.914
	D12cpd	**-0.519, 0.016*†**	-0.132, 0.579

Abbreviations: CS: contrast sensitivity; POAG: primary open-angle glaucoma; PXG: pseudoexfoliative glaucoma. CS frequencies: A3–D12cpd = 3 to 12 cycles/degree. Spearman's ρ and *p*-values are shown. Statistically significant p-values are shown in bold. * $p < 0.05$ (uncorrected). † Significant after Benjamini–Hochberg false discovery rate (FDR) correction across all 40 comparisons.

Table 4. *Correlation analysis of contrast sensitivity with structural and vascular parameters*

Parameter	CS Frequency	POAG (ρ, p)	PXG (ρ, p)
GCC thickness (µm)	A3cpd	0.189, 0.412	0.225, 0.345
	B6cpd	0.243, 0.286	0.312, 0.177
	C9cpd	0.377, 0.096	0.384, 0.082
	D12cpd	0.462, 0.034*	**0.455, 0.044***
RNFL thickness (µm)	A3cpd	0.136, 0.398	0.173, 0.488
	B6cpd	0.215, 0.312	0.248, 0.270
	C9cpd	0.278, 0.201	0.295, 0.198
	D12cpd	0.319, 0.122	0.341, 0.135
Whole image VD (%)	A3cpd	0.102, 0.660	**0.624, 0.003*†**
	B6cpd	0.273, 0.232	**0.620, 0.004*†**
	C9cpd	0.257, 0.262	**0.659, 0.002*†**
	D12cpd	0.255, 0.264	**0.651, 0.002*†**
Inside disc VD (%)	A3cpd	-0.018, 0.938	**0.681, 0.001*†**
	B6cpd	0.277, 0.224	**0.608, 0.004*†**
	C9cpd	0.060, 0.794	0.414, 0.070
	D12cpd	0.087, 0.707	**0.657, 0.002*†**
Peripapillary VD (%)	A3cpd	0.066, 0.776	**0.620, 0.004*†**
	B6cpd	0.192, 0.404	**0.644, 0.002*†**
	C9cpd	0.234, 0.308	**0.579, 0.008*†**
	D12cpd	0.245, 0.284	**0.630, 0.003*†**
Superior hemisphere VD (%)	A3cpd	0.146, 0.528	0.523, 0.018*
	B6cpd	0.289, 0.204	**0.579, 0.007*†**
	C9cpd	0.369, 0.100	**0.562, 0.010*†**
	D12cpd	0.356, 0.114	**0.545, 0.013*†**
Inferior hemisphere VD (%)	A3cpd	0.055, 0.813	**0.631, 0.004*†**
	B6cpd	0.231, 0.313	**0.665, 0.002*†**
	C9cpd	0.217, 0.345	**0.619, 0.005*†**
	D12cpd	0.230, 0.316	**0.586, 0.008*†**

Abbreviations: CS: contrast sensitivity; VD: vessel density; POAG: primary open-angle glaucoma; PXG: pseudoexfoliative glaucoma; GCC: ganglion cell complex; RNFL: retinal nerve fiber layer. CS frequencies: A3–D12cpd = 3 to 12 cycles/degree. Spearman's ρ and p-values are shown. Statistically significant p-values are shown in bold. * $p < 0.05$ (uncorrected). † Significant after Benjamini–Hochberg false discovery rate (FDR) correction across all 56 comparisons.

Table 5. *ANCOVA Results: Effect of Glaucoma Subtype and Covariates on Contrast Sensitivity*

Source	A3cpd		B6cpd		C9cpd		D12cpd	
	p	η^2p	p	η^2p	p	η^2p	p	η^2p
Glaucoma type (POAG vs. PXG)	0.860	0.001	0.151	0.068	0.685	0.006	0.568	0.011
Visual acuity (logMAR)	**0.003**	0.253	**0.001**	0.309	**0.009**	0.209	**0.003**	0.264
Age (years)	0.742	0.004	0.585	0.010	0.948	0.001	0.792	0.002
Lens status	0.087	0.095	0.487	0.016	0.307	0.035	0.276	0.039
Glaucoma stage	0.678	0.006	0.420	0.022	0.715	0.005	0.262	0.042
RNFL thickness (µm)	0.387	0.025	0.399	0.024	0.899	0.001	0.623	0.008
GCC thickness (µm)	0.090	0.093	0.317	0.033	0.170	0.062	0.055	0.117
Mean deviation (dB)	0.771	0.003	0.511	0.015	0.598	0.009	0.288	0.038
Visual field index (%)	0.779	0.003	0.591	0.010	0.994	0.001	0.653	0.007
Adjusted Means (SE) and Group Comparison								
POAG adjusted mean (SE)	1.213 (0.057)		1.239 (0.077)		0.944 (0.068)		0.544 (0.061)	
PXG adjusted mean (SE)	1.229 (0.060)		1.421 (0.082)		0.989 (0.072)		0.600 (0.065)	
Mean difference, POAG−PXG (p)	−0.016 (0.860)		−0.182 (0.151)		−0.044 (0.685)		−0.056 (0.568)	

Abbreviations: POAG: primary open-angle glaucoma; PXG: pseudoexfoliative glaucoma; RNFL: retinal nerve fiber layer; GCC: ganglion cell complex; SE: standard error; η^2p: partial eta squared; A3–D12cpd: spatial frequencies (3–12 cycles/degree). All models included glaucoma type as the between-subjects factor and age, lens status, glaucoma stage, visual acuity (logMAR), RNFL thickness, GCC thickness, mean deviation, and visual field index as covariates. Adjusted means are estimated at the grand mean of all covariates. Statistically significant p-values are shown in bold.

Table 6. *Multiple linear regression analysis for contrast sensitivity*

Variable	VIF	A3cpd			B6cpd			C9cpd			D12cpd		
		β	95% CI	p	β	95% CI	p	β	95% CI	p	β	95% CI	p
Adj. R^2 / Model p	—	**0.358 / 0.007**			**0.338 / 0.010**			**0.312 / 0.016**			**0.344 / 0.009**		
Glaucoma type (POAG vs. PXG)	1.587	−0.081	−0.401, 0.239	0.619	0.150	−0.185, 0.485	0.369	−0.017	−0.358, 0.324	0.919	0.080	−0.251, 0.411	0.629
VA (logMAR)	1.362	**−0.488**	**−0.784, −0.192**	**0.003**	**−0.586**	**−0.896, −0.276**	**0.001**	**−0.520**	**−0.836, −0.204**	**0.002**	**−0.552**	**−0.859, −0.245**	**0.001**
IOP (mmHg)	1.443	**−0.321**	**−0.643, −0.001**	**0.046**	−0.170	−0.508, 0.168	0.286	−0.258	−0.603, 0.087	0.116	−0.078	−0.422, 0.266	0.622
GCC thickness (µm)	3.319	0.390	−0.085, 0.865	0.106	0.217	−0.281, 0.715	0.369	0.323	−0.186, 0.832	0.192	0.451	−0.057, 0.959	0.066
RNFL thickness (µm)	3.444	−0.236	−0.701, 0.229	0.329	0.130	−0.357, 0.617	0.594	−0.103	−0.600, 0.394	0.680	−0.147	−0.644, 0.350	0.545
Lens status	1.476	0.271	−0.037, 0.579	0.092	0.086	−0.234, 0.406	0.590	0.108	−0.220, 0.436	0.507	0.117	−0.202, 0.436	0.465
Age (years)	1.986	0.021	−0.382, 0.424	0.909	−0.068	−0.445, 0.309	0.714	0.073	−0.287, 0.433	0.701	0.022	−0.337, 0.381	0.906
Glaucoma stage	1.743	−0.042	−0.382, 0.298	0.806	0.186	−0.173, 0.545	0.287	0.086	−0.276, 0.448	0.628	0.180	−0.177, 0.537	0.302
VFI (%)	1.366	−0.155	−0.601, 0.291	0.311	0.012	−0.433, 0.457	0.940	0.019	−0.379, 0.417	0.904	0.177	−0.220, 0.574	0.253
Sex	1.334	−0.049	−0.343, 0.245	0.745	−0.202	−0.510, 0.106	0.191	−0.203	−0.518, 0.112	0.195	−0.111	−0.416, 0.194	0.464

Abbreviations: POAG, primary open-angle glaucoma; PXG, pseudoexfoliative glaucoma; VA, visual acuity; IOP, intraocular pressure; VFI, visual field index; RNFL, retinal nerve fiber layer; GCC, ganglion cell complex; β, standardized beta coefficient; CI, 95% confidence interval of standardized β; VIF, variance inflation factor; A3–D12cpd, spatial frequencies (3–12 cycles/degree). Separate models were fitted for each spatial frequency. All models included glaucoma type, age, sex, lens status, IOP, glaucoma stage, VFI, RNFL thickness, GCC thickness, and VA as predictors. Statistically significant p-values are shown in bold.

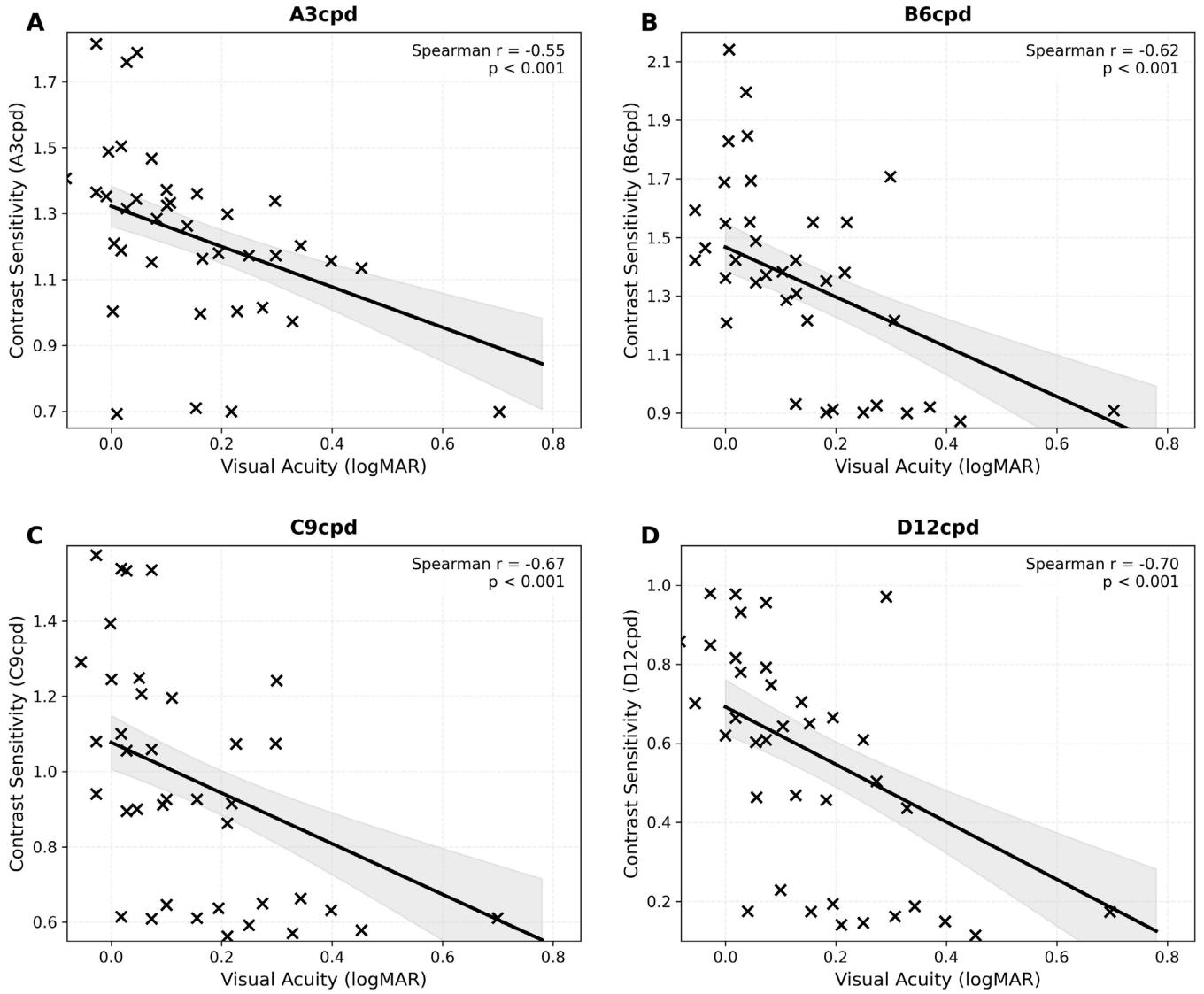

Figure 1 *Scatter plots depicting the Spearman correlation between visual acuity (logMAR) and contrast sensitivity at four spatial frequencies in the overall glaucoma cohort (n = 40). Each panel represents a spatial frequency: (A) 3 cpd (A3cpd), (B) 6 cpd (B6cpd), (C) 9 cpd (C9cpd), and (D) 12 cpd (D12cpd). Each × symbol represents one patient. The solid line indicates the linear regression fit line and the shaded area represents the 95% confidence interval. Spearman r and p values are shown for each panel. One patient with logMAR > 0.8 was excluded from the figure for display purposes; Spearman correlations were calculated on the full cohort (n = 40).*

In this study, CS did not differ significantly between POAG and PXG patients matched for disease severity; however, the clinical factors associated with CS differed between the two groups. By integrating structural, functional, and vascular parameters—including OCTA-derived metrics—our analysis provides a more comprehensive perspective on the factors contributing to CS in each subtype.

Contrast sensitivity is a fundamental component of human vision and is often impaired in glaucoma, with severity reflecting disease progression.[6] This likely results from damage to magnocellular and parvocellular pathways sensitive to luminance contrast, making CS testing a valuable tool for detecting early functional loss.[8] Studies report CS reduction even in early glaucoma, sometimes preceding measurable changes in VA.[9, 10] Despite its clinical relevance, CS is underused in routine glaucoma evaluations, as diagnostic protocols prioritize VF testing.[1] Given its ability to detect deficits before significant VF loss, CS assessment may provide earlier, functionally meaningful insights into visual impairment and quality-of-life impact.

CS did not differ significantly between POAG and PXG after adjustment for potential confounders, supporting comparable CS levels between glaucoma subtypes. Consistently, Wilensky et al.[12] reported an association between CS reduction and VF loss in glaucoma patients with preserved VA, without differentiating between glaucoma subtypes. Similarly, Rao et al.[1] also compared CS across glaucoma subtypes in a smaller cohort limited to advanced disease. While no significant differences were observed using the Pelli–Robson test, the Spaeth/Richman test demonstrated quadrant-specific differences, whereas central CS remained comparable. Collectively, these findings suggest that CS impairment may be a common feature of glaucoma, with observed differences potentially influenced more by testing methodology and disease characteristics than by glaucoma subtype alone.

Our findings suggest that in POAG, CS was more closely associated with VF parameters, supporting a relationship between contrast sensitivity and functional visual impairment. This is consistent with prior studies reporting greater CS deficits in POAG patients with more severe VF damage, supporting an association between CS and functional visual impairment.[11] In addition, CS at higher spatial frequencies (B6–D12cpd) demonstrated significant associations with MD in the POAG group after FDR correction. Similar observations by Wilensky[12] and Bambo[13] further support the complementary role of CS alongside VF testing in functional assessment. However, both Fatehi et al.[6] and the present study found only limited overall correlations between global VF indices and CS, suggesting that these measures capture partially distinct dimensions of visual dysfunction. In contrast, Rao et al.,[1] who focused specifically on advanced glaucoma, reported a stronger relationship between CS and MD, although differences in disease severity and CS testing methods may partly explain the variation in findings. Overall, these findings highlight the complex relationships among CS, structural damage, and visual function in glaucoma and support a multimodal approach to functional evaluation.

In PXG, CS showed more consistent associations with OCTA-derived vascular metrics, particularly peripapillary vessel density, indicating a closer relationship with microvascular parameters. Vascular contributions, including impaired blood flow, endothelial dysfunction, and disrupted autoregulation, have been well-documented in PXG.[14,15] The accumulation of pseudoexfoliative material within vascular structures may further compromise microcirculation, potentially contributing to both structural injury and functional visual impairment. Supporting this concept, previous OCTA studies have demonstrated reduced peripapillary and macular vessel density in PXG, even when disease stage is comparable.[16-18] Moreover, Harris et al.[19] reported an association between cerebral blood flow and CS in glaucoma, further underscoring the broader contribution of vascular factors to CS impairment.

PXG patients were significantly older than those with POAG, consistent with the known age-related increase in PXG prevalence.[20] Although age could theoretically influence CS outcomes, it was not independently associated with CS in either the ANCOVA or multivariate regression analyses, indicating that the age difference between groups did not confound the main findings. Nevertheless, given the relatively small sample size, a residual confounding effect cannot be completely excluded.

GCC thickness showed a nominally significant positive correlation with CS at the highest spatial frequency (D12cpd) in both groups; however, neither association

survived FDR correction. Previous studies have reported associations between GCC thickness and CS in POAG patients. Fatehi et al.[6] and Pang et al.[21] demonstrated significant relationships between structural retinal damage and CS, particularly at higher spatial frequencies. These findings suggest that structural measures such as GCC thickness may contribute to CS performance, although the strength and consistency of these associations appear to vary across glaucoma populations and analytical approaches.

In the present study, higher IOP was associated with lower CS only at the lowest spatial frequency. Previous studies have similarly suggested that elevated IOP may negatively influence CS, especially at lower spatial frequencies.[22-24] However, the relationship between IOP and CS remains inconsistent across studies. While Fatehi et al.[6] reported no significant association, Kuerten et al.[25] demonstrated improvement in CS following IOP reduction. Given that the IOP association in our study was limited to a single spatial frequency, these findings should be interpreted cautiously.

Glaucoma patients with preserved VA often experience significantly reduced CS compared to healthy individuals, emphasizing the limitations of VA assessments alone in evaluating functional vision.[6] Rao et al.[1] noted a negative correlation between CS and VA, though it was not statistically significant, possibly due to their exclusively pseudophakic sample minimizing lens-related effects. In our study, VA consistently emerged as the strongest CS predictor, suggesting CS impairment reflects broader visual dysfunction beyond subtype differences. This aligns with research showing binocular VA and CS are closely tied to daily visual performance, supporting the value of CS in clinical assessments.[2]

The retrospective cross-sectional design and relatively small sample size represent the main limitations of this study. Furthermore, the multiple linear regression models incorporated a relatively large number of predictor variables relative to the sample size, which may have increased the risk of overfitting. Although the use of adjusted R^2 and variance inflation factor analysis partially mitigates this concern, the regression findings should be interpreted as exploratory and require validation in larger prospective cohorts. In addition, CS was assessed using the CSV-1000 system, which evaluates discrete photopic spatial frequencies but does not capture mesopic or scotopic performance or provide a continuous CS function, potentially overlooking subtle deficits. More comprehensive tools, such as the Freiburg Visual Acuity and Contrast Test or quick CSF, may allow broader functional assessment. Although media opacities and ocular surface disease were among the exclusion criteria, the presence of subclinical lens changes may have exerted a residual confounding effect on CS measurements. While high refractive errors were excluded, a more limited refractive range could have further reduced optical variability. Lens status was included as a covariate in the analyses; however, the duration of pseudophakia was not recorded. Additionally, pupil size was not assessed, which represents a potential uncontrolled optical confounder.

Despite its limitations, this study provides important insights into CS impairment in POAG and PXG. Unlike prior research focused on structural damage, we explored CS in relation to functional, structural, and vascular parameters in each subtype. Our findings highlight CS assessment as a valuable tool for detecting functional deficits not captured by VA or VF tests. The observed associations between CS and microvascular parameters in PXG further support the relevance of vascular factors in this subtype and encourage further investigation into their clinical implications.

In conclusion, CS levels were comparable between POAG and PXG patients matched for disease severity. Nevertheless, the clinical factors associated with CS showed different association patterns between the two groups: in POAG, CS showed stronger associations with visual field parameters, whereas in PXG, microvascular measures were more prominently associated with CS. These findings highlight the potential value of CS as a complementary functional measure in glaucoma evaluation, and warrant validation in larger prospective cohorts.

Acknowledgements: The authors thank all clinical personnel involved in patient care and data acquisition during the study period.

REFERENCES

1. Rao A, Pal A and Mohapatra S. Spaeth/Richman Contrast Sensitivity in Staging Glaucoma. *Transl Vis Sci Technol* 2020; 9: 39. 20201222. DOI: 10.1167/tvst.9.13.39.
2. Richman J LL, Lankaranian D et al. Importance of visual acuity and contrast sensitivity in patients with glaucoma. *Arch Ophthalmol* 2010; 128: 1576–1582.
3. Lin S, Mihailovic A, West SK, et al. Predicting Visual Disability in Glaucoma With Combinations of Vision Measures. *Transl Vis Sci Technol* 2018; 7: 22. 20180413. DOI: 10.1167/tvst.7.2.22.
4. Owsley C. Contrast sensitivity. *Ophthalmol Clin North Am* 2003; 16: 171-177. DOI: 10.1016/s0896-1549(03)00003-8.
5. Richman J, Zangalli C, Lu L, et al. The Spaeth/Richman contrast sensitivity test (SPARCS): design, reproducibility and ability to identify patients with glaucoma. *Br J Ophthalmol* 2015; 99: 16-20. 20140722. DOI: 10.1136/bjophthalmol-2014-305223.
6. Fatehi N, Nowroozizadeh S, Henry S, et al. Association of Structural and Functional Measures With Contrast Sensitivity in Glaucoma. *Am J Ophthalmol* 2017; 178: 129-139. 20170323. DOI: 10.1016/j.ajo.2017.03.019.
7. Hodapp EA, Parrish RK and Anderson DR. Clinical Decisions In Glaucoma. In: 1993.
8. McKendrick AM, Sampson GP, Walland MJ, et al. Contrast sensitivity changes due to glaucoma and normal aging: low-spatial-frequency losses in both magnocellular and parvocellular pathways. *Invest Ophthalmol Vis Sci* 2007; 48: 2115-2122. DOI: 10.1167/iovs.06-1208.
9. Wood JM and Lovie-Kitchin JE. Evaluation of the efficacy of contrast sensitivity measures for the detection of early primary open-angle glaucoma. *Optom Vis Sci* 1992; 69: 175-181. DOI: 10.1097/00006324-199203000-00002.
10. Liu JL, McAnany JJ, Wilensky JT, et al. M&S Smart System Contrast Sensitivity Measurements Compared With Standard Visual Function Measurements in Primary Open-Angle Glaucoma Patients. *J Glaucoma* 2017; 26: 528-533. DOI: 10.1097/IJG.0000000000000659.
11. Jang JY and Lee EJ. Contrast sensitivity in glaucoma patients with visual field defects at different locations. *Sci Rep* 2023; 13: 40. 20230102. DOI: 10.1038/s41598-022-27262-z.
12. J. T. Wilensky AH, and R. P. Mills,. Comparison of contrast sensitivity visual acuity, and Humphrey visual field testing in patients with glaucoma. *Transactions of the American Ophthalmological Society* 2001; 99: 213-218.
13. Bambo MP, Ferrandez B, Guerri N, et al. Evaluation of Contrast Sensitivity, Chromatic Vision, and Reading Ability in Patients with Primary Open Angle Glaucoma. *J Ophthalmol* 2016; 2016: 7074016. 20161031. DOI: 10.1155/2016/7074016.
14. Galassi F, Giambene B and Menchini U. Ocular perfusion pressure and retrobulbar haemodynamics in pseudoexfoliative glaucoma. *Graefe's Archive for Clinical and Experimental Ophthalmology* 2008; 246: 411-416.
15. Chatziralli I, Milionis I, Christodoulou A, et al. The Role of Vessel Density as Measured by Optical Coherence Tomography Angiography in the Evaluation of Pseudoexfoliative Glaucoma: A Review of the Literature. *Ophthalmol Ther* 2022; 11: 533-545. 20220224. DOI: 10.1007/s40123-022-00483-1.
16. Suwan Y, Geyman LS, Fard MA, et al. Peripapillary Perfused Capillary Density in Exfoliation Syndrome and Exfoliation Glaucoma versus POAG and Healthy Controls: An OCTA Study. *Asia Pac J Ophthalmol (Phila)* 2018; 7: 84-89. 20171122. DOI: 10.22608/apo.2017318.
17. Subasi S, Yuksel N, Basaran E, et al. Comparison of vessel density in macular and peripapillary regions between primary open-angle glaucoma and pseudoexfoliation glaucoma using OCTA. *International Ophthalmology* 2021; 41: 173-184. DOI: 10.1007/s10792-020-01564-5.
18. Park JH, Yoo C, Girard MJA, et al. Peripapillary Vessel Density in Glaucomatous Eyes: Comparison Between Pseudoexfoliation Glaucoma and Primary Open-angle Glaucoma. *J Glaucoma* 2018; 27: 1009-1016. DOI: 10.1097/ijg.0000000000001062.
19. Harris A, Siesky B, Zarfati D, et al. Relationship of Cerebral Blood Flow and Central Visual Function in Primary Open-angle Glaucoma. *Journal of Glaucoma* 2007; 16: 159-163.
20. Greslechner R, Helbig H and Spiegel D. [Secondary open-angle glaucoma: pseudoexfoliative glaucoma, pigmentary glaucoma and neovascular glaucoma]. *Ophthalmologe* 2022; 119: 425-438. 20220401. DOI: 10.1007/s00347-022-01609-3.
21. Pang R, Peng J, Cao K, et al. Association between contrast sensitivity function and structural damage in primary open-angle glaucoma. *British Journal of Ophthalmology* 2024; 108: 801-806. DOI: 10.1136/bjo-2023-323539.
22. Waisbourd M, Parker S, Ekici F, et al. A prospective, longitudinal, observational cohort study examining how glaucoma affects quality of life and visually-related function over 4 years: design and methodology. *BMC Ophthalmol* 2015; 15: 91. 20150801. DOI: 10.1186/s12886-015-0088-x.
23. Ekgardt VF and Dorofeev DA. [Spatial contrast sensitivity in patients with primary open-angle glaucoma and ocular hypertension]. *Vestn Oftalmol* 2020; 136: 25-35. DOI: 10.17116/oftalma202013601125.
24. Owidzka M, Laudanska-Olszewska I and Omulecki W. Contrast sensitivity assessment in primary open angle glaucoma and ocular hypertension. *Klin Oczna* 2016; 118: 7-10.
25. Kuerten D, Fuest M, Walter P, et al. Association of ocular blood flow and contrast sensitivity in normal tension glaucoma. *Graefes Arch Clin Exp Ophthalmol* 2021; 259: 2251-2257. 20210521. DOI: 10.1007/s00417-021-05235-8.