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Effects of aging on optical quality and visual function

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Background: We assessed the effects of aging on visual function and optical quality in a healthy adult population and provide reference values for different age ranges.
Methods: We conducted a prospective study with 198 healthy volunteers from 31 to 70 years of age. The visual acuity (VA) and contrast sensitivity (CS) at 3, 6, 12 and 18 cycles per degree (cpd) frequencies were assessed, together with values of optical quality and intraocular scattering obtained with a double-pass system (Optical Quality Analysis System – OQAS), specifically the modulation transfer function cutoff frequency (MTF_{cutoff}), the Strehl ratio, the OQAS values (OV) at contrasts of 100, 20 and nine per cent and the objective scatter index (OSI). We studied the change of these variables with age and obtained standard values for optical quality and intraocular scattering parameters for four age groups: 31 to 40, 41 to 50, 51 to 60 and 61 to 70 years.
Results: We found significant correlations between age and all variables analysed and significant differences among the age groups considered except for CS (3 cpd) ($p = 0.067$). Ageing particularly affected low-contrast parameters, such as the OV nine per cent and the OSI, which decreased to 37 and 50 per cent of their original values, respectively. The OSI was found to provide high sensitivity and specificity values, when healthy and caratactous eyes were considered. The results suggest that optical deficits are compensated until 50 years of age with sensory and perceptual factors, as smaller changes were found for visual function than for objective measurements of optical quality and intraocular scattering.
Conclusions: Measures of optical quality assessed by subjective psychophysical and objective techniques varied differently with age. Values obtained for each age group can be used to determine normal limits of optical quality and intraocular scattering for diagnosis of ocular conditions.

Key words: age, contrast sensitivity, intraocular scattering, modulation transfer function, optical quality, visual acuity, visual function

Age-related changes in visual function have been extensively investigated using psychophysical tests. For example, visual acuity (VA) in normal healthy eyes reaches optimal levels in the mid-twenties and displays gradual linear decline thereafter. Similarly, older adults have impaired contrast sensitivity (CS) at intermediate and high spatial frequencies, which starts at the age of 30 and progresses into old age,[1] a deficit that increases with increasing spatial frequency.[2,3] This decline has been attributed to a decrease in retinal illuminance in older eyes; however, reduced visual performance has also been associated with factors beyond observable structural changes in the eye that affect sensory and perceptual performance, such as the density of photoreceptors, the efficacy of phototransduction and photopigment regeneration and the quality of synaptic transmission and signal processing in the retina and visual pathway.[2,4]

More recently, new objective systems to analyse optical quality have been used to better elucidate the effects of aging upon vision; however, methods such as wavefront sensors and double-pass systems[5] only consider optical changes and do not take into account posterior neural and perceptual factors. Guirao and colleagues[6] used a double-pass system to determine the modulation transfer function (MTF) as a function of age in 20 participants and found that optical performance declined with age (a reduced MTF), which suggests age-related decline in CS could be partially explained by an increase in higher-order aberrations[7,8] in particular changes in spherical aberration and coma of the anterior corneal surface. Changes in the aberrations of the crystalline lens with age and the loss of the balance between corneal and lenticular aberrations present during youth also contribute to the progressive reduction of retinal image quality.

Neural factors may also play a role in age-related changes in vision, as older adults still display reduced CS compared to younger adults when monochromatic aberrations are corrected using adaptive optics.[9] Optical variables other than monochromatic aberrations such as retinal straylight, which causes disability glare, may play a role.[10] Van den Berg and colleagues[11] found that straylight measured with a psychophysical compensation comparison method increases with age, doubling at 65 years of age and trebling by the age of 77 relative to that in a newborn's eye.

The study of the optical quality of the eye has become more widespread since the commercialisation of a new clinical instrument based on the double-pass technique (Optical Quality Analysis System 2 [OQAS 2], Visiometrics S L, Terrassa, Spain),[12,13] which has been used in the evaluation of patients undergoing refractive and cataract surgery.[14–19] Previously, we reported on the optical quality and intraocular scatter values in healthy young subjects measured with this system.[20] The reference values obtained allow the discrimination of healthy from abnormal eyes, in which the optical quality or sensory function is impaired. Kamiya and colleagues[21] conducted a similar study and found significant negative correlations between parameters related to the optical quality of the eye and age and a significant positive correlation between intraocular scattering and age. Similarly, Miao and colleagues[22] examined interocular scatter and found that high myopia has more influence on retinal image quality and scattering than moderate and low myopia.

None of the former studies provide reference values for optical quality and intraocular scattering parameters for a wide range of ages. Furthermore, no study has analysed the relationship between the decline in objective parameters and psychophysical deficits in relation to the characteristics of visual function, such as CS at different spatial frequencies, which might also be affected by sensory and perceptual processing. We analyse the decline of the optical quality of the eye and the increase of intraocular scattering, as a consequence of aging and provide normal values beyond 30 years of age. We compare these values with the decline of visual performance with age to establish reference values for the optical quality of the eye and intraocular scattering.

METHODS

This prospective study was conducted on volunteers aged 31 to 70 years from the University Vision Centre (CUV) of the Technical University of Catalonia (Terrassa, Barcelona, Spain) between September 2009 and June 2014. Written informed consent was obtained before any examination along with ethics committee approval. The study followed the tenets of the Declaration of Helsinki (2004 Tokyo revision).

Participants underwent a comprehensive ophthalmic examination, including anterior segment observation with slitlamp, fundus photographs with a non-mydriatic retinal camera (model TRC-NW6S, Topcon, Tokyo, Japan), assessment of intraocular pressure with a non-contact tonometer, retinoscopy and manifest subjective refraction. Visual acuity was measured with a Bailey–Lovie chart and CS with the CSV-1000E test (VectorVision, Greenville, Ohio, USA) under photopic conditions at frequencies of 3, 6, 12 and 18 cycles per degree (cpd).

Participants were enrolled in the study only if they had normal age-related lens changes (that is, nuclear sclerotic changes only). Those diagnosed with significant cataracts by the ophthalmological service at the University Vision Centre were excluded. Other criteria for exclusion were corneal opacities, anterior segment disease, abnormal posterior pole evaluation, intraocular pressure values over 21 mmHg, abnormal tear film and previous ocular surgery. Inclusion criteria were eyes with VA of at least 6/7.5 and with spherical equivalent (SE) and cylinder (C) under 3.00 D. Strict exclusion criteria for refractive errors were imposed to avoid issues of colinearity between refraction and optical quality as well as refraction and age previously reported.[22,23]

A total of 198 subjects participated in the study. From them, 36 were excluded due to refractive errors in both eyes, 52 to the presence of significant cataract and eight to other reasons, which were mainly corneal or retinal pathology or previous ocular surgery. From the remaining participants only one eye was included in the analysis, which was randomly selected.

Optical quality and intraocular scattering measurements

Optical quality and intraocular scatter were measured using the OQAS 2 system. The following parameters related to the MTF were obtained:[20] the MTF_{cutoff}, the Strehl ratio and the OQAS values (OV) at 100, 20 and nine per cent contrasts. The objective scatter index (OSI) was also measured.[15,18] A 4.0 mm artificial pupil was used to compute these parameters.

The MTF_{cutoff} is calculated as that corresponding to a 0.01 MTF value, as there is background noise in the profile computed from the real recorded double-pass image. The system computes the Strehl ratio in two dimensions as the ratio between the areas under the MTF curve of the measured eye and that of the aberration-free eye.[6] The three OVs are normalised values of three spatial frequencies that correspond to the MTF values of optical quality for three contrast conditions used in ophthalmological practice: 100 per cent (OV100%), 20 per cent (OV20%) and nine per cent (OV9%). These values can be used to obtain more specific information on the performance of the eye's optics at different contrasts. This information is less obvious when more general parameters that integrate the information of all available spatial frequencies are considered. OV100% is directly related to the MTF_{cutoff} (MTF_{cutoff} divided by 30 cpd) and therefore, to the patient's VA, although it is not affected by retinal and neural factors. OV20% and OV9% are computed from smaller frequencies linked to 0.05 and 0.1 MTF values, respectively. In addition, these two last frequencies have been normalised, so that the values obtained can be comparable to standard decimal VA values (Figure 1 top). The OSI parameter quantifies the 'near-angle' scattering and is computed as the ratio of the amount of light within an annular area of 12 and 20 minutes of arc (inner and outer radii) and that recorded within one minute of arc of the central peak in the acquired double-pass image (Figure 1 bottom). Although, it does not include information from regions outside one degree of arc of the point spread function of the eye as proposed by other authors,[24–26] it has been shown to correlate with cataract gradation (LOCS III) in several studies[15,18] provided that lower order aberrations are corrected. Thus, it quantifies the objective contribution of forward scatter that impairs visual performance.

Statistical analysis

The Kolmogorov–Smirnov test was used to evaluate the normal distribution of all variables analysed: the psychophysical variables (VA and CS) as well as the optical quality and intraocular scattering parameters (MTF_{cutoff}, Strehl ratio, OV at 100, 20 and nine per cent contrasts and OSI).

The correlations of variables with age were assessed using either Pearson's or Spearman's correlation coefficients for those with normal and non-normal distributions, respectively. Partial and simple correlations controlling and not controlling for age between the optical quality and intraocular scatter and the psychophysical variables were performed.

In addition, to study the significance of changes in the age ranges studied, the subjects were divided into four age groups: 31 to 40, 41 to 50, 51 to 60 and 61 to 70 years. Although such grouping is arbitrary, several authors have used this approach to examine the changes in the visual function with age.[6,8,27,28]

Balanced analysis of variance was used to analyse the influence of gender, right and left eyes, spherical equivalent and cylinder

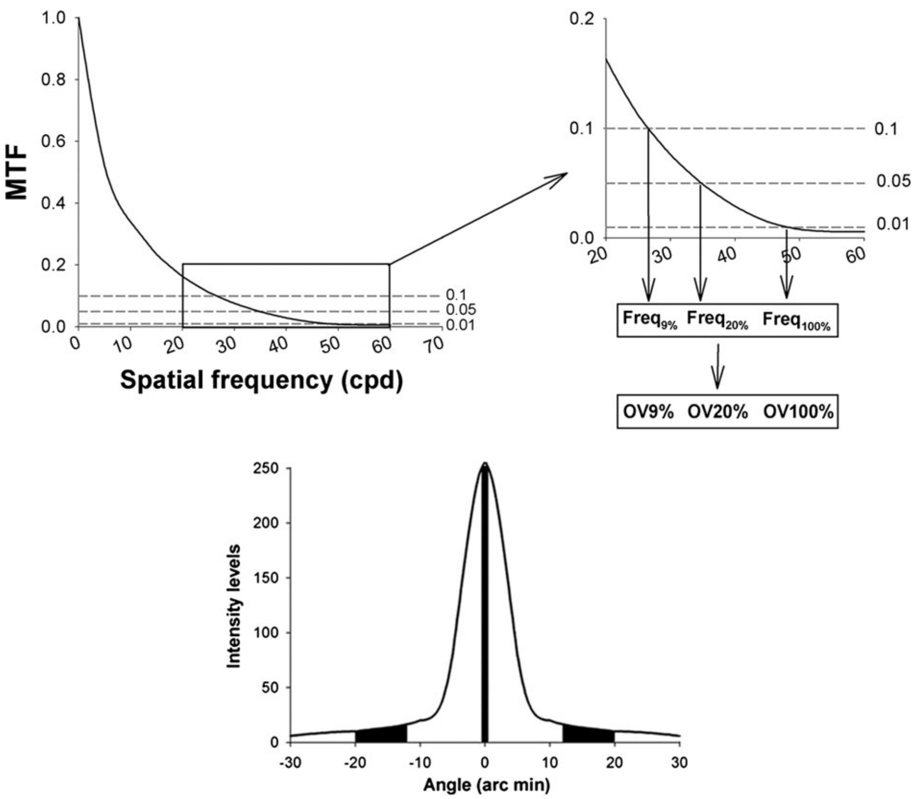

Figure 1. Schematic diagram showing the computation of Optical Quality Analysis System (OQAS) values, OV100%, OV20% and OV9% from the modulation transfer function (MTF) curve. The three spatial frequencies from which they are derived ($freq_{100\%}$ or MTF_{cutoff}, $freq_{20\%}$, $freq_{9\%}$), which correspond to MTF values of 0.01, 0.05 and 0.1, respectively, are shown (top). The computation of the objective scatter index from the double-pass image acquired is also shown (bottom).

among age groups. An analysis of variance with a Bonferroni post-hoc analysis was performed to establish significant differences among age groups, when parametric analysis was possible. For non-parametric data, the Kruskal–Wallis and Jonckheere–Terpstra's tests were used.

The results are shown as mean and standard deviation (SD). Additionally, the corresponding range (minimum and maximum) is also given for variables related to optical quality and intraocular scatter. The lower limits of normal values for optical quality parameters are defined at the 95 per cent confidence interval by mean -1.96 × SD. For the intraocular scattering the upper limits of normal values are calculated as the mean + 1.96 × SD. Since the excluded population showed a strong asymmetry related to age, mostly between 61 to 70 years of age, the sensitivity (Sn) and specificity (Sp) of normal values were also calculated for the group of patients between 61 and 70 years who met the refraction criteria but were previously excluded because of an incipient cataract, that is, with LOCS III indexes lower than 4, had been detected. Sensitivity was calculated from eyes with diagnosed cataract that were found to have pathology and specificity from healthy eyes that were found to have no pathology.

Finally, to study the decrease of the optical quality parameters and the increase of intraocular scatter with age, non-linear regression models were used from which the coefficients of determination were computed (r^2). For the former, it was as follows:

$$P_y = C_1 \cdot \left(1 - 0.5 \cdot \left[\frac{y}{C_2}\right]^{C_3}\right) \qquad (1)$$

where y is the age, P_y is the optical quality parameter (MTF_{cutoff}, Strehl ratio, OV at 100, 20 or nine per cent and coefficients C_1, C_2 and C_3 are estimated by means of a least-squares fit). Specifically, C_1 represents the value of P_y as a newborn, C_2 is the age that P_y is halved at, while C_3 is related with the exponential way in which P_y decreases.

For the OSI parameter, the value of which increases with age, the model used was as shown below:

$$OSI_y = C_1 \cdot \left(1 + \left[\frac{y}{C_2}\right]^{C_3}\right) \qquad (2)$$

In this case, y is the age at which the OSI parameter doubles its value.

Data were analysed using the SPSS software for Windows (V.20.0). A value of $p < 0.05$ was considered statistically significant.

RESULTS

A total of 102 (51 right and 51 left) healthy eyes of 102 participants (54.1 per cent female) were included in the study. The mean age (± SD) was 48.2 ± 10.9 years (range: 31 to 70 years). Manifest refraction for spherical equivalent was −0.07 ± 1.12 D (−2.88 to +2.75 D) and 0.47 ± 0.54 D (0.00 to 3.00 D) for cylinder. All variables related to optical quality and intraocular scatter showed a normal distribution ($p > 0.05$) unlike the psychophysical variables.

Additionally, 36 (20 right and 16 left) eyes of 36 participants (63.8 per cent female), who were excluded because they had been diagnosed with a cataract, were later considered for the sensitivity and specificity calculations. Mean and range (minimum to maximum) were 66 ± 4 years (61 to 70 years). Manifest refraction for spherical equivalent was +0.63 ± 1.18 D (−1.25 to +2.75 D) and for cylinder 0.43 ± 0.55 D (0.00 to 2.00 D).

Significant correlations were observed between age and all variables analysed with the only exception of CS at 3.0 cpd ($p = 0.076$) (Table 1). The visual function parameters (VA and CS) degraded with age, although correlations were stronger for parameters related to optical quality and intraocular scatter. Specifically, the OSI parameter had the strongest correlation ($r = 0.636$, $p < 0.001$), suggesting the most relevant change with age was the increase of intraocular scattered light. OV100% had the weakest negative correlation ($r = -0.473$, $p < 0.001$), whereas the strongest correlation was for OV9% ($r = -0.531$, $p < 0.001$). Consequently, the decrease in optical quality with age is greater for lower contrasts. With regard to CS, higher spatial frequencies revealed stronger negative correlations; the most

	r	p-value
VA†	0.308	0.003*
CS (3 cpd)†	−0.185	0.076
CS (6 cpd)†	−0.223	0.032*
CS (12 cpd)†	−0.248	0.017*
CS (18 cpd)†	−0.437	<0.001*
MTF_{cutoff} (cpd)‡	−0.472	<0.001*
Strehl ratio‡	−0.516	<0.001*
OV 100%‡	−0.473	<0.001*
OV 20%‡	−0.528	<0.001*
OV 9%‡	−0.531	<0.001*
OSI‡	0.636	<0.001*

*Statistically significant correlations. CS: contrast sensitivity, MTF: modulation transfer function, OSI: objective scatter index, OV: Optical Quality Analysis System values, VA: visual acuity

Table 1. Spearman's† and Pearson's‡ correlation coefficients (r) and corresponding significance (p-value) between each analysed variable and age (cpd: cycles per degree)

	Correlation	MTF_{cutoff}	Strehl ratio	OV100%	OV20%	OV9%	OSI
VA	Simple	0.401**	0.312*	0.401**	0.399**	0.330*	−0.245*
	Partial	0.282*	0.251*	0.282*	0.286*	0.264*	−0.120
CS (3 cpd)	Simple	0.112	0.175	0.112	0.137	0.149	−0.204*
	Partial	0.053	0.037	0.053	0.056	0.034	−0.088
CS (6 cpd)	Simple	0.312*	0.317*	0.312*	0.321*	0.305*	−0.263*
	Partial	0.259*	0.195*	0.259*	0.239*	0.206*	−0.155
CS (12 cpd)	Simple	0.405**	0.348*	0.405**	0.380**	0.334*	−0.266*
	Partial	0.379**	0.265*	0.379**	0.347**	0.281*	−0.155
CS (18 cpd)	Simple	0.403**	0.350*	0.403**	0.424**	0.367**	−0.397**
	Partial	0.274*	0.212*	0.274*	0.302*	0.240*	−0.178*

Statistically significant correlations: *$p < 0.05$, **$p < 0.001$
CS: contrast sensitivity, MTF: modulation transfer function, OSI: objective scatter index, OV: Optical Quality Analysis System values, VA: visual acuity

Table 2. Simple and partial correlation coefficients controlling and not controlling for age, respectively, between optical quality and intraocular scattering (MTF_{cutoff} [cpd], Strehl ratio, OV at 100, 20 and nine per cent contrasts and OSI) and psychophysical (VA, CS [log] at 3, 6, 12 and 18 cpd spatial frequencies) variables

Age group	n	Age (years)		Eyes (n)		Gender (n)		SE (D)		C (D)
		Mean	SD	Right	Left	Female	Male	Mean	SD	Mean
31–40	24	34	2	11	13	12	12	−0.24	0.92	0.43
41–50	30	44	3	15	15	16	14	−0.11	0.94	0.41
51–60	28	54	3	15	13	15	13	−0.21	1.06	0.64
61–70	20	65	4	10	10	12	8	0.16	1.41	0.37

Table 3. Characteristics of age groups

Age group	VA		CS (3 cpd)		CS (6 cpd)		CS (12 cpd)		CS (18 cpd)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
31–40	1.47	0.34	1.73	0.20	1.90	0.27	1.54	0.26	1.03	0.27
41–50	1.45	0.21	1.68	0.26	1.85	0.24	1.52	0.24	1.02	0.24
51–60	1.39	0.22	1.64	0.17	1.82	0.21	1.45	0.28	0.89	0.23
61–70	1.20	0.22	1.62	0.21	1.74	0.22	1.36	0.35	0.63	0.34

Table 4. Visual acuity (VA) and contrast sensitivity (CS) (log) at 3, 6, 12 and 18 cycles per degree (cpd) spatial frequencies, for the age groups considered. The mean and standard deviation (SD) are shown.

significant corresponded to 18 cpd ($r = -0.437$, $p < 0.001$).

To examine the relationship between visual function and optical quality, partial correlations controlling for age were also calculated. Moderate correlations were observed between all optical quality variables (MTF_{cutoff}, Strehl ratio and OVs) and VA, as well as between optical quality variables and CS at all frequencies except for 3.0 cpd. There was no association between OSI and the parameters of visual function (VA and CS except for 18 cpd) but moderate correlations were observed when age was not a mediating variable (Table 2).

No statistically significant differences were found between age groups in relation to gender, right and left eyes, spherical equivalent or cylinder (Table 3). The means for each analysed variable for each age group are shown in Tables 4 and 5 and the median and interquartile range is displayed in boxplots in Figures 2 and 3.

The analysis of variance revealed significant differences among age groups for optical quality and intraocular scatter and for some psychophysical variables such as VA and CS at 18 cpd (Kruskal–Wallis, $p < 0.05$) but not 12 cpd ($p = 0.198$), 6 cpd ($p = 0.269$) or 3 cpd ($p = 0.346$). The Jonckheere–Terpstra's test revealed that statistically significant differences ($p < 0.05$) could always be established when considering VA and CS at 18 cpd and the 61 to 70 age group. The comparisons among younger age groups did not yield statistically significant differences in terms of VA or CS. Bonferroni post-hoc analysis of variables related with optical quality and intraocular scatter revealed a different pattern. For the OV100% there were no significant differences among the first three decades of age, from 31 to 60 years. In contrast, OV20% and OV9% reported differences between the 31 to 40 and 41 to 50 age groups

Age group	Mean	SD	Range (min–max)	Normal limit (low)	Sn.%	Sp.%	Mean	SD	Range (min–max)	Normal limit (low)	Sn. %	Sp.%
	MTF_{cutoff}						Strehl ratio					
31-40	44.6	6.8	31.1–53.3	31.2			0.265	0.051	0.178–0.390	0.164		
41-50	42.8	7.1	28.6–54.6	28.8			0.232	0.056	0.170–0.420	0.122		
51-60	39.9	7.9	27.5–52.7	24.4			0.209	0.050	0.128–0.312	0.111		
61-70	32.5	7.3	18.9–44.5	18.3	63.0	100	0.179	0.046	0.115–0.264	0.088	51.9	100
	OV100%						OV20%					
31-40	1.49	0.23	1.04–1.78	1.04			1.55	0.27	1.04–2.07	1.02		
41-50	1.43	0.24	0.95–1.82	0.96			1.45	0.33	0.89–2.20	0.81		
51-60	1.33	0.26	0.92–1.76	0.81			1.31	0.32	0.82–1.98	0.67		
61-70	1.08	0.24	0.63–1.48	0.61	63.0	100	0.99	0.27	0.57–1.57	0.46	52.9	100
	OV9%						OSI					
31-40	1.60	0.33	1.05–2.36	0.95			0.46	0.15	0.23–0.70	0.75		
41-50	1.40	0.38	0.92–2.59	0.66			0.55	0.19	0.14–0.86	0.93		
51-60	1.25	0.34	0.66–1.94	0.58			0.70	0.15	0.31–1.03	0.99		
61-70	0.99	0.31	0.57–1.56	0.39	51.9	100	0.96	0.35	0.38–1.56	1.64	82.9	100

Table 5. Modulation transfer function cutoff (MTF_{cutoff}) (cycles per degree), Strehl ratio, Optical Quality Analysis System values (OV) at 100, 20 and nine per cent contrasts and OSI for the age groups considered. The mean and standard deviation (SD), range (minimum-maximum), lower limits of normal at the 95 per cent level of agreement (upper for the objective scatter index) are shown. Additionally, the sensitivity (Sn) and specificity (Sp) for the 61 to 70 age group are given when healthy eyes and those with cataracts are considered.

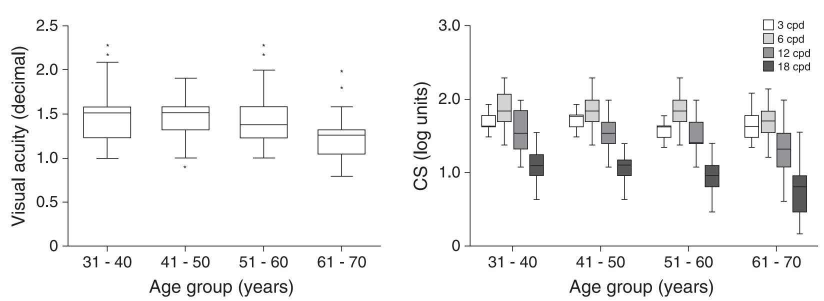

Figure 2. Decline of visual acuity (VA) and contrast sensitivity (log) at spatial frequencies of 3, 6, 12 and 18 cycles per degree in relation to age. Box is the interquartile range; dark line is the median; end of lines are minimum and maximum values.

and the 51 to 60 and 61 to 70 age groups but not between the 41 to 50 and 51 to 60 age groups. Finally, when considering the OSI, statistically significant differences were evident between age groups older than 50 years but not between the 31 to 40 and 41 to 50 age groups.

Table 5 provides normal values beyond 30 years of age for the variables related to optical quality and intraocular scatter. The limits of normal for each variable are given as well as the sensitivity and specificity, when the healthy and cataractous eyes of patients aged 61 to 70 years are taken into consideration. As can be seen, the proposed limits of normal provided sensitivity values close to 100 per cent for all the optical quality variables. The OSI showed also a high specificity (82.9 per cent), whereas the rest of the variables did not provide acceptable specificity values. This was already expected, as the OSI is prominent in eyes with cataracts.

Figure 4 shows the CS function for each age group; CS remains practically unaltered until the age of 50. A significant and progressive decrease with age is more noticeable at higher spatial frequencies after 50 years.

Figure 5 compares the ratios between each variable analysed for each age group with the 31 to 40 age group, to highlight differences in variables with age. The Strehl ratio showed a negative linear correlation with age: a decline of about 10 per cent for each decade between 30 and 70 years. This decrease in optical quality did not manifest as a functional visual deficit, as VA and CS remained stable until 50 years of age. The maximum loss at 61 to 70 years of age was found for 18 cpd: a decrease of about 30 per cent. For other frequencies the decline was smaller, only five per cent for 3 cpd. Similarly, VA showed a marked decline only in the last decade, with a total loss of 15 per cent of its original value at 31 to 40 years of age.

With regard to the other parameters that describe ocular optical quality (MTF_{cutoff} and OVs at different contrasts), those related to low contrasts are more affected by age. In particular, MTF_{cutoff} and OV100%, both closely related to VA (and thus with high contrasts), suffer only a decline of about 25 per cent over 50 years of age in relation to their value in the 31 to 40 decade. The decline is more progressive for parameters related to lower contrasts, that is, OV20% and OV9%. For the Strehl ratio, the loss is about 35 per cent. The OSI has a relevant role in

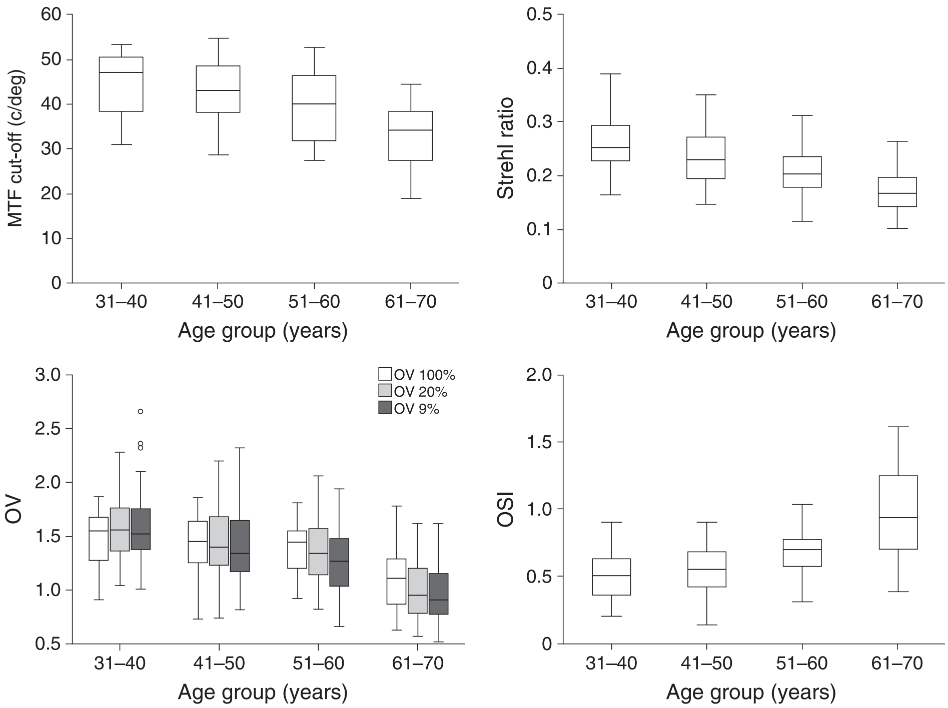

Figure 3. Change of the modulation transfer function cutoff (MTF_{cutoff}) (cycles per degree), Strehl ratio, Optical Quality Analysis System (OQAS) values (OV) at 100, 20 and nine per cent contrasts and objective scatter index (OSI) in relation to age group. Box is the interquartile range; dark line is the median; end of lines are minimum and maximum values.

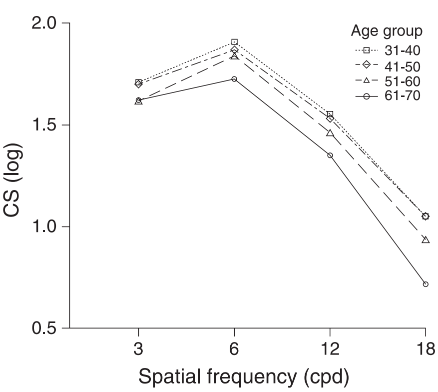

Figure 4. Mean contrast sensitivity for the age groups considered for spatial frequencies of 3, 6, 12 and 18 cycles per degree

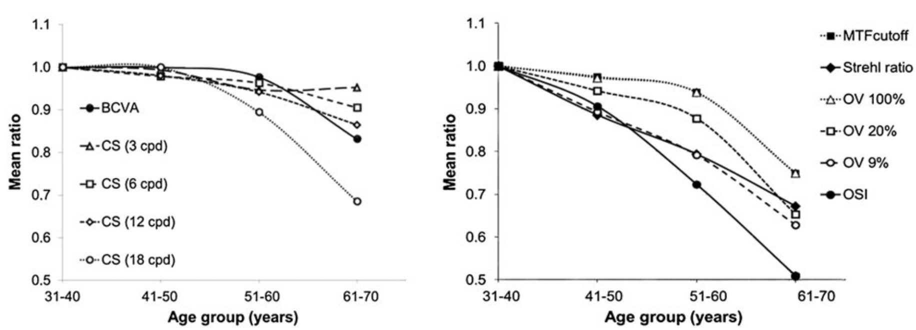

Figure 5. Mean ratio of all psychophysical variables (left) and optical quality and intraocular scattering parameters (right) corresponding to each age group normalised to the 31 to 40 age group. Mean values for the visual acuity (VA), contrast sensitivity (log) at spatial frequencies of 3, 6, 12 and 18 cycles per degree, modulation transfer function cutoff (MTF_{cutoff}) (cpd), Strehl ratio, Optical Quality Analysis System (OQAS) values (OV) at 100, 20 and nine per cent contrasts and objective scatter index (OSI) are shown.

the aging eye, as it is the most affected with an increase of about 50 per cent in the oldest subjects. The increase of intraocular scatter is particularly relevant beyond the age of 60.

Table 6 shows the fitting coefficients obtained for each analysed parameter, the corresponding 95 per cent confidence intervals and the coefficients of determination (r^2). From this analysis, it can be concluded that on average the OSI doubles its value by 63 years of age and such an increase occurs approximately with a power of four (C_3), which is in agreement with previous findings of other authors.[29]

Optical quality parameters related to high contrast (MTF_{cutoff} and OV100%) halve at a later age (72 years). It can also be seen that the lower the contrast, the more linear the decrease (coefficient C_3 is 2.6, 4.6 and 6.1 for OV9%, OV20% and OV100%, respectively).

DISCUSSION

Martinez-Roda and colleagues[20] reported normal values of ocular optical quality and visual performance for a healthy population aged 18 to 30 years. Specifically, the authors used the OQAS 2 system based on the double-pass technique and psychophysical parameters such as VA and CS tests. The

	C_1	95% CI	C_2	95% CI	C_3	95% CI	r^2
MTF_{cutoff}	44.1	41.1–47.1	72.1	67.2–77.1	6.1	1.8–10.0	0.279
Strehl ratio	0.308	0.150–0.466	70.7	53.2–88.2	1.6	1.4–4.7	0.268
OV100%	1.47	1.37–1.57	72.1	67.2–77.1	6.1	2.9–10.0	0.280
OV20%	1.56	1.39–1.73	69.2	65.1–73.4	4.6	1.3–7.9	0.319
OV9%	1.71	1.26–2.15	68.4	61.3–75.5	2.6	0.4–5.6	0.289
OSI	0.46	0.35–0.56	63.0	55.8–70.1	4.3	2.8–6.4	0.467

MTF_{cutoff}: modulation transfer function cutoff, OSI: objective scatter index, OV: Optical Quality Analysis System values

Table 6. Coefficients C_1, C_2, C_3 and 95 per cent confidence intervals (95% CI) for the non-linear models for optical quality and intraocular scattering parameters studied (coefficient of determination: r^2)

comparison of these values with those obtained in the current study reveal that visual function remains practically unaltered after the age of 30 and that a significant decline does not occur until the age of 50 and particularly in the 61 to 70 year decade. After 60 years of age, CS loss increases with increasing spatial frequency, whereas low frequency sensitivity is only minimally impacted by aging.[3]

With regard to optical quality parameters, an independent analysis needs to be carried out for each level of contrast considered; on the one hand, high-contrast parameters such as MTF_{cutoff} and OV100% are not much affected by age and a marked decline was only obtained after 50 years of age. In contrast, variables related with overall optical quality, such as the Strehl ratio and the OV of lower contrasts (20 and nine per cent are linked to a more progressive decline; however, the first age group considered in the current study (31 to 40 years) obtained very similar values to those reported for individuals 18 to 30 years of age; only beyond the age of 40, a noticeable decrease was found. The difficulty of resolving low contrast stimuli has already been reported. High contrast VA tends to underestimate the degree of functional visual loss suffered by many older individuals, while spatial vision measured under conditions of reduced contrast or luminance reveal significant impairments in a large portion of the elderly.[30] Some authors have attributed these changes to the reduction of retinal illuminance due to pupillary miosis, the change of transparency of ocular tissues, especially the crystalline lens and the increased optical aberrations of the aging eye that can reduce image contrast.[3,8]

Finally, the OSI assessment highlighted a decline that increased exponentially with age, with doubled values for the last decade considered (61 to 70 years), in agreement with other studies[11,31] that have used different methods to evaluate scattered light in the eye and have reported a rapid increase in forward scatter after the age of 45.

It is worth noting the usefulness of the limits of normal for variables related to optical quality and intraocular scattering reported in this study for individuals beyond 30 years of age. The sensitivity and specificity values obtained for each variable support the fact that they could be used to improve the early diagnosis of certain ocular diseases. In this case, OSI is a good parameter to detect cataract.

Kamiya and colleagues[21] also measured the MTF_{cutoff}, Strehl ratio and OSI in a population aged 20 to 69 years with the OQAS instrument. Their results correlate well with ours for the Strehl ratio, which in both cases declines progressively with age; however, they found a linear decline with age for the MTF_{cutoff} ($r = -0.606$), whereas our results show a marked decline after 50 years of age. With regard to the OSI, they reported a positive correlation between intraocular scatter and age ($r = 0.691$) and suggested that the Strehl ratio and the OSI change differently, that is, some extra intraocular scatter occurs in the eyes of the older population, as a result of the decrease in the transparency of the crystalline lens and the cornea. These results agree with our findings, since OSI also increased with age, in particular after the age of 50.

In agreement with previous studies, our study shows that loss of vision in older adults is largely optical in origin, as objective optical measures are linked to a decline with age.[6,7] Indeed, we found a decrease in optical quality beyond 30 years of age, especially when the Strehl ratio and parameters related to low contrasts were considered. Our results also suggest that these optical deficits are compensated during the first decades of adult life by means of sensory and perceptual factors, which through neural adaptation preserve visual function until the age of 50. The preserved parameters of visual processing and visual behaviour and the neurological mechanisms involved are poorly understood;[3] however, research suggests that perceptual learning and plasticity of the visual system could be used to improve visual function in older individuals.[32,33] The results obtained in this study also highlight that beyond the age of 50 this compensation is less effective, resulting in a decline in visual performance. The mean ratios between values of psychophysical parameters and objective parameters (optical quality and intraocular scatter) among different age groups support this finding (Figure 5). Those obtained by means of objective outputs are generally higher, suggesting that the objectively measured optical changes are larger than the psychophysical ones.

In conclusion, our study demonstrates that visual function, optical quality and intraocular scatter change with age, in particular, parameters related to low contrast stimuli and scattered light. These results suggest that optical deficits are compensated throughout the first decades of adult life by means of sensory or perceptual factors, as the changes in visual function were smaller than objective outputs, in particular until the age of 50. Our study also contributes optical quality and intraocular scatter reference values for individuals up to 70 years of age. These reference values can be used as complementary information for the diagnosis of ocular conditions, such as the presence of cataract.

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