Appendix A
Mathematical Notations

A.1 Definition of Nicknamed Functions

Circle function:

$$\operatorname{circ}\left(\frac{r}{D/2}\right) = \operatorname{circ}\left(\frac{\sqrt{x^2+y^2}}{D/2}\right) = \begin{cases} 1 & r \leq D/2 \\ 0 & r > D/2. \end{cases} \tag{A.1}$$

Cusp function:

$$\operatorname{cusp}\left(\frac{r}{R}\right) = \begin{cases} \frac{2}{\pi}\left[acs\left(\frac{r}{R}\right) - \frac{r}{R}\sqrt{1-\left(\frac{r}{R}\right)^2}\right] & \left|\frac{r}{R}\right| \leq 1 \\ 0 & \left|\frac{r}{R}\right| > 1. \end{cases} \tag{A.2}$$

Rectangle function:

$$\operatorname{rect}\left(\frac{x}{W/2}\right) = \begin{cases} 1 & x \leq W/2 \\ 0 & x > W/2. \end{cases} \tag{A.3}$$

Sinc function:

$$\operatorname{sinc}(x) = \frac{\sin(x)}{x}. \tag{A.4}$$

Sombrero function:

$$\operatorname{somb}(r) = \frac{2J_1(r)}{r}, \tag{A.5}$$

where $J_1(x)$ is the Bessel function of the first kind, first order.
Struve function:

$$H_1(x) = \sum_{m=0}^{\infty} (-1)^m \frac{\left(\frac{x}{2}\right)^{2(m+1)}}{\Gamma\left(m+\frac{3}{2}\right)\Gamma\left(m+\frac{5}{2}\right)}, \tag{A.6}$$

where $\Gamma(\cdot)$ is the Gamma function.

A.2 Definition of Functional Operators

Convolution:

$$\mathrm{conv}[f(x), g(x)] = \int_{-\infty}^{\infty} f(y) \cdot g(x-y) \cdot dy \equiv \mathrm{conv}[g(x), f(x)]. \tag{A.7}$$

Correlation:

$$\mathrm{corr}[f(x), g(x)] = \int_{-\infty}^{\infty} f^{*}(y) \cdot g(x+y) \cdot dy. \tag{A.8}$$

Fourier transform:

$$FT\{f(x)\} = \int_{-\infty}^{+\infty} f(x) e^{-2\pi j \xi x} dx = F(\xi). \tag{A.9}$$

Inverse Fourier transform:

$$FT^{-1}\{F(\xi)\} = \int_{-\infty}^{\infty} F(\xi) e^{2\pi j x \xi} d\xi = f(x). \tag{A.10}$$

Hankel transform:

$$HT\{f(r)\} = 2\pi \int_{0}^{\infty} r \cdot f(r) \cdot J_0(2\pi \rho r) dr = F(\rho), \tag{A.11}$$

where $J_0(x)$ is the Bessel function of the first kind, zero order.
Inverse Hankel transform:

$$HT^{-1}\{F(\rho)\} = 2\pi \int_{0}^{\infty} \rho \cdot f(\rho) \cdot J_0(2\pi r \rho) d\rho \equiv HT\{F(\rho)\}. \tag{A.12}$$

Appendix B
Herzberger Dispersion Formula

The basic form of the Herzberger formula[1] is

$$n(\lambda) = \gamma_1 + \gamma_2\lambda^2 + \frac{\gamma_3}{\lambda^2 - \lambda_0^2} + \frac{\gamma_4}{(\lambda^2 - \lambda_0^2)^2}. \tag{B.1}$$

For any dispersive medium, the four coefficients γ_1 through γ_4 have to be determined through the best fit of experimental refractive index data. Equivalently, this relationship can be cast in the form

$$n(\lambda) = a_1(\lambda)n(\lambda_1) + a_2(\lambda)n(\lambda_2) + a_3(\lambda)n(\lambda_3) + a_4(\lambda)n(\lambda_4), \tag{B.2}$$

with the four coefficients $a_i(\lambda)$ given by

$$a_i(\lambda) = \gamma_{1i} + \gamma_{2i}\lambda^2 + \frac{\gamma_{3i}}{\lambda^2 - \lambda_0^2} + \frac{\gamma_{4i}}{(\lambda^2 - \lambda_0^2)^2}.$$

In matrix form:

$$a_i(\lambda) = \underline{\Lambda} \cdot \underline{\gamma_i} = \begin{vmatrix} 1 & \lambda^2 & \dfrac{1}{\lambda^2 - \lambda_0^2} & \dfrac{1}{(\lambda^2 - \lambda_0^2)^2} \end{vmatrix} \cdot \begin{vmatrix} \gamma_{1i} \\ \gamma_{2i} \\ \gamma_{3i} \\ \gamma_{4i} \end{vmatrix},$$

and

$$n(\lambda) = \underline{\Lambda} \cdot \underline{\underline{\gamma}} \cdot \underline{n} = \begin{vmatrix} 1 & \lambda^2 & \dfrac{1}{\lambda^2 - \lambda_0^2} & \dfrac{1}{(\lambda^2 - \lambda_0^2)^2} \end{vmatrix} \cdot \begin{vmatrix} \gamma_{11} & \gamma_{12} & \gamma_{13} & \gamma_{14} \\ \gamma_{21} & \gamma_{22} & \gamma_{23} & \gamma_{24} \\ \gamma_{31} & \gamma_{32} & \gamma_{33} & \gamma_{34} \\ \gamma_{41} & \gamma_{42} & \gamma_{43} & \gamma_{44} \end{vmatrix} \cdot \begin{vmatrix} n_1 \\ n_2 \\ n_3 \\ n_4 \end{vmatrix}.$$

In particular, Eq. (B.2) must be verified at each wavelength λ_i, $i = 1$ to 4, which implies $a_i(\lambda_i) = 1; a_j(\lambda_i)|_{j\neq i} \equiv 0$ in Eq. (B.2). This translates to

$$\begin{vmatrix} 1 & \lambda_1^2 & \dfrac{1}{\lambda_1^2 - \lambda_0^2} & \dfrac{1}{(\lambda_1^2 - \lambda_0^2)^2} \\ 1 & \lambda_2^2 & \dfrac{1}{\lambda_2^2 - \lambda_0^2} & \dfrac{1}{(\lambda_2^2 - \lambda_0^2)^2} \\ 1 & \lambda_3^2 & \dfrac{1}{\lambda_3^2 - \lambda_0^2} & \dfrac{1}{(\lambda_3^2 - \lambda_0^2)^2} \\ 1 & \lambda_4^2 & \dfrac{1}{\lambda_4^2 - \lambda_0^2} & \dfrac{1}{(\lambda_4^2 - \lambda_0^2)^2} \end{vmatrix} \cdot \begin{vmatrix} \gamma_{i1} \\ \gamma_{i2} \\ \gamma_{i3} \\ \gamma_{i4} \end{vmatrix} = \begin{vmatrix} \delta_{i,1} \\ \delta_{i,2} \\ \delta_{i,3} \\ \delta_{i,4} \end{vmatrix}, \tag{B.3}$$

where $\delta_{j,i}$ = Kronecker's delta.

Solutions of the four linear systems in Eq. (B.3) for $i = 1$ to 4 give the 16 coefficients γ_{ij}. Choosing $\lambda_0^2 = 0.028\ \mu\text{m}^2$; $\lambda_1 = \lambda_i = 0.3650146\ \mu\text{m}$; $\lambda_2 = \lambda_F = 0.4861327\ \mu\text{m}$; $\lambda_3 = \lambda_C = 0.6562725\ \mu\text{m}$; and $\lambda_4 = \lambda_t = 1.01398\ \mu\text{m}$; results in

$$\underline{\underline{\gamma}} = \begin{vmatrix} 0.66149637 & -4.20170826 & 6.29866119 & -1.75844930 \\ -0.40355469 & 2.73533632 & -4.69448133 & 2.36269971 \\ -0.28047241 & 1.50549063 & -1.57515162 & 0.35013340 \\ 0.03385993 & -0.11593535 & 0.10293414 & -0.02085872 \end{vmatrix}. \tag{B.4}$$

These values coincide with those of Herzberger to the third or fourth decimal figure, with discrepancies arising primarily because of the finer definition of wavelengths λ_1 to λ_4.[2] They are reported here to overcome a few misprints contained in the paper by Navarro, Santamaría, and Bescós (see Refs. 3,4).

B.1 References

1. M. Herzberger, "Colour correction in optical systems and a new dispersion formula," *Opt. Acta* **6**, 197–215 (1959).
2. Schott Glaswerke, Optical Glass Technical Catalog, Mainz, Germany.
3. R. Navarro, J. Santamaría, and J. Bescós, "Accomodation-dependent model of the human eye with aspherics," *J. Opt. Soc. Am. A* **2**, 1273–81 (1985).
4. J. E. Greivenkamp, J. Schwiegerling, J. M. Miller, and M. D. Mellinger, "Visual acuity modeling using optical raytracing of schematic eyes," *Am. J. Ophthalmol.* **120**, 227–240 (1995).

Appendix C
Determination Coefficient R^2

Given n couples of observations (x_i, y_i) and the model function $f = f(x, \underline{a})$, where $\underline{a}$ is a set of m unknown parameters, the fitting problem requires minimization of the discrepancy between observed data y_i and values $f_i = f(x_i, \underline{a})$ predicted under the model. According to the method of maximum likelihood, through the assumption of a Gaussian parent distribution determining the probability of making any particular observation, the quantity to be minimized is the sum of squares of residuals:

$$SSq_{res} = \sum_{i=1}^{n} (y_i - f_i)^2. \tag{C.1}$$

The degree of variability or dispersion of the observations is accounted for by the total sum of squares (or deviance):

$$SSq_{tot} = \sum_{i=1}^{n} (y_i - \bar{y})^2 \tag{C.2}$$

where $\bar{y} = \frac{1}{n} \sum_{i=1}^{n} y_i$ is the mean of the observed data, and SSq_{tot} is proportional to the sample variance. The equivalent of Eq. (C.2) for the values predicted by the model is called the explained (or regression) sum of squares, and is given by

$$SSq_{mod} = \sum_{i=1}^{n} (f_i - \bar{y})^2. \tag{C.3}$$

The general definition of the determination coefficient R^2 is

$$R^2 = 1 - \frac{SSq_{res}}{SSq_{tot}}. \tag{C.4}$$

In case of linear regression—that is, when the model $f(x, \underline{a})$ is a linear function of parameter set $\underline{a}$—the following partition holds:

$$SSq_{tot} = SSq_{res} + SSq_{mod}, \tag{C.5}$$

so that R^2 can be expressed as

$$R^2 = \frac{SSq_{mod}}{SSq_{tot}}. \tag{C.6}$$

Eq. (C.6) gives R^2 in terms of the explained variance, comparing the variance of the model predictions with the total variance of the data. Under such conditions, R^2 equals the square of the correlation coefficient between observed and predicted data values, and its value ranges in [0, 1].

If $f(x, \underline{a})$ is a nonlinear function of parameters $\underline{a}$, then the partition in Eq. (C.5) does not hold, becoming

$$SSq_{tot} = SSq_{res} + SSq_{mod} + CPS, \tag{C.7}$$

with

$$CPS = 2\sum_{i=1}^{n}(y_i - f_i)(f_i - \bar{y}). \tag{C.8}$$

The additional term of cross-product sum (CPS) is not identically zero as for linear functions, and can assume either sign. As a consequence, the computational definition of Eq. (C.4) can even yield R^2 values greater than unity or negative.

Rigorously speaking, in nonlinear regression the determination coefficient cannot be interpreted as a goodness-of-fit indicator, quantifying the fraction of deviance explained by the model relative to the total deviance of data. By willing to preserve a pregnant meaning for Eq. (C.6)—as for linear regressions— this could be evaluated as

$$R^2_{eff} \equiv \frac{SSq_{mod}}{SSq_{tot}} = 1 - \frac{SSq_{res} + CPS}{SSq_{tot}}. \tag{C.9}$$

A numerical example is helpful to clarify the situation, and the case of the chromatic difference of refraction (Section 5.1) is considered here. For the nonlinear regression of Fig. 5.1, the relevant statistical parameters are as follows: $SSq_{tot} = 56.479$; $SSq_{res} = 1.696$; $SSq_{mod} = 53.856$; and $CPS = 0.927$, which correctly satisfy the balance in Eq. (C.7). According to Eqs. (C.4) and (C.8), the two values $R^2 = 0.970$ and $R^2_{eff} = 0.954$ are obtained, which is not a significant difference.

However, the relevance of R^2 (or R^2_{eff}) must not be overrated. By looking at Eqs. (C.2)–(C.4), it can be realized that the determination coefficient quantifies how much more variation in data is explained by the model considered, compared to a null model having only a constant, equal to the data mean. There are two main concerns: how good the model is, and how good the mean is at explaining the data variation, because the better the mean is, the worse the model will look, even though the model is good.

Therefore, the goodness of fit (even for linear regression) should be jointly evaluated through a qualitative impression (by eye inspection: how well the fit curve interprets the data behavior[1]), and quantitative indication (determination coefficient: how close to unity R^2 is). The eye can often succeed in finding out the fitting behavior that minimizes the distance from the data (SSq_{res}), but fails to rate the quality of the fit. R^2 represents a quality index of immediate comprehension, though with the limits of interpretation outlined before.

For the sake of simplicity only the R^2 values are provided here.

C.1 References

1. H. J. Motulsky and L. A. Ransnas, “Fitting curves to data using nonlinear regression: a practical and nonmathematical review,” *FASEB J.* **1**, 365–374 (1987).

Appendix D
Optical Parameters of the CAGE Eye Model

D.1 Geometrical Parameters

Medium	Thickness (mm)	Curvature radius (mm)	p-value
Air	∞		
		7.7	0.72
Cornea	0.5		
		6.8	0.78
Aqueous humor	3.1		
		10	−0.89
Anterior lens cortex	0.546		
		7.911	1.2
Lens nucleus	2.419		
		−5.76	−0.64
Posterior lens cortex	0.635		
		−6	−1.3
Vitreous body	17.185		

D.2 Chromatic Dispersion Parameters

Using Eq. (5.1),

$$n(\lambda) = a_1(\lambda)n_i + a_2(\lambda)n_F + a_3(\lambda)n_C + a_4(\lambda)n_t, \tag{D.1}$$

with

Medium	n_i 365 nm	n_F 486.1 nm	n_C 656.3 nm	n_t 1014 nm
Aqueous/vitreous	1.35675	1.34036	1.33208	1.29400
Cornea	1.39634	1.38082	1.37222	1.33985
Lens cortex	1.41153	1.39095	1.38200	1.34433
Lens nucleus	1.43192	1.41208	1.40230	1.37720

$$a_i(\lambda) = \gamma_{1i} + \gamma_{2i}\lambda^2 + \frac{\gamma_{3i}}{\lambda^2 - \lambda_0^2} + \frac{\gamma_{4i}}{(\lambda^2 - \lambda_0^2)^2}$$

and coefficients γ_{1i} given by the matrix in Eq. (B.4).

D.3 Paraxial Properties at Five Wavelengths

D.3.1 Dioptric Powers of Individual Interfaces and Components

Optical element	Wavelength (nm) 400	 490	 **587.6**	 680	 770
Ant. corneal surf.	50.429	49.432	**48.831**	48.148	47.302
Post. corneal surf.	−5.979	−5.947	**−5.882**	−5.923	−6.053
Cornea	44.559	43.592	**43.053**	42.329	41.354
Ant. lens cortex surf.	5.264	5.055	**5**	4.991	4.996
Ant. lens nucleus surf.	2.793	2.662	**2.528**	2.605	2.851
Post. lens nucleus surf.	3.836	3.657	**3.472**	3.578	3.915
Post. lens cortex surf.	8.773	8.425	**8.333**	8.319	8.327
Lens	20.415	19.567	**19.111**	19.265	19.848
Eye	61.113	59.515	**58.636**	58.084	57.653

D.3.2 Separations Between Cardinal Points

In millimeters, with F as focal point, P as principal point, N as nodal point, E as pupil, V as vertex, with suffixes f for front and b for back, where, for example, E_f corresponds to the entrance pupil and E_b to the exit pupil

Separation	Wavelength (nm)				
	400	490	**587.6**	680	770
V_fV_b	7.2	7.2	**7.2**	7.2	7.2
V_fF_f	−14.994	−15.448	**−15.706**	−15.84	−15.91
V_fF_b	23.688	24.131	**24.385**	24.538	24.646
V_fP_f	1.37	1.355	**1.348**	1.377	1.435
V_fP_b	1.636	1.612	**1.601**	1.632	1.697
V_fN_f	7.058	7.071	**7.078**	7.066	7.039
V_fN_b	7.325	7.328	**7.331**	7.321	7.3
V_fE_f	3.031	3.041	**3.047**	3.055	3.065
V_fE_b	3.669	3.666	**3.665**	3.666	3.668
$P_fN_f = P_bN_b$	5.689	5.716	**5.73**	5.689	5.604
$F_fP_f = N_bF_b$	16.363	16.802	**17.054**	17.217	17.345
$F_fN_f = P_bF_b$	22.052	22.518	**22.785**	22.906	22.949

D.4 Ray-Transfer Matrix Elements

From anterior cornea to posterior lens surface

Matrix element	Unit	Wavelength (nm)				
		400	490	**587.6**	680	770
A_E	–	0.74768	0.75186	**0.75426**	0.7569	0.76019
B_E	m	$5.1527 \cdot 10^{-3}$	$5.188 \cdot 10^{-3}$	**5.2076**$\cdot 10^{-3}$	$5.2273 \cdot 10^{-3}$	$5.2506 \cdot 10^{-3}$
C_E	–	−61.113	−59.515	**−58.636**	−58.084	−57.653
D_E	D	0.9163	0.91936	**0.92097**	0.92003	0.91725

Appendix E
Visual Acuity Lines

Qualitative VA evaluations such as counting fingers and hand motion have been quantitatively measured to correspond to logMAR values of +1.85 (range 1.7 to 2) and +2.28 (range 2.05 to 2.48),[1] although very different equivalences have also been proposed.[2,3]

E.1 References

1. K. Schulze-Bonsel, N. Feltgen, H. Burau, L. Hansen, and M. Bach, "Visual acuities 'hand motion' and 'counting fingers' can be quantified with the Freiburg visual acuity test," *Invest. Ophthalmol. Vis. Sci.* **47**, 1236–1240 (2006).
2. J. T. Holladay, "Proper method for calculating average visual acuity," *J. Refract. Surg.* **13**, 388–391 (1997).
3. S. Grover, G. A. Fishman, R. J. Anderson, M. S. V. Tozatti, J. R. Heckenlively, R. G. Weleber, A. O. Edwards, and J. Brown, Jr., "Visual acuity impairment in patients with retinitis pigmentosa at age 45 years or older," *Ophthalmology* **106**, 1780–1785 (1999).

Table E.1 Comparison of VA levels (lines) in different notations, together with values of MAR and maximum angular frequency ψ_M. The relevant equations connecting all of these quantities are reported in Section 18.2.

VA notations					MAR	Max	
		Decimal	Snellen fraction		(arcmin	frequency	Notes
LogMAR	Decimal	fraction	6 m	20 ft	arcsec)	ψ_M (cpd)	
+2	0.01	0.1/10	6/600	20/2000	100^{m}	0.3	Near total blindness
+1.9	0.0125	0.125/10	6/480	20/1600	$79^{m}26^{s}$	0.38	
+1.8	0.016	0.16/10	6/380	20/1250	$63^{m}06^{s}$	0.48	
+1.7	0.02	0.2/10	6/300	20/1000	$50^{m}07^{s}$	0.6	Profound visual impairment
+1.6	0.025	0.25/10	6/240	20/800	$39^{m}48^{s}$	0.75	
+1.5	0.032	0.32/10	6/200	20/630	$31^{m}37^{s}$	0.95	
+1.4	0.04	0.4/10	6/150	20/500	$25^{m}07^{s}$	1.19	
+1.3	0.05	0.5/10	6/120	20/400	20^{m}	1.5	Severe visual impairment (legal blindness)
+1.2	0.063	0.63/10	6/100	20/320	$15^{m}50^{s}$	1.89	
+1.1	0.08	0.8/10	6/75	20/250	$12^{m}35^{s}$	2.38	
+1	0.1	1/10	6/60	20/200	10^{m}	3	
+0.9	0.125	1.25/10	6/48	20/160	8^{m}	3.78	Moderate visual impairment
+0.8	0.16	1.6/10	6/38	20/125	$6^{m}18^{s}$	4.75	
+0.7	0.2	2/10	6/30	20/100	5^{m}	6	
+0.6	0.25	2.5/10	6/24	20/80	4^{m}	7.5	
+0.5	0.32	3.2/10	6/20	20/63	$3^{m}09^{s}$	9.5	Mild vision loss
+0.4	0.4	4/10	6/15	20/50	$2^{m}30^{s}$	11.9	
+0.3	0.5	5/10	6/12	20/40	2^{m}	15	
+0.2	0.63	6.3/10	6/10	20/32	$1^{m}35^{s}$	18.9	
+0.1	0.8	8/10	6/7.5	20/25	$1^{m}15^{s}$	23.8	Range of normal vision
0	1	10/10	6/6	20/20	1^{m}	30	
−0.1	1.25	12.5/10	6/5	20/16	$0^{m}47^{s}$	37.8	
−0.2	1.6	16/10	6/3.75	20/12.5	$0^{m}38^{s}$	47.5	
−0.3	2	20/10	6/3	20/10	$0^{m}30^{s}$	60	Supernormal vision
−0.4	2.5	25/10	6/2.4	20/8	$0^{m}24^{s}$	75.4	
−0.5	3.2	32/10	6/2	20/6.3	$0^{m}19^{s}$	94.9	
−0.6	4	40/10	6/1.5	20/5	$0^{m}15^{s}$	120	

Appendix F

List of Acronyms

2AFC	Two alternatives forced choice
2D	Bidimensional
AECD	Airy-disk energy content diameter
ALSF	Amplitude line spread function
ASF	Amplitude spread function
BF	Binocularity factor
BFD	Back focal distance
BLINCS	Bilogarithmic integral of normalized contrast sensitivity
CAGE	Chromatic aspherical Gullstrand exact
CDR	Chromatic difference of refraction
ChTF	Coherent transfer function
CIE	Commission Internationale de l'Éclairage
cpd	Cycles per degree
CPS	Cross products sum
CRT	Cathode ray tube
CS	Contrast sensitivity
CSF	Contrast sensitivity function
CTF	Contrast transfer function
DDD	Discriminable difference diagrams
DL	Diffraction limited
DLHE	Diffraction limited with hard-edge pupil
DLSC	Diffraction limited with Stiles–Crawford tapered pupil
DoG	Difference of Gaussians
ESA	External spherical aberration
FFT	Fast Fourier transform
FT	Fourier transform
FWHM	Full width at half maximum
GRIN	Graded index
GVA	Grating visual acuity
HE	Hard edge
ICS	Integrated contrast sensitivity
IFT	Inverse Fourier transform
INCS	Integral of normalized contrast sensitivity
IQ	Image quality
ISA	Internal spherical aberration

jnd	Just noticeable difference
LCA	Longitudinal chromatic aberration
LGN	Lateral geniculate nucleus
LI	Lateral inhibition
LINCS	Logarithmic integral of normalized contrast sensitivity
LSA	Longitudinal spherical aberration
LSF	Line spread function
MAR	Minimum angle of resolution
MCF	Mutual coherence function
MIF	Mutual intensity function
MIS	Mutual intensity spectrum
MON	Monochromatic illumination spectrum
MTF	Modulation transfer function
MTFA	Modulation transfer function area
OC	Optimum cornea
OPD	Optical path difference
OTF	Optical transfer function
PF	Psychometric function
PSF	Point spread function
PTF	Phase transfer function
REC	Radial energy content
RF	Receptive field
RG	Retinal gain
RMSE	Root mean square error
SA	Spherical aberration
SECD	Sinc-lobe energy content diameter
SLE	Spectral luminous efficiency
SNR	Signal-to-noise ratio
SPH	Spherical Gullstrand eye model
SQF	Subjective quality factor
SQRI	Square root integral
SR	Strehl ratio
TA	Ray transverse aberration
TEC	Transverse energy content
TMF	Threshold modulation function
TSA	Transverse spherical aberration
UR	Struve ratio
UVL	Ultimate visual limit
VA	Visual acuity
vpt	Visual performance tile
WHT	Broadband illumination spectrum
WRC	Windowing resolution correction

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The Pizzomunno monolith emerging from the Adriatic Sea at Vieste, Italy. The very embryo of this book was conceived while swimming in these wonderful waters. The photo is a tribute to the *genius loci*, and to his gift of serendipitous inspiration.

Pier Giorgio ("Giò") Gobbi was born in 1953 in Mantua, Italy, where he completed his classical studies at the Liceo-Ginnasio Virgilio. In 1976 he graduated cum laude in Electrical Engineering at the University of Pavia as an alumnus of the historical Collegio Ghislieri. He has been involved in various research fields including physics of laser-produced plasmas, physics and technology of laser sources, design of medical optoelectronic instrumentation, biomedical applications of lasers, physics of visual refraction, and eye modeling. He is author/co-author of more than 70 publications in scientific journals and books, more than 50 presentations at scientific conferences, and 10 national and international patents. He is currently with the Scientific Institute Hospital San Raffaele in Milan.