Contrast Sensitivity of the
HUMAN EYE
and Its Effects on Image Quality

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Printed in the United States of America.

to my wife Tineke,
and my children Koen, Yvonne and Marianne

Contents

Preface

In this book, a new model is given for the contrast sensitivity of the human eye with which a large number of published measurements can be explained. Furthermore, a metric is given for the calculation of the perceived quality of an image from the physical parameters of the image and the psychophysical parameters of the human visual system. The book represents the comprehensive results of about ten years of investigation in these areas. The contrast sensitivity model is based on the assumption that it is determined by the presence of internal noise in the visual system. First a fundamental mathematical analysis is given for the general properties of image noise and for the effects of noise on the perception threshold of the visual system. The effect of internal noise on contrast sensitivity is further elaborated in following chapters for various aspects of the visual system. The results are given in the form of equations that can easily be used for practical application. They are compared with a large number of empirical data. The last chapters of the book are devoted to the effect of contrast sensitivity on perceived image quality. In this part, a model is given for the nonlinear behavior of the visual system at suprathreshold levels of modulation and a metric is given for the description of image quality with the aid of the physical parameters of the imaging system and the psychophysical parameters that can be derived from the contrast sensitivity. In the last chapter, the effect of various parameters on image quality is treated, and several examples are given where the predicted image quality is compared with measurements.

The reason for the research on the subjects treated in this book, was the need for an objective measure of perceived image quality, which I felt during my professional work on the development of CRTs for television and computer display. It was clear that besides the physical data of the image, the contrast sensitivity of the eye plays an important role in such a measure. However, for the contrast sensitivity of the eye, which depends on luminance and field size, only a few measurements were available. Furthermore, it was not clear how the contrast sensitivity of the eye had to be combined with the physical parameters of the image to obtain a good measure for image quality. Therefore, I started an intensive study on these subjects after the end of my professional career. For the effect of resolution on image quality, I found that the nonlinear behavior of the visual system could be taken into account by applying a square-root relation between modulation and perceived image quality. Later it appeared that the so obtained image quality metric could not only be applied for the effect of resolution, but also for the effect of other parameters on image quality, like luminance and image size. For the effect of noise on image quality, I assumed that it was caused by the effect of noise on contrast sensitivity. To investigate this further, I made a study of published measurement data of the effect of various types of image noise on contrast sensitivity. After an evaluation of these results, the idea arose that the remarkable dependence of contrast sensitivity on luminance and field size could maybe be explained by the presence of internal noise in the visual system. However, to obtain a complete description of the contrast sensitivity function of the eye, still a number of additional assumptions had to be made. I tested these assumptions by comparing them with a large number of published data. Furthermore, I also tried to apply the same basic principles to other aspects of contrast sensitivity. The so obtained information appeared to be very useful for a further evaluation of a good image quality metric.

After having presented a part of my investigations in papers and in short courses, the idea arose to present the results more completely in a comprehensive book. For the first edition of this book, I chose the form of a dissertation at the Technical University of Eindhoven, because an important part of the measurements that I used for my investigations were made at the Institute of Perception Research (IPO) of this university. I was very glad that Prof. Roufs of this institute, who was in charge of the work on visual perception, was willing to act as supervisor of my dissertation. I am very grateful for the many hours he spent on reading the manuscript of the dissertation in a critical way and his suggestions for improvements. I am also very grateful for the support that I received during my investigations from Prof. van Nes of the same institute and from Dr. van Meeteren of the Institute for Perception TNO in Soesterberg. I also would like to thank Prof. Hooge and Prof. Butterweck of the Department of Electrical Engineering of the Technical University of Eindhoven for their advice on the mathematical treatment of the noise in Chapter 2, and I also would like to thank Dr. Tyler of the Smith-Kettlewell Eye Research Institute in San Francisco for his useful comments on Chapter 5 about the temporal contrast sensitivity. In particular, I would like to express my special thanks to my wife for her patience during the many hours that I spent on the manuscript of this book.

The present book is the textbook edition of the dissertation. It differs from the original version by the use of a hardcover, the addition of a subject index and a list of symbols, and by a few other changes and small text corrections that were made to adapt it to this application.

Peter Barten August, 1999

List of symbols

Latin symbols

Symbol	Description	Unit
$a(u,v,w)$	amplitude of sinusoidal luminance variation	cd/m^2
A	available surface area per retinal cell	deg^2
	MTFA value	cycles/deg
$A(u,v,w)$	complex amplitude of sinusoidal luminance variation	cd/m^2
c	constant for nonlinear behavior of modulation	-----
	velocity of light	m/sec
	velocity of traveling wave	deg/sec
C	contrast factor	-----
C_{ab}	aberration constant of eye lens	arc min/mm
d	diameter of eye pupil	mm
	center-to-center distance of retinal cells	arc min
d'	detectability index	-----
D	field diameter	deg
e	numerical value of the natural logarithm (2.771828...)	-----
e	eccentricity	deg
e_g	constant used in density distribution of ganglion cells	deg
E	retinal illuminance	Td
$f(r)$	receptive field of spatial inhibition	deg^{-2}
$F(u)$	MTF of spatial inhibition filter	-----
	integrand of one-dimensional image quality metric	cond. dep.
$F(u,v)$	integrand of two-dimensional image quality metric	cond. dep.
$F(u,\vartheta)$	integrand of polar image quality metric	cond. dep.
$F(u,v,w)$	Fourier transform of luminance pattern	deg^2 sec cd/m^2
$G(u,w)$	MTF of spatiotemporal inhibition process	-----
h	Planck's constant	Joule sec
	vertical size of television image	deg
$h(t)$	temporal impulse response function	$msec^{-1}$

Symbol	Description	Unit
$h_1(t)$	impulse response function for MTF given by $H_1(w)$	$msec^{-1}$
$h_2(t)$	impulse response function for MTF given by $H_2(w)$	$msec^{-1}$
$H(w)$	MTF of temporal impulse response function	-----
$H_1(w)$	MTF of temporal processing of photo-receptor signal	-----
$H_2(w)$	MTF of temporal processing of spatial inhibition signal	-----
I	ICS value	cycles/deg
j	$\sqrt{-1}$	-----
j	flux density of photons	$deg^{-2}\ sec^{-1}$
$j(u)$	image quality contribution	jnd
J	image quality measure	jnd
	SQRI value	jnd
J'	modified SQRI value	jnd
k	signal-to-noise ratio at 50% detection probability	-----
k^*	signal-to-noise ratio at det. prob. different from 50%	-----
K	Kell factor (0.7)	-----
K	normalization factor SQF metric	-----
l	relative threshold elevation	-----
L	luminance	cd/m^2
$\bar{L}$	average luminance	cd/m^2
L'	output luminance	cd/m^2
L_{max}	maximum luminance	cd/m^2
ΔL	luminance difference	cd/m^2
m	modulation	-----
m_0	modulation of reference signal	-----
m_n	average modulation of noise wave components	-----
m_{rel}	relative modulation of reference signal	-----
m_t	modulation threshold	-----
m_t'	increased modulation threshold	-----
Δm	modulation difference	-----
Δm_t	threshold of modulation difference	-----
Δm_{trel}	relative threshold of modulation difference	-----
$M(u)$	MTF of imaging system	-----
$M_{lat}(u)$	MTF of lateral inhibition process	-----
$M_{opt}(u)$	optical MTF of the eye	-----
n	number of photons	-----
	number of stages of impulse response function	-----
n_1	number of stages of the function $H_1(w)$	-----
n_2	number of stages of the function $H_2(w)$	-----
$\bar{n}$	average number of photons	-----
N	number of retinal cells per unit area	deg^{-2}
N_c	number of cones per unit area	deg^{-2}

Symbol	Description	Unit
N_{c0}	number of cones per unit area in center of retina	deg^{-2}
N_g	number of ganglion cells per unit area	deg^{-2}
N_{g0}	number of ganglion cells per unit area in center of retina	deg^{-2}
N_{max}	maximum number of integration cycles	-----
N_r	number of rods per unit area	deg^{-2}
N_v	number of visual scan lines	-----
p	detection probability	%
	photon conversion factor	photons/sec/deg^2/Td
	center-to-center distance of pixels	deg
p_{2AFC}	probability of correct response in a 2AFC experiment	%
$P(\lambda)$	spectral energy distribution of light source	Joule/sec
Q	SQF value	-----
r	radial distance on retina	arc min
s	signal strength	cond. dep.
	row spacing of retinal cells	arc min
s_0	signal strength at 50% detection probability	cond. dep.
s_g	row spacing of ganglion cells	arc min
S	contrast sensitivity	-----
t	time	sec
Δt	small variation of t	sec
T	temporal size	sec
T_e	integration time of the eye	sec
T_o	presentation time	sec
u	spatial frequency	cycles/deg
	spatial frequency in x direction	cycles/deg
u_0	spatial frequency limit of lateral inhibition process	cycles/deg
u_n	spatial frequency of the noise	cycles/deg
u_N	Nyquist limit of spatial frequency	cycles/deg
u_{max}	maximum spatial frequency	cycles/deg
	maximum spatial frequency in x direction	cycles/deg
u_{min}	minimum spatial frequency	cycles/deg
	minimum spatial frequency in x direction	cycles/deg
u_{nmax}	maximum spatial frequency of noise	cycles/deg
	maximum spatial frequency of noise in x direction	cycles/deg
u_{nmin}	minimum spatial frequency of noise	cycles/deg
	minimum spatial frequency of noise in x direction	cycles/deg
Δu	small variation of u	cycles/deg
Δu_n	small variation of u_n	cycles/deg
v	spatial frequency in y direction	cycles/deg
v_{max}	maximum spatial frequency in y direction	cycles/deg
v_{min}	minimum spatial frequency in y direction	cycles/deg

Symbol	Description	Unit
ν_{nmax}	maximum spatial frequency of noise in y direction	cycles/deg
ν_{nmin}	minimum spatial frequency of noise in y direction	cycles/deg
$V(\lambda)$	spectral sensitivity function for photopic light	-----
$V'(\lambda)$	spectral sensitivity function for scotopic light	-----
w	temporal frequency	Hz
x	integration variable	cond. dep.
	spatial variable in x direction	deg
Δx	small variation of x	deg
X	spatial size in x direction	deg
X_o	object size in x direction	deg
X_{max}	maximum integration area in x direction	deg
y	spatial variable in y direction	deg
Δy	small variation of y	deg
Y	spatial size in y direction	deg
Y_o	object size in y direction	deg
Y_{max}	maximum integration area in y direction	deg
z	integration limit of normal probability integral	-----

Greek symbols

Symbol	Description	Unit
α	relative active time of displayed luminance	-----
	constant for signal threshold of Weibull function	cond. dep.
β	steepness constant of Weibull function	-----
γ	exponent of displayed luminance variation	-----
γ_0	optimum value of γ	-----
ε	energy photon	Joule
η	quantum efficiency	%
ϑ	polar angle	deg
λ	wave length of light	nm
ν	light frequency of photon	sec^{-1}
π	numerical angle (3.1416...)	-----
σ	standard deviation	cond. dep.
	standard deviation of optical line-spread function	arc min
σ_0	standard dev. opt. line-spread function at small pupil size	arc min
σ_{ret}	part of this stand. dev. caused by discrete structure retina	arc min
σ_{00}	remaining part of this standard deviation	arc min
σ_{hor}	standard deviation of blur in horizontal direction	arc min
σ_{vert}	standard deviation of blur in vertical direction	arc min

Symbol	Description	Unit
σ_{dia}	standard deviation of blur in diagonal direction	arc min
σ_m	standard deviation of the modulation	-----
σ_n	relative standard deviation of the noise	-----
σ_n	relative standard deviation of the number of photons	-----
σ_r	relative standard deviation of the luminance	-----
τ	time constant of impulse response function	msec
τ_1	time constant of the function $H_1(w)$	msec
τ_{10}	value of τ_1 at low retinal illuminance and small field size	msec
τ_2	time constant of the function $H_2(w)$	msec
τ_{20}	value of τ_2 at low retinal illuminance and small field size	msec
$\Phi(u,v,w)$	spectral density	deg^2 sec
Φ_0	spectral density of neural noise	deg^2 sec
Φ_d	spectral density of nonwhite noise	cond. dep.
Φ_n	spectral density of white noise	cond. dep.
Φ_{ph}	spectral density of photon noise	deg^2 sec
$\Psi(u_n,u)$	weighting function of masking	-----

Remark:
In equations, non-standard units of variables have to be adapted to the standard units m, sec, deg, etc., unless otherwise specified.