VISUAL TOLERANCES FOR SIMULATOR OPTICS

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ABSTRACT

This paper discusses problems associated with the determination of tolerances for optical systems which are directly coupled to the human eye. Adequate total performance of the combined physical and physiological optical systems is shown to be dependent upon modifications of the optical image by the eye and processing of the retinal image by the brain. Physical, physiological, and psychological interactions are considered for application to simulator optical design.

INTRODUCTION

In designing optics for training simulators, the eye must be considered as an integral part of the system. Unlike photographic optics, in which the image is evaluated on a basis provided by the quantitative methods of physics, optics which are directly coupled to the eye are dependent upon perceptual and physiological criteria for acceptance of image quality. The optical designer's objective is to provide satisfactory performance at a minimum cost. This requires a knowledge of the tolerances of the human observer for optical aberrations.

In the field of optical design, the tolerances for physical optics have been based on the quarter-wave limit established by the third Lord Rayleigh in 1878. After studying the paths of light through optical systems, he concluded that the imagery is practically perfect if the differences between the optical paths leading to a selected focus did not exceed this limit. This does not mean that an inferior system will not produce satisfactory images for a particular purpose, but it indicates a limit for the most exacting work that is worth striving for but is hardly worth exceeding (Hardy and Perrin, 1932). This theorem has been reduced to various formulas that give tolerances which may be applied directly to any specific aberration. A. E. Conrady (1943) proposed some modifications of these formulas in the case of coma, astigmatism, and curvature of field in order to increase the tolerances resulting from the Rayleigh limit. For the type of optical systems used in visual simulation, however, even these modified tolerances are unnecessarily severe. What, then, are the visual tolerances for simulator optics? Or, if not known precisely, how can they be determined?

OPTICAL ABERRATIONS

There are other limitations besides diffraction that prevent an optical image from being a perfect copy of its corresponding object. These departures of an image from the predictions of first-order theory are called optical aberrations.

A lens suffers from seven major aberrations — five monochromatic and two chromatic. The five monochromatic aberrations are sometimes referred to as the Seidel aberrations after the German mathematician Ludwig von Seidel (1821-1896) who developed the third-order theory as a series of five correction terms for considering the behavior of the more oblique rays in a lens system. These five aberrations, which apply to light of a single wavelength, are: (1) spherical aberration, (2) coma, (3) astigmatism, (4) curvature of field, and (5) distortion. As in the case of spherical aberration in which two components are considered, chromatism is divided into (1) longitudinal and (2) lateral chromatic aberration. A description of these can be found in any textbook on optics. The human eye suffers from the same aberrations. In addition, binocular vision is concerned with imbalances between the two eyes. These imbalances may result from angular deviations of the visual axes of the two eyes or differences in magnification, color, or illumination presented to each eye individually.

Some work has been done concerning the aberrations of the human eye. The visual system is a delicately balanced one in which the eye's optics appear almost ideal for an aperture of about 2.5 mm. in diameter. Acuity is reduced by diffraction if the pupil is less than 2 mm. in diameter, or by spherical aberration if the pupil is over 3 mm. in diameter. Helmholtz's observation (Gubisch, 1967), made over a century ago, remains valid:

> "For the eye has every possible defect that can be found in an optical instrument, and even some which are peculiar to itself; but they are all so counteracted, that the inexactness of the image which results from their presence very little exceeds, under ordinary conditions of illumination, the limits which are set to the delicacy of sensation by the dimensions of the retinal cones. But as soon as we make our observations under somewhat changed conditions, we become aware of the chromatic aberration, the astigmatism, the blind spots, the venous shadows, the imperfect transparency of the media, and all the other defects of which I have spoken."

Some of these aberrations appear to function as error signal generators that influence control mechanisms for ocular adjustment. For instance, Fincham (1951) found that about 60 per cent of his subjects lost the ability to accommodate if the object was viewed in monochromatic light. This is suggestive that the chromatic aberration of the eye helps to provide an adequate stimulation for changes in accommodation.

OPTOMETRIC TOLERANCES

The question of primary importance to the designer concerns the amount of compensation that the eye can provide for aberrations of an optical system external to the eye; and for how long a period of time this ocular adjustment can be maintained without visual fatigue.

A starting point may be found in the tolerance standards of the optometric profession and military specifications for binoculars. However, the optical systems used for simulators are generally biocular, that is, viewing with both eyes in a device containing a single optical axis. Binocular systems have two optical axes which can be adjusted so that the visual axes of the two eyes are properly aligned with respect to each other. In biocular systems, both eyes share a common axis. This compounds the optical design correction problems, as variations in collimation and magnification across the exit pupil can cause fusion problems, especially for images near the edge of the field.

Some data on binocular instrument and optometric tolerances are listed in table 1. The actual image defects of the "Duoview" biocular visual system, as reported by Redifon Flight Simulation Limited, are included for comparison. Spooner (1973) reports that distortion and "swimming" (changes in the image with head position) are imperceptible in this system. The variations in these data are probably the result of differences in test conditions, measurement techniques, and in the experimenter's definition of tolerance. For instance, Gold's (1972) permissible binocular disparity tolerances were based on a psychometric rating system used to measure visual stress levels for sustained 15-second viewing. Time is an important variable in determining the tolerance values.

In analyzing the data shown in table 1, the distinction must be made between <u>instrument tolerances</u> and <u>eye tolerances</u> for collimation; the two being opposite in direction. For instance, when the optical axes of an instrument diverge, the eyes must converge in order to compensate. This is why the instrument tolerances, shown in the table, are larger for divergence and smaller for convergence. The tighter instrument tolerance on convergence results from the fact that any converging light will cause the eyes to diverge in an attempt to fuse the images, resulting in eye strain and in some instances, nausea. It may seem that, in general, there is a great amount of angular deviation to which the fusion reflex will respond in the horizontal than in the vertical direction.

In addition to the information listed in table 1, some supplementary comments are made in the following paragraphs.

<u>Spherical aberration</u> - The size of the aperture stop plays a major role in the control of this aberration. The iris of the eye serves to admit only a small bundle of rays from a limited surface area of the optical system. (Ophthalmic lenses of meniscus shape are not designed to minimize spherical aberration)(Borish, 1970).)

Tscherning (1904) demonstrated with an "aberrascope" that the spherical aberration of the eye changes during accommodation. As the eye accommodates, the aberration gets less and less until a point is reached (at 2.9 diopter in one subject) where there is essentially no spherical aberration at all. When the eye accommodates more than this, the aberration becomes negative (overcorrected) which means that rays entering through the edge of the pupil are brought to a focus behind those passing through the center. While individual differences in experiments of this kind are not unusual, the general trends are similar (Davson, 1969).

Illumination level must be considered as there is increased positive spherical aberration due to pupil dilation in dim illumination. Night myopia was noticed as early as 1883 by Lord Rayleigh. This is nearsightedness developed by the eye in dim illumination, requiring negative lenses to counteract the decrement in visual acuity. There are several causes for this: changes in accommodation, the combination of chromatic aberration and the Purkinje shift, and the fact that a point is not imaged on the retina as a point but forms a caustic along the visual axis near the retina due to the spherical aberration (Avant, 1968).

The magnitude of night myopia is a matter of dispute with values varying from nearly zero to more than 2 diopters. These variations in results are probably due to differences in experimental conditions and individual differences.

Coma - Where the pupil of the eye is the aperture stop of the system, it limits the bundle of rays from the lens to a very small diameter which in turn limits the coma. (Ophthalmic lenses are not usually corrected for coma.)

Astigmatism - 0.75 diopter of residual astigmatism is given as a limiting amount (Borish, 1970). Some individuals, however, have difficulty attaining satisfactory vision with lesser amounts, while some will tolerate greater amounts. Individual preferences or tolerances of the extent of blur which each finds acceptable tend to influence this. In general, as the age level of the person increases, the amount of residual astigmatism which elicits a demand for correction drops below 0.75 diopter.

Curvature of field - Field curvature and astigmatism are closely related aberrations. When marginal astigmatism is eliminated, the locus of points in image space form a parabolic surface called the Petzval surface. One diopter of field curvature is considered tolerable in eyepiece design (Shenker, 1972).

Distortion - The tolerance for distortion varies greatly, depending upon the use to which the optical system in question will be put. Ophthalmic lenses are not commonly corrected for distortion.

Chromatic aberration - The eye is not an achromatic system. It has about one diopter of chromatic aberration. Plus-ophthalmic lenses tend to increase the total chromatic aberration of the lens/eye system, whereas negative lenses tend to correct the chromatic aberration of the eye (Borish, 1970). This aberration is ignored in ordinary ophthalmic lenses.

In summary, this brief review indicates that coma and spherical aberration are not important in ophthalmic lenses because the pupil of the eye serves as a stop to limit the area of the lens through which light enters the eye. This limits the magnitude of these aberrations to relatively small amounts. Distortion and chromatic aberration are also ignored. Radial astigmatism and field curvature are the only ones of prime importance in ophthalmic lens design since they alter the focus of light passing through peripheral portions of the lens, thereby limiting the visual field through which clear vision can be provided (Borish, 1970).

Magnification - Ogle (1961) stated that a 0.5 per cent difference in magnification between the two eyes can be discriminated by persons with normal visual acuity. According to Richards (1962), magnification differences to the two eyes of 1 to 2 per cent or more usually result in visual strain and discomfort. Some people cannot tolerate more than 0.5 per cent whereas others may tolerate a little more than 2 per cent. Differences of 5 per cent usually preclude binocular vision. For instrument design, this reference recommends not more than 2 per cent.

Illumination - The amount of light to the two eyes should be balanced, preferably to within 10 per cent (MIL-HDBK-141). (Luminance difference,table 1.)

Chromatic differences - Beamsplitters should be neutral in order to prevent light of two significantly different wavelengths (e.g., red and blue) being directed to separate eyes. Should each eye receive a different color simultaneously, the accommodation of each would have to be different as a result of the chromatic aberration of the eye, and strain will result. Differences in spectral transmissions should not exceed about 12 per cent.

Vertical imbalance should not exceed 0.5 prism diopter (about 17 minutes of arc). Horizontal imbalance need not be quite so small, but in excess of this value would be fatiguing (MIL-HDBK-141). Spectacle prescription holds to about 0.25 prism diopter horizontally and 0.125 prism diopter vertically (Sheppard, 1952).

APPLICATION TO SIMULATOR OPTICS

The tolerances discussed and shown in table 1 may serve as a guide for visual simulation design; however, the design correction problems of biocular-type optics may require tighter tolerances than these. Note that the collimation errors over the field of view of the "Duoview" biocular system exceed the convergence tolerances but fall within the divergence and dipvergence tolerances listed in the table. Based on experience at the Farrand Optical Company, 1/29th diopter (24 minutes of arc) collimation tolerance appears to be in the proper order of magnitude for the design of biocular displays having infinity as their nominal focal setting. This limits the parallelism tolerances for the two eyes to an intersection distance from the eyes of the observer of a minimum of 9 meters. However, Shenker (1972) stresses the importance of 0 convergence in these systems.

These questionable tolerances should be determined experimentally by using a biocular display with variable optical parameters which can be set at known values. Subjects could then be used to test the effects of various amounts of aberrations on eye fatigue while viewing across different portions of the exit pupil and over extended time periods of uninterrupted viewing. A research program of this type was conducted recently by Theodore Gold (1972) of the Sperry Rand Corporation to establish binocular disparity tolerances for head-up displays. The experimental device he used provided on-axis viewing through twin optical channels. His results are listed in table 1.

Dr. Gottfried Rosendahl of the Naval Training Equipment Center's Physical Sciences Laboratory plans to refine and add to the limited tolerance data that we have been able to derive from the various sources cited. This will be a joint effort which will involve psychophysical experimentation to determine the human visual tolerances and a lens analysis and design computer program (e.g., the ACCOS-V used on the SIGMA-7) to design reflective and refractive optics for biocular, virtual image systems. We anticipate that this work will provide a foundation upon which to build cost-effective visual simulators by providing more realistic specifications for their optical systems.

TABLE 1. VISUAL TOLERANCES

Eye/Instrument	TOLERANCES								REFERENCES
	Magn. diff.	Lum. diff.	Color diff.	Field curv.	Astigm. Diff.	Collimation			
						Converg.	Diverg.	Dipverge.	
Binoculars									MIL-B-17311(SHIPS) 25 Sep 1952
Type I (7x50)	1%			2 D.		14 min.	28 min.	14 min.	
Type II (6x42)	1%			1 D.					
Binoculars M19 & M20 (7x50)	2%					0	40 min.	15 min.	MIL-B-60884A(MU) 12 Mar 1970
Binocular (7x50)						0	24 min.	15 min.	Shenker, M. (1972)
Binocular collimated projection (tol. for eyes)						9 min.	* 3 min. 22.5 sec.	3 min. 22.5 sec.	Gold, T. (1972)
Eyes	1-2%	10%	12%			17 min.	17 min.	17 min.	MIL-HDBK-141 Optical Design (1962)
Eyes					0.75D.				Borish, I.M. (1970)
Eyepieces				1 D.	1 D.				Shenker, M. (1972)
Spectacles						9 min.	9 min.	4 min.	Sheppard, C.F. (1952)
"Duoview" biocular system (tol. for eyes)						< 20 min.	< 10 min.	<10 min.	Spooner, A.M. (1973)

* 3'22.5" = 1 milliradian

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GLOSSARY

Accommodation - A function of the human eye, whereby its total refracting power is varied in order to see objects clearly at different distances.

Beamsplitter - An optical device for dividing a light beam into two separate beams. A simple beamsplitter is a plane parallel glass plate with one surface coated with a dielectric or metallic coating which acts as a partial reflector. After striking this surface, part of the incident beam is transmitted through the plate and part is reflected. The thickness of the metallic coating will determine the proportions of light reflected and transmitted. It may be necessary to match the reflected and transmitted beam not only for brightness (luminance), but for color. In these cases, it will be necessary to use a material at the interface which gives the same color of light, both by transmission and reflection. Where color matching at the surface or interface cannot be accomplished, a color correcting filter may be placed in one of the beams.

Brightness - The effect upon sensation by means of which an observer is able to distinguish differences in luminance.

Caustic - Rays that pass through consecutive zones intersect in a curve known as a caustic. Rotation of the caustic about the axis gives a three-dimensional figure, the caustic surface. The point, or cups, of the caustic lies on the axis at the paraxial focus.

Collimation - The process of aligning the optical axis of an optical system to the reference mechanical axes or surfaces of an instrument; or the adjustment of two or more axes with respect to each other. The process of making light rays parallel.

Convergence - The bending of light rays towards each other, as by a convex or plus lens. Horizontal rotation of the eyes inwards for viewing near objects.

Diopter - (symbol D. or abbreviated DIOPT.) A unit of refraction power of a lens or prism. In a lens or lens system, it is numerically equal to the reciprocal of the focal length measured in meters. For example, if a lens has a focal length of 25 centimeters (i.e., 1/4 meter), its power is 4 diopters. A prism diopter is the power of a prism to deviate a ray of light by one centimeter at a distance of one meter from the prism.

Dipvergence - The vertical angular disparity between the images of a common object seen through the left and right systems in a binocular instrument. It is defined as plus when the right image is below the left image.

Divergence - The bending of light rays away from each other, as by a concave or minus lens, or by a convex mirror. In a binocular instrument, divergence is the horizontal disparity between the images of a common object, as seen through the left and right systems. It is defined as positive when the right image is to the right of the left image. When applied to the eyes, divergence is an outward horizontal rotation of the eyes.

First-order theory - For a ray in the vicinity of the optical axis (a paraxial ray), the slope angle becomes so small that only the first term of the equation expressing the sine of the angle may be used. The higher order terms may be ignored. It is also called the *GAUSS theory* from the mathematician who first developed it. Rays traced by means of first-order theory will show only a few of the aberrations. However, if we take the first *two* terms into account, we find all the aberrations. Because the second term in the expansion is of the third order, theory derived from this term is known as *third-order* theory.

Luminance - The ratio of the luminous intensity emitted in a given direction by an infinitesimal area of the source to the projection of that area of the source upon the plane perpendicular to the given direction. Usually stated as luminous intensity per unit area; i.e., *luminous flux* per unit solid angle emitted per unit projected area.

Meniscus - A lens having surfaces, one which is *convex*, the other *concave*.

Myopia - Nearsightedness.

Paraxial - Near the optical axis.

Psychometrics - Psychological measurement. Measurement of aspects of behavior or personality.

Psychophysics - The study of quantitative relations between physical stimuli and the resulting conscious sensations, particularly in the determination of sensory thresholds.

Purkinje (Purkyně) shift - As the illumination decreases, the eye becomes relatively more sensitive to the blue end of the spectrum and decreasingly sensitive to the red end. This shift appears to begin at an illumination level of about 1 lumen per square foot.

ABOUT THE AUTHOR

MR. JOSEPH A. PUIG is Research Psychologist in the Human Factors Laboratory at the Naval Training Equipment Center. He received his B.A. and M.S. degrees from New York University and an M.A. in Experimental Psychology from St. John's University. In 1958, he joined the Grumman Aircraft Engineering Corporation where he participated in the Lunar Module Program as Group Leader, Visibility and Optics Section. This assignment involved human factors research as applied to spacecraft controls and displays, lighting, and visibility. After 10 years with Grumman, he joined the Naval Training Equipment Center in 1968. His major duties here involve the evaluation of training systems, and studies in the application of human factors principles to simulation. He is a member of the Institute of Electrical and Electronic Engineers.