Contrast Sensitivity and Reading Through Multifocal Intraocular Lenses

Hiromi Akutsu, MA; Gordon E. Legge, PhD; Michael Showalter; Richard L. Lindstrom, MD;
Ralph W. Zabel, MD; Virginia M. Kirby, MS

• Multifocal intraocular lenses are intended to increase depth of focus for patients with cataracts, but optical considerations predict reduced retinal-image contrast. We evaluated visual performance through multifocal intraocular lenses by measuring contrast sensitivity functions and reading speed for age-matched groups with multifocal and monofocal intraocular lenses and two normal control groups. Contrast sensitivity functions of the patients with multifocal lenses did not differ significantly for optical distances differing by 2.5 diopters, indicating substantial depth of focus. Normal and monofocal contrast sensitivity functions were nearly identical, and both were about a factor of two higher than multifocal contrast sensitivity functions. Patients with multifocal lenses showed deficits in reading speed only for low-contrast text (<30%) and small letters (0.2° and 1.0°).

(*Arch Ophthalmol.* 1992;110:1076-1080)

Multifocal intraocular lenses (IOLs) increase depth of field for patients with cataracts by simultaneously creating images on the retina that are conjugate with two or more depth planes. An object in one of these depth planes—such as a page of text at a normal reading distance—will produce a focused image on the retina superimposed on a highly defocused image of the same object. The defocused image is thought to act like a veiling source of light that reduces the contrast of the focused image. Analogous considerations led to the prediction of a contrast reduction for concentric bifocal contact lenses,[1] subsequently confirmed by psychophysical measurements.[2-4]

Optical measurements indicate that contrast is reduced to 25% of normal values by a concentric-zone bifocal IOL[5] (for a 6-mm pupil). For the diffractive IOL (3M Vision Care, St Paul, Minn) used in the present study, simple optical theory predicts that the focused image will be reduced to about 40% of normal contrast.[6] Consistent with theory, optical measurements of the IOL's modulation transfer function (MTF) by Holladay and his colleagues[7] indicated a twofold to threefold reduction in image contrast above about 5 cycles/degree (c/deg).

A key step in understanding the visual characteristics of multifocal IOLs is to determine whether patients show an enhanced depth of focus and reduced contrast sensitivity consistent with optical theory and measurement. The contrast sensitivity function (CSF) for sine-wave gratings provides a detailed characterization of the visual response to contrast. It is a behavioral analogue of the optical MTF.

Our first purpose was to determine whether patients with diffractive multifocal IOLs would show the predicted increased depth of field and twofold to threefold reduction in contrast sensitivity. We measured sine-wave CSFs for patients with multifocal and monofocal lens implants and normal phakic subjects. Measurements were conducted at near, intermediate, and far focus for the multifocal group. In addition, we measured contrast thresholds for letter identification across a range of character sizes and compared the results with those obtained with the Pelli-Robson chart.[15]

Previous measurements of acuity and contrast sensitivity indicate an increased depth of focus for patients with multifocal lenses.[8-13] Only one of the published studies compared the CSFs of patients with multifocal and monofocal IOLs.[10] They found no difference between multifocal and monofocal CSFs (both measured at the far focus).

If patients with multifocal IOLs show evidence of a reduction in contrast sensitivity, it is important to ask about the consequences for real-world visual function. Reading is a key real-world task. Previous research has documented the effects of contrast and character size on reading speed.[14] Our second purpose was to evaluate the effect of contrast attenuation through multifocal IOLs on reading speed.

SUBJECTS AND METHODS

There were seven subjects in each of four groups (Table 1). Age was matched for the *multifocal, monofocal, young-normal,* and *old-normal* groups. The young-normal group was included for comparison. All 28 subjects had distance visual acuities of 20/32 (log minimal angle of resolution, 0.2) or better. All measurements were conducted monocularly. Optical powers are given relative to the subject's distance correction.

Patients in the multifocal group had dif-

Accepted for publication February 19, 1992.

From the Department of Psychology, University of Minnesota, Minneapolis (Messrs Akutsu and Showalter and Dr Legge); Phillips Eye Institute, Center for Teaching and Research, Minneapolis (Drs Lindstrom and Zabel); and 3M Vision Care, St Paul, Minn (Ms Kirby).

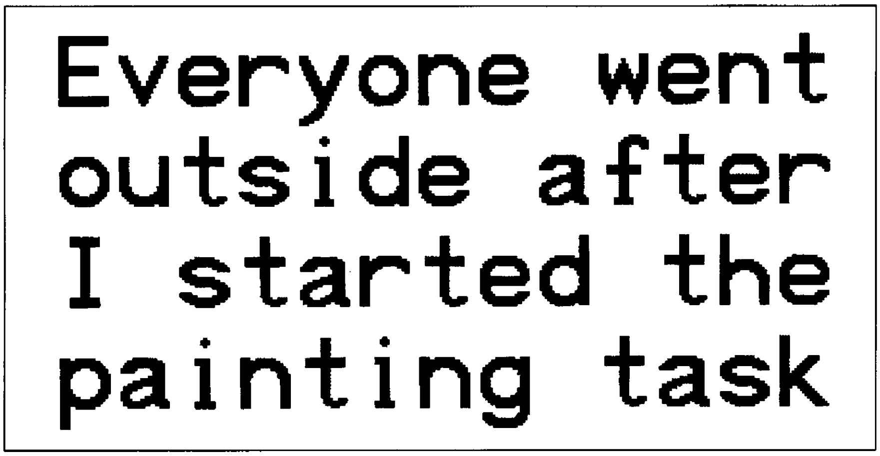
Presented in part at the annual meeting of the Association for Research in Vision and Ophthalmology, April 29, 1991, Sarasota, Fla.

Reprint requests to Department of Psychology, University of Minnesota, 75 E River Rd, Minneapolis, MN 55455-0344 (Mr Akutsu).

Table 1.—Subjects' Acuities and Contrast Sensitivities*

Subject	Age, y	Visual Acuity, LogMAR			Contrast Sensitivity, Log U
		Far Focus	Intermediate Focus	Near Focus	
Young-Normal Group					
1	20	0.0	0.1	0.1	1.73
2	37	0.0	0.1	0.2	1.80
3	32	−0.1	−0.1	0.0	1.65
4	33	0.0	−0.1	−0.1	1.80
5	20	0.0	0.0	0.0	1.80
6	22	−0.1	−0.1	−0.1	1.95
7	24	−0.1	−0.2	−0.1	1.80
Mean±SD	26.9±6.5	−0.043±0.049	−0.043±0.105	0.0±0.107	1.79±0.08
Old-Normal Group					
8	57	0.0	0.6	1.0	1.65
9	66	0.1	0.5	0.9	1.65
10	70	0.0	0.5	0.7	1.57
11	68	0.1	0.4	0.6	1.65
12	68	−0.1	0.1	0.0	1.65
13	64	0.1	0.3	0.7	1.80
14	70	0.1	0.5	0.8	1.43
Mean±SD	66.1±4.2	0.043±0.073	0.414±0.155	0.671±0.301	1.63±0.10
Monofocal IOL Group					
15	68	0.0	0.2	0.6	1.73
16	76	0.0	0.2	0.7	1.58
17	66	0.1	0.4	0.4	1.58
18	73	0.0	0.2	0.8	1.65
19	70	0.0	0.4	0.7	1.50
20	75	0.0	0.1	0.0	1.65
21	63	0.0	0.7	0.9	1.50
Mean±SD	70.1±4.5	0.014±0.035	0.314±0.188	0.586±0.280	1.60±0.08
Multifocal IOL Group					
22	62	0.0	0.5	0.1	1.50
23	65	0.0	0.5	0.0	1.50
24	68	0.1	0.4	0.0	1.65
25	79	0.2	0.5	0.1	1.50
26	64	0.0	0.2	0.3	1.50
27	61	0.0	0.3	0.7	1.80
28	69	0.0	0.1	0.0	1.43
Mean±SD	66.9±5.6	0.043±0.073	0.357±0.150	0.171±0.237	1.55±0.12

*MAR indicates minimal angle of resolution; IOL, intraocular lens. Contrast sensitivity was measured with the Pelli-Robson chart.



Everyone went outside after I started the painting task

Fig 1.—An example of text used in the reading experiment. To measure reading speed, exposure time was decreased until the subject could not complete reading the text. The character size was varied by changing the viewing distance.

fractive multifocal IOLs (3M model 815 LE) implanted. Patients in the monofocal group received monofocal IOLs (3M model 15 LE) that were identical to the multifocal IOLs in all respects except for the optical element. Design characteristics common to both implants included three-piece construction, all-polymethylmethacrylate composition incorporating an ultraviolet-absorbing chromophore, modified C haptics, convex-concave optic shape, 6.0-mm diameter, 10° posterior angulation, and A constant of 116.5. The concave surface of the multifocal implant (model 815 LE) has, in addition, concentric zone plates that provide 3.5 diopters (D) of near correction (roughly 2.4 D in the spectacle plane[6(pp119-120)]).

Visual testing of patients was conducted at least 4 months after the implant surgery. Clinical examination verified that there was no abnormal tilt or decentration of the lens, or other ocular pathology. Patients 17 and 21 in the monofocal group and patient 22 in the multifocal group were found to have trace capsular haze.

Old-normal subjects were examined clinically before testing to ensure that they were free of ocular disease. The young-normal subjects were college students. They were recruited into the study based on normal acuity and self-reports of good ocular health.

Visual acuity was measured at a 4-m viewing distance with a Light House Early Treatment Diabetic Retinopathy Study chart (The Light House Inc, New York, NY) illuminated to 100 cd/m^2. Acuities were also measured for all subjects at the same viewing distance with the addition of −2.50-D and −1.25-D spectacle lenses to simulate targets at near and intermediate focus. Letter contrast sensitivities were measured with the Pelli-Robson chart[15] at 1 m. Contrast sensitivity functions were measured with sine-wave gratings at 4 m. The spatial frequencies were 1, 2, 4, 8, 16, and 24 c/deg. The gratings were displayed on a specially designed cathode ray tube monitor (Joyce Electronics Ltd, Cambridge, England) with linear contrast-voltage response and a mean luminance of 170 cd/m^2. Threshold contrast was estimated by means of the Quest staircase procedure.[16] In each trial, a grating of specified contrast appeared on the left or right of the screen. The subject pressed a button indicating on which side the grating was present. The Quest algorithm changed grating contrast, dependent on the subject's responses, to obtain a threshold estimate. Each staircase consisted of 40 trials. Two thresholds were measured at each spatial frequency for each subject. The reciprocal of mean threshold is contrast sensitivity. For the patients in the multifocal group only, CSF measurements were also made with the addition of −2.50-D and −1.25-D spectacle lenses to simulate targets at near and intermediate focus.

In this article, we use the Michelson definition of contrast for both gratings and letters. Contrast is equal to $(L_{max}-L_{min})/(L_{max}+L_{min})$, where L_{max} and L_{min} are maximum and minimum stimulus luminances, respectively (peaks and valleys for gratings, background and characters for letters). Michelson contrast ranges from 0 to 1.0.

Contrast thresholds were measured for

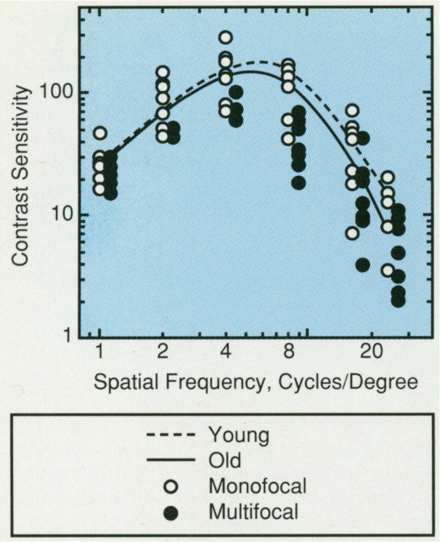


Fig 2.—Contrast sensitivity functions for sine-wave gratings at far focus. Average contrast sensitivity functions are plotted for the young-normal subjects and old-normal subjects. Individual data are shown for monofocal patients and multifocal patients.

Table 2.—Mean CSF Data for Four Groups at Far Focus*

	CSF by Spatial Frequency, Cycles/Degree					
Group	1	2	4	8	16	24
Young	27.0	76.1	153.2	150.7	40.4	14.4
Old	27.2	70.7	135.4	118.8	27.3	8.0
Monofocal	28.4	83.6	140.3	107.9	29.6	8.4
Multifocal	20.3	46.6	69.2	36.7	13.1	4.7

*CSF indicates contrast sensitivity function. Data are geometric means based on two measures for each subject.

isolated letters displayed at the center of a video screen (dark characters against a light background of 300 cd/m^2). Letter size ranged from 0.1° to 6.0° (20/24 to 20/1440 Snellen equivalent), accomplished by changing viewing distance and video zoom. Letter contrast was reduced by making the letters less dark (ie, increasing letter luminance toward the background level). The targets were 10 Sloan optotypes, digitized as 32×32-pixel images. Contrast was reduced 0.1 log unit if the subject correctly identified six or more letters in a series of eight at a given contrast level. Contrast threshold was defined as the lowest contrast for which the subject met this criterion. Two such thresholds were measured and the mean was computed.

Reading speed (words per minute) was measured with a computer-based technique.[17] Subjects read aloud short sentences that appeared for timed intervals on a video display (Fig 1). In successive presentations, the exposure time was decreased until the subject could no longer read the complete sentence. Reading speed was computed as the number of words correctly read divided by the exposure time. Reading speed was measured as a function of text contrast (5%, 10%, 30%, and 98%) and character size (0.2°, 1°, and 6°). Character size was varied by changing viewing distance, with special care to refract subjects appropriately.

Analysis of variance was used to test for group or stimulus variable effects, or their interaction. We used Tukey's Honestly Significant Difference[18] to evaluate pairwise differences between groups. In the following text, statements about statistical significance refer to a criterion *P* value of .05.

RESULTS

The pairwise comparison of old-normal and monofocal groups revealed only one statistically significant difference (reading speed for 0.2° characters of 10% contrast). In the following, we explicitly cite comparisons of multifocal and old-normal groups, but nearly identical findings emerged from comparisons of multifocal and monofocal groups.

Contrast-sensitivity functions are shown in Fig 2. The young-normal subjects showed greater sensitivity at high spatial frequencies, in agreement with previous findings.[19] Mean sensitivities for the four groups are shown in Table 2.

The CSFs for the normal and monofocal groups did not differ significantly. Both were significantly higher than the CSFs in the multifocal group. The difference averaged about a factor of two. In addition, there was a significant frequency-by-group interaction indicating that the multifocal deficit was frequency dependent. Multifocal sensitivities were nearest normal for the lowest two spatial frequencies (1 and 2 c/deg) and showed greatest departure at 8 c/deg. Relative to normal, mean multifocal contrast sensitivities were 75% at 1 c/deg, 66% at 2 c/deg, 51% at 4 c/deg, 31% at 8 c/deg, 48% at 16 c/deg, and 59% at 24 c/deg.

If we assume that the patients in the multifocal group differed from the old-normal subjects only because of the contrast attenuation of the IOL, we can estimate the IOL's MTF by taking the ratio of multifocal to old-normal CSFs. A value of 1.0 means no contrast attenuation due to the IOL. Figure 3 shows such contrast sensitivity ratios for the multifocal and monofocal groups. Also shown is the MTF measured optically by Holladay and his colleagues.[7] The monofocal values did not differ significantly from 1.0, indicating no contrast attenuation. The multifocal ratios dropped below 1.0, indicative of contrast attenuation. There was good agreement between the multifocal data and the MTF measured by Holladay and his colleagues.

Depth of focus can be evaluated in Fig 3 from the multifocal data for near and intermediate focus. Multifocal CSFs for near, intermediate, and far focus (spanning 2.5 D) did not differ significantly. This tolerance to defocus is further illustrated by the acuity data in Table 1. At the near focus, multifocal acuities were significantly higher than those of the monofocal and old-normal groups. The far- and intermediate-focus acuities did not differ significantly between the three groups.

Figure 4 shows contrast thresholds for letter identification as a function of angular character size. Two patients in the multifocal group (patients 22 and 27) and one subject in the old-normal group (subject 13) could not reach criterion performance at the maximum letter contrast (98%) for 0.1° letters, so this condition was excluded from the statistical analysis. Group comparisons showed no significant differences between the normal and monofocal subjects. Thresholds were significantly higher for the multifocal group at the two smallest character sizes analyzed (0.3° and 1.0°), but not for larger characters. Pelli-Robson letter contrast sensitivities, based on characters subtending about 3°, did not differ significantly between the three groups (Table 1).

Figure 5 shows reading speed (words per minute) as a function of contrast for three character sizes. For some low-contrast conditions, there were subjects who could not read at all (Table 3). (In the statistical analysis, these subjects were assigned a reading rate of 10 words per minute.) For the largest character size (6°), there were no significant differences in reading performance among the groups at any contrast. For the 1° characters, reading speed for the multifocal group was significantly lower than that for the other groups only for the lowest-contrast (5%) text. For the smallest characters (0.2°), patients in the multifocal group did not differ significantly at the highest contrast but read significantly more slowly than the old-normal subjects at 10% and 30% contrast. Table 3 shows that all groups (including the young-normal) had difficulty reading the 0.2° text at 5% contrast.

To summarize the reading results, the patients in the multifocal group read at normal rates when the text contrast was high. They read more slowly than their monofocal or normal contemporar-

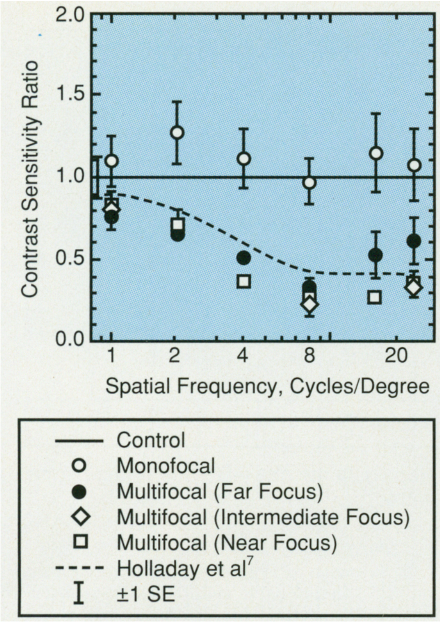


Fig 3.—Behavioral estimates of modulation transfer functions as ratios of multifocal (closed circles, far focus; open diamonds, intermediate focus; and open squares, near focus) or monofocal (open circles) contrast sensitivity to old-normal contrast sensitivity. Compare with the optical modulation transfer function measured by Holladay et al.[7] The horizontal line at 1.0 indicates normal sensitivity.

Table 3.—Numbers of Subjects Who Could Not Read in Specific Conditions

	0.2° Characters				1.0° Characters				6.0° Characters			
Group Contrast	5%	10%	30%	98%	5%	10%	30%	98%	5%	10%	30%	98%
Young	5	0	0	0	0	0	0	0	1	0	0	0
Old	6	0	0	0	0	0	0	0	1	0	0	0
Monofocal	7	3	0	0	0	0	0	0	2	1	0	0
Multifocal	7	6	1	0	2	0	0	0	0	0	0	0

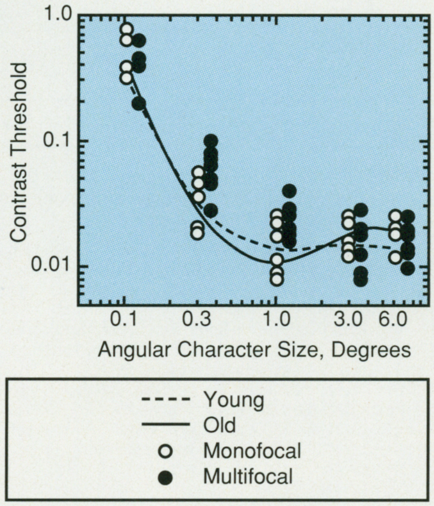


Fig 4.—Contrast thresholds for letter identification as a function of angular character size from 0.1° to 6.0° (20/24 to 20/1440 Snellen equivalent). Average data are plotted for the young-normal subjects and old-normal subjects. Individual data are shown for the monofocal and multifocal patients.

ies at low text contrasts, especially near the acuity limit.

COMMENT

Our results showed behaviorally that vision through the multifocal IOL trades off a reduction in contrast sensitivity for an increased depth of field. The CSF results indicate that the contrast sensitivities of patients with multifocal IOLs are lower than those of age-matched normal subjects or patients with monofocal IOLs. The difference can be explained entirely by the optical MTF of the multifocal IOL.[7] The reduction in multifocal contrast sensitivity is spatial frequency dependent, being less than a factor of two at 1 and 2 c/deg and a little more than a factor of two at higher frequencies. The frequency effect is consistent with the optical MTF and has implications for character-size effects in letter recognition and reading (see below). Also in agreement with optical theory, multifocal contrast sensitivities did not differ significantly at near and far focus.

Our CSF results differed from the only previous study comparing CSFs of subjects with monofocal and multifocal IOLs. Olsen and Corydon[10] found no difference in monofocal and multifocal CSFs. Their failure to find a difference may be related to use of the Vistech chart (Vistech Consultant Corp, Dayton, Ohio), which is less sensitive than the grating technique we used.[20] In a later study, Olsen and Corydon[11] compared multifocal and monofocal contrast sensitivities measured with the Pelli-Robson chart. They used a viewing distance for which the characters subtended 0.5° and found multifocal sensitivities reduced to about 72% of monofocal sensitivities. Our results for isolated letters (Fig 4) showed a greater reduction in sensitivity (to about 50%) for this character size.

What is the significance of a loss of contrast sensitivity for letter recognition and reading? Previous research has shown that reading and letter recognition require spatial frequencies extending up to about 2 cycles per character width.[21,22] For example, letters subtending 1° require spatial frequencies up to 2 c/deg, but letters subtending 0.2° require frequencies up to 10 c/deg.

Letters on the Pelli-Robson chart, when viewed from 1 m as in our study, subtend about 3° and thus require only low spatial frequencies (<1 c/deg) for identification. As shown in Fig 2, the multifocal deficit at 1 c/deg is small or nonexistent, so it is not surprising that patients with multifocal lenses show no deficit in the Pelli-Robson test. Lehmann[13] also reported no deficits in Pelli-Robson testing of patients with multifocal IOLs. The letter-identification data in Fig 4 show that multifocal contrast thresholds are elevated relative to the other groups for 1° characters and smaller. This is consistent with the CSF data because these are letters that require 2 c/deg and higher frequencies for identification.

For people with normal vision, text contrast can be reduced to about 10% while having only slight effects on reading speed.[14] Below 10%, reading speed drops off rapidly. Only near the acuity limit does normal reading speed require high contrast. On these grounds, we would expect multifocal reading speed to be normal except for low text contrast or for letters near the acuity limit. This is exactly what we found. Multifocal reading speed for 6° characters was normal. For 1° characters, multifocal reading speed was normal except for low text contrast. For 0.2° (12 minutes of arc), which is near the acuity limit, multifocal reading speed was reduced at all contrasts but the highest. These results establish a link between the contrast-transmission properties of the multifocal IOL and reading performance.

Our findings indicate that the loss of contrast sensitivity due to multifocal IOLs will have little impact on reading speed unless the text has tiny letters or low contrast. At a standard reading distance (40 cm), the text letters in *Archives of Ophthalmology* subtend approximately 0.26°. Patients with multifocal IOLs will show no deficits in reading this text as long as the contrast remains high. They may encounter some difficulty in reading newsprint at 40 cm if the contrast is poor. Problems with fine print may be exacerbated in dim light (for instance, reading a menu in a poorly lit restaurant) when contrast sensitivity is further reduced for everyone. Highway signs may require rapid reading near the acuity limit. (Regulations require lettering on freeway signs to be at least 8 inches,[23] equivalent to

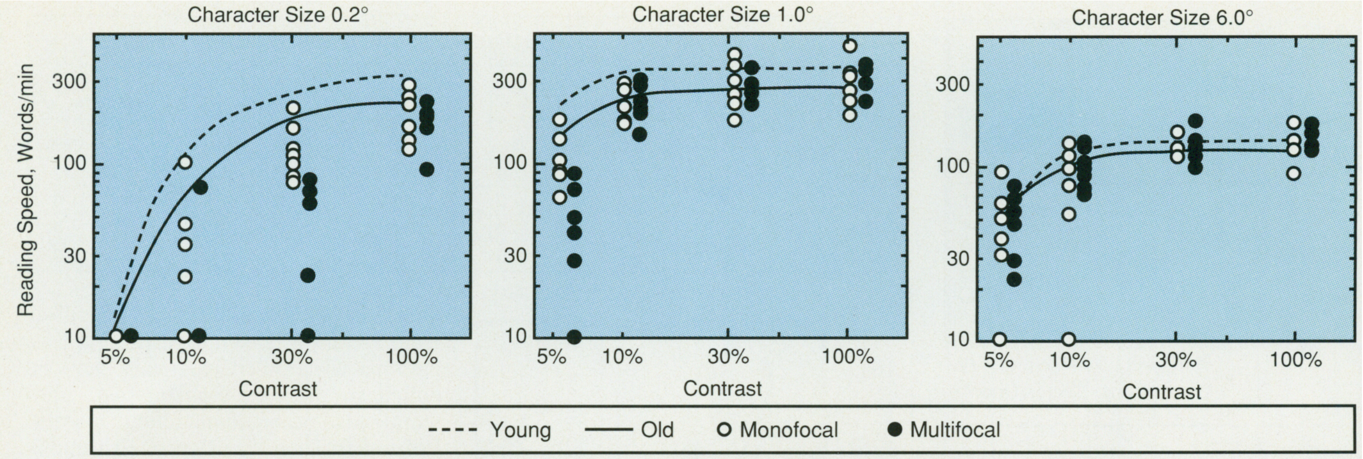


Fig 5.—Reading speed as a function of contrast for three character sizes: 0.2°, 1.0°, and 6.0°. Average data are plotted for the young-normal subjects and old-normal subjects. Individual data are shown for the monofocal and multifocal patients.

0.1° at a viewing distance of 100 m.) Since reading speed becomes highly dependent on retinal contrast near the acuity limit, patients with multifocal IOLs may need to be slightly closer to such signs before reading them rapidly.

It is rare to encounter low-contrast text (<30%). Veiling glare on a computer screen is one case in which this can occur. In such a case, patients with multifocal IOLs may experience greater difficulty than normal readers, and so care in adjusting lighting conditions may be important.

Reading is a visual task that typically uses high-contrast images of medium or high resolution. How would the multifocal IOL be expected to affect performance on other real-world visual tasks? Low-resolution tasks, such as visually guided walking,[24,25] should be unaffected because the multifocal IOL has little or no effect on low-frequency contrast sensitivity. Faces are stimuli with features having a range of contrasts. One study[26] showed that contrast thresholds for face recognition are quite low, indicating that normal vision can tolerate much more than a twofold attenuation of contrast in this task. Accordingly, we would expect patients with multifocal IOLs to have little trouble with face recognition. For the most part, human vision is designed to tolerate large changes in image contrast with small effects on performance. Only under low-contrast viewing or near the acuity limit (where tolerance to contrast reduction breaks down) would we expect patients with multifocal IOLs to experience any difficulty.

This research was supported by a grant from the 3M Vision Care and a fellowship from the Graduate School of the University of Minnesota, Minneapolis (Mr Akutsu).

We thank Andrew Luebker for his technical assistance, Dena Naylor for help with subject recruitment, and Steve Maa for technical assistance.

Drs Legge and Lindstrom receive payments as consultants for the 3M Vision Care. Ms Kirby is an employee of the 3M Vision Care. Messrs Akutsu and Showalter and Dr Zabel have no commercial or proprietary interest in the 3M diffractive multifocal IOL.

References

1. Klein SA, Ho Z. Multizone bifocal contact lens design. *Soc Photo-Optical Instr Engineers.* 1986; 679:25-35.
2. McGill E, Ames K, Erickson P, Robboy M. Quality of vision with hydrogel simultaneous vision bifocal contact lenses. *Int Contact Lens Clinic.* 1987;14:476-482.
3. Collins MJ, Brown B, Bowman KJ. Contrast sensitivity with contact lens corrections for presbyopia. *Ophthalmol Physiol Opt.* 1989;9:133-138.
4. Charman WN, Walsh G. Retinal image quality with different designs of bifocal contact lenses. *Trans Br Contact Lens Assoc.* 1986;9:13-19.
5. Atebara NH, Miller D. An optical model to describe image contrast with bifocal intraocular lenses. *Am J Ophthalmol.* 1990;110:172-177.
6. Simpson MJ. The diffractive multifocal intraocular lens. *Eur J Implant Refract Surg.* 1989; 1:115-121.
7. Holladay JT, van Dijk H, Lang A, et al. Optical performance of multifocal intraocular lenses. *J Cataract Refract Surg.* 1990;16:413-422.
8. Duffey RJ, Zabel RW, Lindstrom RL. Multifocal intraocular lenses. *J Cataract Refract Surg.* 1990;16:423-429.
9. Hansen TE, Corydon L, Krag S, Thim K. New multifocal intraocular lens design. *J Cataract Refract Surg.* 1990;16:38-41.
10. Olsen T, Corydon L. Contrast sensitivity in patients with a new type of multifocal intraocular lens. *J Cataract Refract Surg.* 1990;16:42-46.
11. Olsen T, Corydon L. Contrast sensitivity as a function of focus in patients with the diffractive multifocal intraocular lens. *J Cataract Refract Surg.* 1990;16:703-706.
12. Vanderschueren I, Zeyen T, D'heer B. Multifocal IOL implantation: 16 cases. *Br J Ophthalmol.* 1991;75:88-91.
13. Lehmann RP. Paired comparison of contrast sensitivity in diffractive multifocal IOLs and conventional monofocal IOLs. *Aust N Z J Ophthalmol.* 1990;18:325-328.
14. Legge GE, Rubin GS, Luebker A. Psychophysics of reading, V: the role of contrast in normal vision. *Vision Res.* 1987;27:1165-1177.
15. Pelli DG, Robson JG, Wilkins AJ. The design of a new letter chart for measuring contrast sensitivity. *Clin Vis Sci.* 1988;2:187-199.
16. Watson AB, Pelli DG. QUEST: a bayesian adaptive psychometric method. *Perception Psychophysics.* 1983;33:113-120.
17. Legge GE, Ross JA, Luebker A, LaMay JM. Psychophysics of reading, VIII: the Minnesota Low Vision Reading Test. *Optom Vis Sci.* 1989;66: 843-853.
18. Howell DC. *Statistical Methods for Psychology.* Boston, Mass: PWS Publishers; 1982.
19. Owsley C, Sekuler R, Siemsen D. Contrast sensitivity throughout adulthood. *Vision Res.* 1983; 23:689-699.
20. Rubin GS. Reliability and sensitivity of clinical contrast sensitivity tests. *Clin Vis Sci.* 1988;2: 169-177.
21. Legge GE, Pelli DG, Rubin GS, Schleske MM. Psychophysics of reading, I: normal vision. *Vision Res.* 1985;25:239-252.
22. Parish DH, Sperling G. Object spatial frequencies, retinal spatial frequencies, noise and the efficiency of letter discrimination. *Vision Res.* 1991;31:1399-1415.
23. US Federal Highway Administration. *Manual on Uniform Traffic Control Devices: For Streets and Highways.* Washington, DC: US Dept of Transportation, Federal Highway Administration; 1988.
24. Pelli DG. The visual requirements of mobility. In: Woo GC, ed. *Low Vision: Principles and Applications.* New York, NY: Springer-Verlag NY Inc; 1987:134-146.
25. Marron JA, Bailey IL. Visual factors and orientation-mobility performance. *Am J Optom Physiol Opt.* 1982;59:413-426.
26. Isenberg L, Luebker A, Legge GE. Image enhancement of faces for normal and low vision. *Invest Ophthalmol Vis Sci.* 1989;30(suppl):396. Abstract.