Psychophysics of Reading

III. A Fiberscope Low-Vision Reading Aid

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Existing reading aids providing magnification in excess of 6× (24 diopters) are awkward to use, expensive, or not portable. The authors have developed a new type of reading aid, a low-resolution fiberscope, that provides magnification up to 40× (160 diopters), and is easy to use, inexpensive, and portable. The fiberscope consists of an objective–lens assembly, a flexible bundle of optical fibers, and an eyepiece that together transmit an image from the page to the reader's eye. Complete construction details are included. The design is based on the authors' previous findings that reading requires a field of only four characters and a resolution of only 2 cycles/character. After only half an hour of training, a diverse group of low-vision readers read with the fiberscope at rates between 12 and 95 words/minute. Low-vision readers with central field loss had a median reading rate of only 18 words/min, whereas those with intact central fields had a median reading rate of 67 words/min, not far short of the median rate of 73 words/min for normal readers using the fiberscope. This is consistent with the authors' previous findings that low-vision readers with central field loss read much more slowly than those with intact central fields, even when optimal magnification is provided. The authors conclude that the fiberscope may be very useful as an inexpensive portable reading aid for people requiring high magnification. Invest Ophthalmol Vis Sci 26:751–763, 1985

The National Society for the Prevention of Blindness[1] has estimated that 1.5 million people in the United States have severely impaired vision, that is, cannot read a newspaper, even with glasses. Most of these people can read if sufficient magnification is available. A variety of simple optical reading aids can provide high magnification. These aids are portable and inexpensive. Generally, the underlying principle is to increase the size of the retinal image by bringing the page closer to the eye; the aid provides the extra lens power necessary for accommodation. However, for many people, reading with magnification greater than six-fold (or lens power exceeding 24 diopters) is unsatisfactory because the page is less than 42 mm from the person's eye, and scanning is difficult.*†[2,3]

Reading with a lens of 24 diopters or more is awkward. The field is only a few letters wide. The reader must scan the text by moving his or her head along each line. Depth of field is so small that even slight vertical head motions will take the text out of focus. Stand magnifiers, which support the lens at a focal length from the page, are permanently in focus, at the expense of a further reduction in field. At high powers, these simple magnifiers invariably require the reader to move his head relative to the page to scan each line.

Closed-circuit television (CCTV) reading aids can provide high magnification without these inconveniences. Unfortunately CCTV is expensive (about $2,000) and bulky to carry around. Thus, there is a need for a portable inexpensive reading aid that can provide magnification greater than six-fold.

This article is the third in a series on the psychophysics of reading. In the first two articles,[4,5] we determined some of the visual requirements for reading of scanned text by normal and low-vision readers. We used continuous and matrix displays. A continuous display (eg, Fig. 2B) presents images faithfully, except possibly for blur. A matrix display (eg, Fig. 2A) presents an array of discrete samples, each representing the average luminance from a small area of the original. It is possible to make a continuous display from a matrix display by introducing sufficient blur so that the individual samples cannot be resolved.

By measuring the effects on reading of character

: · * The dioptic equivalents are the reciprocals of the reading distance in meters, eg, a rating of 24 diopters means a reading distance of 1/(24 diopter) = 0.042 m.

† By convention, magnification is defined as the ratio of a "standard" unaided reading distance of 0.25 m to the shorter reading distance permitted by the aid, eg, a reading distance of 0.042 m implies a magnification of 0.25 m/0.042 m = 6×.
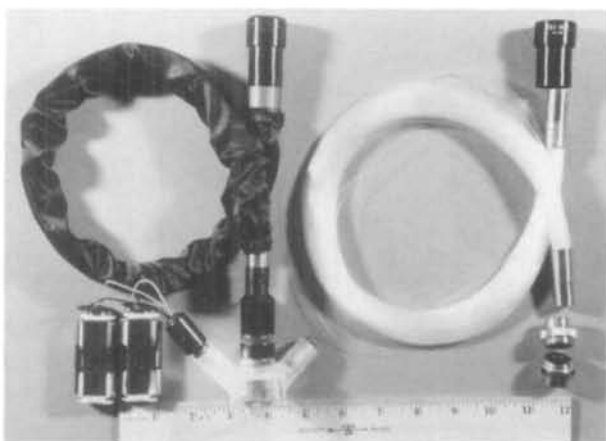
Fig. 1. Fiberscope (*left*), and its optical components (*right*). It provides magnification up to ×40, equivalent to a lens of 160 diopters. From the bottom, the optical components are the objective lenses, the image guide, and the eyepiece. As shown, it has a 1× objective and a 15× eyepiece, for an overall magnification of ×15.

size, window size (number of characters across the display), resolution of continuous displays (ie, spatial-frequency bandwidth in cycles/character), and sample density of matrix displays (number of displayed points making up each character), we found that only a modest amount of visual information was required to achieve maximal reading rates.

For continuous displays, maximal reading rates require only four characters visible at a time, and a resolution of only 2 cycles per character, independent of character size. These results suggest that a continuous display with a resolution of 8 cycles × 8 cycles would satisfy the visual requirements of fast reading, for all character sizes.

For matrix displays, maximal reading rates once again require only four characters visible at a time, but we found that the number of samples per character required for maximal reading rates by people with normal vision increased with character size. The required sampling densities ranged from 20 × 20 for 24° characters to 4 × 4 for acuity sized characters. Moreover, we found that the requirements of low-vision observers were less than or equal to those of normal observers at any given character size. These findings, combined with the requirement of only four characters in the field, indicate that a matrix display with 80 × 80 samples would satisfy the visual requirements of reading, normal or low vision, for characters up to 24° wide.

For a discussion of the reasons for the different requirements of the continuous and matrix displays see Legge et al.[4]

The next section describes the fiberscope reading aid, which may be built by any machine shop using

the construction details in Figure 7 and the Appendix. In the following sections we compare the fiberscope with other aids, describe an experimental evaluation of the fiberscope, and discuss the results.

Materials and Methods

Description of the Fiberscope

Historically,[6] "the possibility of conducting images by means of flexible bundles of fibers was first proposed in two nearly simultaneous patents in the late 1920's." A flexible bundle of optical fibers arranged in the same way at both ends is called an image guide. A fiberscope consists of an image guide fitted with an objective lens at one end and an eyepiece at the other. Most of the commercially available fiberscopes are used to view inaccessible places, eg, inside the human body, or inside machinery. Typically, a large number of fibers are used to give high resolution (eg, 1000 × 1000), resulting in prices in the thousands of dollars.

Figure 1 shows our low-resolution fiberscope.‡,[7] It provides magnification up to 40-fold, equivalent to a lens of 160 diopters. Starting at the bottom, the text is imaged by two objective lenses onto the bottom end of the image guide. The image guide is a bundle of 125 × 125 plastic optical fibers, which are organized the same way at each end. Most of our experiments were made with this resolution, but the results section will show that the resolution may be reduced as low as 38 × 38 with little or no loss of performance. The plastic fibers are each 0.08 mm thick (and thicker in the lower resolution guides) and are quite rugged. The image guide is 2 ft long and flexes easily. The image is transmitted from the bottom end to the top end of the image guide. The observer looks at the image through the eyepiece.

A clear plastic stand supports the objective lens at exactly the correct height above the page for best focus and allows ambient light in to illuminate the text. However, since ambient illumination is rarely sufficient, a built-in pair of focused bulbs illuminate the text as well. Four penlight batteries attached to the side will drive one bulb, producing a luminance (as seen by the user) of 400 cd/m² for about 4 hr.§

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‡ An invention disclosure describing this device was filed with the University of Minnesota Patent Office in July 1980. A preliminary report on the fiberscope was given at the 1981 Annual Meeting of the American Academy of Optometry, Orlando, Florida, on December 14, 1981. The authors have no financial interest in the fiberscope.

§ During this 4-hr period the luminance falls gradually to about one third its initial value, and then abruptly falls to zero. The expected life of the bulb is 150 hr.
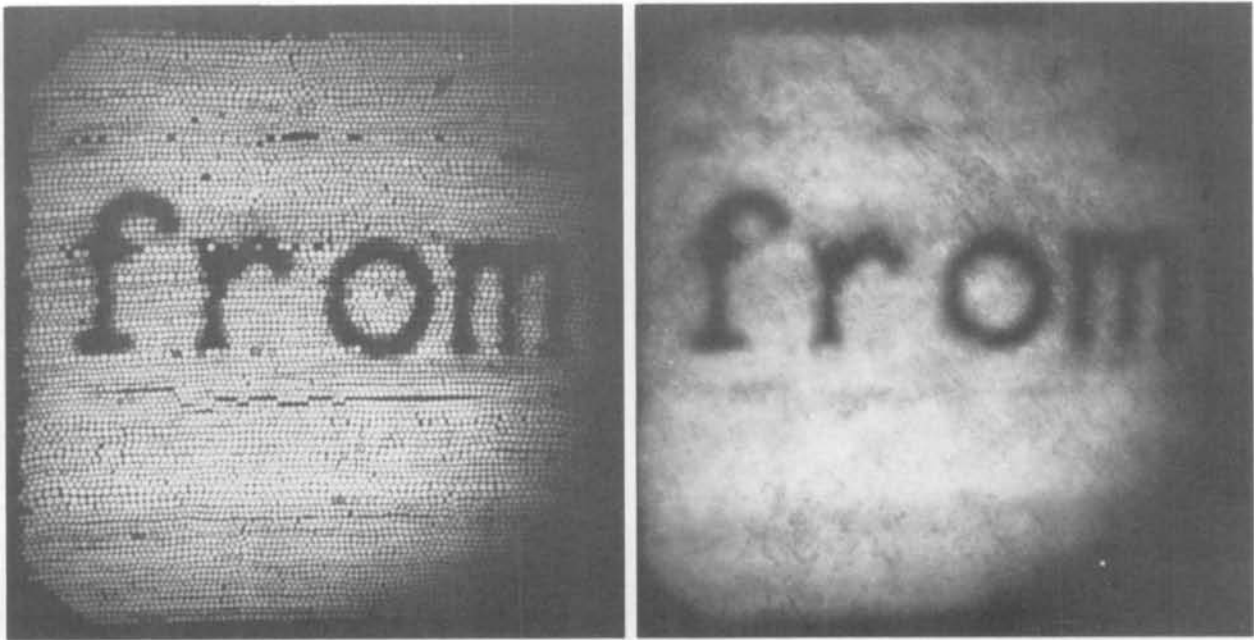
Fig. 2. Text as seen through the fiberscope without (**A**, *left*) and with (**B**, *right*) the optional diffuser in the eyepiece. **A**, *left*. Each disc is the end of an optical fiber, and is essentially uniform, a single sample. The honeycomb appearance results from the hexagonal packing of the individual fibers. The image guide is made up of only 125 × 125 fibers, so the image has 125 × 125 samples. The black discs are broken fibers. **B**, *right*. A ground glass diffuser blurs the image so the individual fibers are not resolved. The diffuser used in **B** has a resolution of 4.2 cycles/character or 17 cycles × 17 cycles. The somewhat blotchy appearance of **B** is due to irregularities of the fibers, which are apparent in **A**.

For extended use, the batteries may be replaced by a 6-volt transformer, providing enough power for both bulbs and a luminance of 800 cd/m². The contrast seen by the user of the fiberscope is the same as the contrast of the page. Most good-quality print has a contrast exceeding 90%.

The fiberscope in Figure 1 is configured to provide a magnification of ×15 (60 diopters). The objective (ie, the assembly including the stand and objective lenses) magnifies only ×1, merely relaying the text onto the image guide; the image guide relays the image to the eyepiece; and the 60-diopters eyepiece magnifies ×15. Overall magnifications of ×5 to ×40 are obtained by appropriate choice of eyepiece (10×, 15×, or 20×) and objective (0.5×, 1×, or 2×). Each user would require only one eyepiece (depending on his acuity) and several different objectives (to image text of different sizes). Two objectives (1× and 2×) suffice to read the common type sizes (eg, newspapers, books, telephone books, and reference books). The objective magnification is chosen to image four to five characters across the image guide. The eyepiece is chosen to give the desired angular subtense (up to 13°) to each of the four to five characters.

Since the image guide twists easily, the reader must rotate the eyepiece end of the image guide until the text is right-side up. We find that tactile bumps on

the objective and eyepiece help the novice to orient the eyepiece correctly.

The parts are inexpensive, about $400 to $700 and 30 hr of machining for a fiberscope with three objectives. The lenses are standard microscope objectives and wide-field eyepieces. The main expense is the image guide, whose cost rises approximately as the square root of the number of fibers. For most of our reading rate measurements, we used a 125 × 125-fiber image guide that cost about $500. However, we have found that nearly the same performance may be attained with a 38 × 38-fiber image guide (costing less than $200) with a ground-glass diffuser that blurs the honeycomb pattern of the individual fibers.

The entire fiberscope may be carried in a purse or coat pocket. We've found it to be very rugged. We have twisted it and dropped it without mishap.

Figures 2A and 2B show views through the fiberscope without (Fig. 2A) and with (Fig. 2B) the optional ground-glass diffuser in the eyepiece. The honeycomb appearance in Figure 2A is due to the individual fibers. Each disc is the end of an optical fiber and is essentially uniform. A few fibers are broken and appear black. The image guide is made up of only 125 × 125 fibers, so the image has 125 × 125 samples. This is one fourth the linear resolution of a television picture, which has about 500 × 500

Fig. 3. Fiberscope in use. The eyepiece is supported near the eye, and the user holds the objective in his right hand and slides it over the text. The user is making a V with his left hand to mark the beginning of the line. We have developed several ways of supporting the eyepiece. The eyepiece may be spectacle-mounted as shown here, hand-held, or supported by a stand.

samples. Our previous study of matrix displays indicated that a resolution of at least 80×80 is required for optimal reading of characters as large as $24°$. Thus, there is little scope for reduction of resolution (and thus cost) of a matrix display like Figure 2A.

However, for a continuous display, as in Figure 2B, our work has shown that the resolution requirements are considerably lower, only 2 cycles/character. To image four characters the continuous display would require only 8×8 cycles for a square field. Figure 2B shows the continuous display which results from using a ground-glass diffuser in the eyepiece to blur the matrix display created by the image guide. According to Shannon's sampling theorem, only 2 samples/cycle are required to transmit a continuous waveform, so an image guide viewed through an ideal blurring device would require a theoretic minimum of only 16×16 fibers for reading. In practice, ground-glass diffusers are not ideal, so a higher resolution is required. An experiment to be described below indicates that a 38×38 fiber image guide in conjunction with a ground-glass diffuser is sufficient for reading.

Figure 3 shows the fiberscope in use. The eyepiece is supported by spectacle frames, while the user holds the objective and slides it over the text. We have developed several ways of supporting the eyepiece. The eyepiece may be spectacle-mounted as shown here, hand-held, or supported at eye level by a stand.

Comparison with Other Devices

The principal advantage of the fiberscope over a simple magnifier is that it allows a normal, comfortable, reading posture; many of our low-vision readers complained of the uncomfortable posture required for reading with their simple magnifiers. One partially sighted reader, not included in this study, suffers from residual neck pain following an injury unrelated to his visual deficit. He relies on hand-held magnifiers for all of his reading, several hours a day. The posture required to use a hand-held magnifier increases the pain, limiting the duration of his reading sessions. When introduced to the fiberscope he was thrilled, because it allowed him to read in a normal posture.

A second advantage of the fiberscope is portability. Reader E (Table 1) is a full-time undergraduate student. She was very excited by the fiberscope (with which she read at 48 words/min) because she's been able to read only with CCTV till now, and it is too heavy to carry to school.

A new aid sharing some of the properties of the fiberscope and CCTV has recently become commercially available. The Viewscan (Wormald International Sensory Aids; New Zealand) displays a roughly 10 cm $\times$ 25 cm image of the text that has passed below a hand-held camera. The camera images only a vertical line at a time. The display builds up the two-dimensional image as the camera is scanned horizontally. Faye[8] and Moshier[9] reported that users of the Viewscan found it very difficult to scan the camera along each line of text. Like CCTV, the Viewscan costs thousands of dollars.

Kantor[10] has recently patented a fiberoptic reading aid, which is not portable because it uses a microscope at the eye, instead of just an eyepiece. The microscope is big and heavy; Kantor recommends a tripod to support it. The microscope is required because Kantor uses a thin (eg, 2.5-mm diameter) image guide. Our experiments with various designs of fiberscopes for reading have convinced us that portability requires a thick (10–15 mm) image guide for two reasons. First, a thick (12 mm) image guide requires only a $20\times$ eyepiece (which can be spectacle-mounted), whereas the thin image guide (2.5 mm) requires a $100\times$ microscope at the observer's eye to attain a $60°$

apparent field of view. Second, the thick image guide we used is made of 80-μm plastic fibers, which are rugged and require only a thin lightproof sheath, making it as flexible as a wet noodle. The thin image guides are made of very fine glass fibers (15–50 μm diameter) and must be protected by a steel gooseneck sheath whose stiffness impedes the manual scanning of the page. (Glass fibers break if bent more sharply than a radius of about 50 fiber diameters. The plastic fibers may be tightly knotted without breaking.) Flexibility is essential for spectacle mounting to prevent uncomfortable torsion on the spectacles caused by the manual scanning of the other end of the image guide.

Experimental Methods

Clinical evaluation: We measured reading performance of 12 partially sighted and three normally sighted people using the fiberscope. The readers represented a wide range of acuities and pathologies. Two had senile macular degeneration, one of the most common causes of low vision. All of the readers had at least a high school education. For each reader we measured reading rates with a fiberscope and reading rates with CCTV (except normal reader N). We also measured the Snellen acuity and Sloan M acuity[2] of each partially sighted reader, asked what aid they customarily used for reading, and, if the aid was available, measured their reading rate using it. Table 1 presents these data and the patients' diagnoses. Ophthalmologist or optometrist reports were available for all partially sighted readers but one, and that reader was able to related a detailed history. One person appears twice in the table (I and M), as she was tested separately with each eye. All subjects gave informed consent prior to participating in the study.

All measurements except the CCTV reading were monocular, with the other eye occluded. CCTV reading was binocular, except for readers I, K, and M, who were tested separately with each eye.

The acuities are reported as Snellen 20-foot equivalents, as the lower acuities required testing at distances less than 20 ft. M-acuity (black-on-white) was measured using the Sloan reading cards at 0.4 m, or at nearer distances (with appropriate refraction) if the acuity was not measurable at 0.4 m.[2]

The reading materials were excerpted from high-school equivalency exams, as in our previous studies.[4] All readers received half an hour of instruction and practice with each device. For each measurement the reader read aloud for 60 sec, and a reading rate was calculated, counting only the words read correctly. This measure was made several times during the

practice session until the reader was comfortable with the device being used, and performance was judged stable. Then four measurements were made and recorded. (In a few cases only two or three measurements were made and recorded.) The average of the recorded measurements is reported in Table 1.

Our fiberscope reading measurements were conducted with the 1X objective and elite type. The square field of view was exactly four characters wide. Contrast, $(L_{max} - L_{min})/(L_{max} + L_{min})$, at the eyepiece end of the image guide exceeded 90%. We tried several eyepieces with each reader, and all readers chose whichever eyepiece they preferred for the subsequent measurements. The fiberscope was supported by a stand that rested on the table.

To read with the fiberscope, the user must slide the objective along the line of text from left to right and return the objective to the beginning of the next line. When we gave the fiberscope to first-time readers they had no problem following a line of text as they read, but had difficulty in finding the beginning of the next line quickly. We instructed them to use the thumb and index finger of the left hand to make a V conforming to the base of the objective assembly, and to hold their fingers in this position at the beginning of the line they were reading, as in Figure 3. They used the right hand to move the fiberscope along the line of text. When they finished the line they could swing the fiberscope quickly back to the beginning of the line, nestling it into the V, and then slide down to the next line. After receiving these instructions most readers had no difficulty finding the next line. Two of the three readers (A, B, and J) who failed to master the V technique had sensory or motor impairments of their hands.

Our CCTV was a Visualtek MV-2 Miniviewer. The reader chose the magnification and viewing distance. Both contrast polarities (ie, black-on-white and white-on-black) were tested. To move the text on the CCTV the reader slid an X–Y table on which the page of text rested.

Effect of resolution: The modulation transfer function (MTF) of an optical imaging system is the ratio of the contrast of its output to the contrast of its input, as a function of spatial frequency (in this case, cycles/character). The modulation transfer function of the fiberscope was measured by manually scanning the fiberscope over printed gratings of various spatial frequencies. The eyepiece was replaced by a microphotometer, which sensed the light from a 0.1-character-wide spot in what would have been the eyepiece's image plane. The analog luminance reading was continuously recorded by a chart recorder. The contrast, $(L_{max} - L_{min})/(L_{max} + L_{min})$, at the image plane

Table 1. Subject data

Reader*	Diagnosis; state of media and fields†	Reading rate in words/min‡			M acuity	Snellen acuity§	Age (yr)	Notes
		Fiberscope	CCTV (black-on-white; white-on-black)					
A	Senile macular degeneration; central field loss	12	23; 23		7 M	$\frac{20}{240}$	71	Did not master the "V" technique; didn't like the fiberscope; thought it was too hard to move it across the page and keep her place; used 8× monocular at 39 words/min
B	Optic nerve atrophy; central field loss	17	48; 54		2 M	$\frac{20}{120}$	27	Has motor limitations which make the fiberscope difficult to use
C	Senile macular degeneration; central field loss	18	28; 28		7 M	$\frac{20}{50}$	70	Uses bifocals at 66 words/min
D	Optic nerve atrophy; central field loss	18	20; 20		7 M	$\frac{20}{240}$	25	Pendular nystagmus made it difficult to look through the fiberscope; uses spectacle-mounted magnifier at 22 words/min
E	Macular degeneration; central field loss	34	94; 94		14 M	$\frac{20}{480}$	29	Uses CCTV daily
F	High myopia, retinal degeneration; central field loss	48	75; —		>40 M	$\frac{20}{320}$	50	M-acuity poorer than 40M; needs 50×; uses CCTV; refused to read white-on-black CCTV because it was "to uncomfortable"; could only read CCTV comfortably if it was black-on-white and the room lights were on
G	Retinal scarring due to congenital toxoplasmosis; central field loss	85	172; 172		2M	$\frac{20}{120}$	32	Uses spectacles at 226 words/min
H	Congenital cataract, surgical aphakia; cloudy media, peripheral field loss	35	35; 36		14 M	$\frac{20}{400}$	28	Was very excited about the fiber-scope; uses spectacle-mounted magnifier at 36 words/min
I	(Left eye) congenital cataract, surgical aphakia; cloudy media	59	75; 85		8 M	$\frac{20}{640}$	34	Normally reads with other eye; readers I and M are the same person
J	Retinal detachments; peripheral field loss	66	95; 95		2.5 M	$\frac{20}{200}$	30	Could not find the beginning of a new line easily; could not use the "V" technique

Table 1. (*Continued*)

		Reading rate in words/min‡					
Reader*	Diagnosis; state of media and fields†	Fiberscope	CCTV (black-on-white; white-on-black)	M acuity	Snellen acuity§	Age (yr)	Notes
K	(Right eye) congenital cataract; cloudy media	67	84; 113	2.5 M	$\frac{20}{240}$	20	well; seems to lack a sense of where his fingers are; uses spectacles at 197 words/min Uses hand-held magnifier at 15 words/min; normally reads with other eye
L	Corneal vascularization due to Stevens-Johnson syndrome; cloudy media	68	65; 82	20 M	$\frac{20}{960}$	33	Uses CCTV daily
M	(Right eye) congenital cataract, surgical aphakia; cloudy media	95	115; 129	2 M	$\frac{20}{120}$	34	Uses spectacles at 183 words/min; readers I and M are the same person
N	Normal vision	68			$\frac{20}{20}$		
O	Normal vision	73	201; 203		$\frac{20}{20}$		
P	Normal vision	77	163; 162		$\frac{20}{20}$		

* A–G: low-vision readers with central field loss; H–M; low-vision readers without central field loss; N–P: normal readers.

† Central field loss refers to absolute scotomas located in the central 5° (radius) of the visual field, and possibly in peripheral regions as well. Peripheral field loss refers to absolute scotomas that are confined to noncentral regions of the visual field. The ocular media are classified as "cloudy" if the ophthal-mologist's report indicates the presence of corneal scarring, cataract, or vitreous debris.

‡ The reading rates represent the arithmetic mean of four 1-min trials, except for a few which are means of two or three trials. The standard errors are small, about 2% of the means.

§ Stated as a 20-ft equivalent.

was calculated from the maximum and minimum values of the serpentine curve on the chart recorder.‖ The contrast of the printed gratings (50% line screens, Letraset; Paramus, NJ) was measured independently, and found to be 90% for the originals and 80% for reductions produced by xerography. The reported MTF value is the ratio of the measured image-plane contrast to the contrast of the printed page. This measurement bypassed the eyepiece, but the optical quality of the eyepiece is so high that its contribution to the overall MTF is negligible.

We then performed an experiment with normal readers to determine whether the effects of resolution on reading found in our earlier work[4] would generalize to reading with the fiberscope. In our previous work, we measured the effect of resolution on reading of

‖ Note: This measurement procedure overestimates the MTF at the higher frequencies by $4/\pi \approx 1.3$ since the fundamental component of the square wave grating has a contrast higher than that of the squarewave grating itself.

CCTV, finding that the required resolution was only 2 cycles/character. In that study we blurred the text by putting a diffuser in front of the TV screen. The diffusion gap between the TV screen and the diffuser determined the MTF of the system. Decreasing the diffusion gap shifted the MTF to higher spatial frequencies. Similarly, in this study, we controlled the MTF of the fiberscope by putting a diffuser inside the eyepiece (at the image plane) separated by a diffusion gap from the image guide. Again the diffusion gap controlled the MTF of the system.

Figure 4 shows the MTF of the fiberscope at four settings of the diffusion gap. The diffusion gap was halved for each successive curve from left to right. Resolution is defined as the spatial frequency at which the contrast gain is 1/e, indicated by the horizontal dashed line. From left to right, the curves shown represent resolutions of 1, 2, 4, and 8 cycles/character.

We used two different diffusers. Normally, the diffuser is a piece of ground glass. Its thickness is the
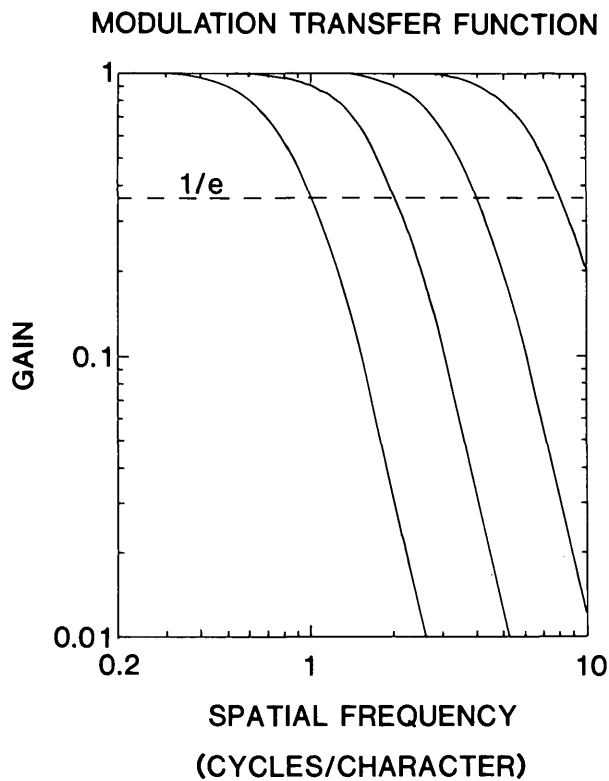
MODULATION TRANSFER FUNCTION

Fig. 4. Modulation transfer function of the fiberscope. The vertical scale is the ratio of the contrast at its output to the contrast of its input. The output is the eyepiece image plane, and the input is a printed grating. Each curve is for a different diffusion gap. From left to right, each curve has half the diffusion gap of the previous curve. The two lefthand curves were measured; the two righthand curves are estimates made by shifting the lefthand curves. We define the resolution of the fiberscope to be the spatial frequency (in cycles/character) at which the MTF falls to 1/e (the horizontal dashed line).

diffusion gap and determines a fixed resolution. In order to vary the resolution (Figs. 4, 5), the ground-glass diffuser was replaced by a short piece of image conduit (a bundle of 25-μm optical fibers fused together, made by American Optical, Fiberoptics Division (Rochester, NY). The separation between the image conduit and the image guide was the diffusion gap and was easily adjusted. The other end of the image conduit was placed in the image plane of the eyepiece.

Results

Effects of Resolution

Since the main expense in building a fiberscope is the cost of the image guide, we did some experiments to determine how low the image guide resolution could be made without significant loss of performance. We have found previously for reading of text scanned on a TV display that for optimal reading rates the minimum resolution for a matrix display is moderate

(20 samples/character), whereas the minimum resolution of a continuous display is very low (2 cycles/character). Since this offers the potential for a large reduction in image guide resolution (and thus cost) we decided to measure the effect of resolution in a continuous display, as in Figure 2B. Using the 125 × 125 fiber image guide, we varied the resolution by adjusting the diffusion gap.

Figure 5 shows the reading rate for one subject as a function of the resolution in cycles/character. Confirming our previous results, reading rate increases with resolution of the continuous display up to a resolution of about 2 cycles/character, beyond which reading rate is independent of resolution.

The finding that only 2 cycles/character is required implies that the sampling density of the image guide could be substantially reduced if the fiberscope is fitted with a diffuser to convert it from a matrix display to a continuous display. The theoretic limit is 2 fibers/cycle, or 4 × 4 fibers/character. Since the
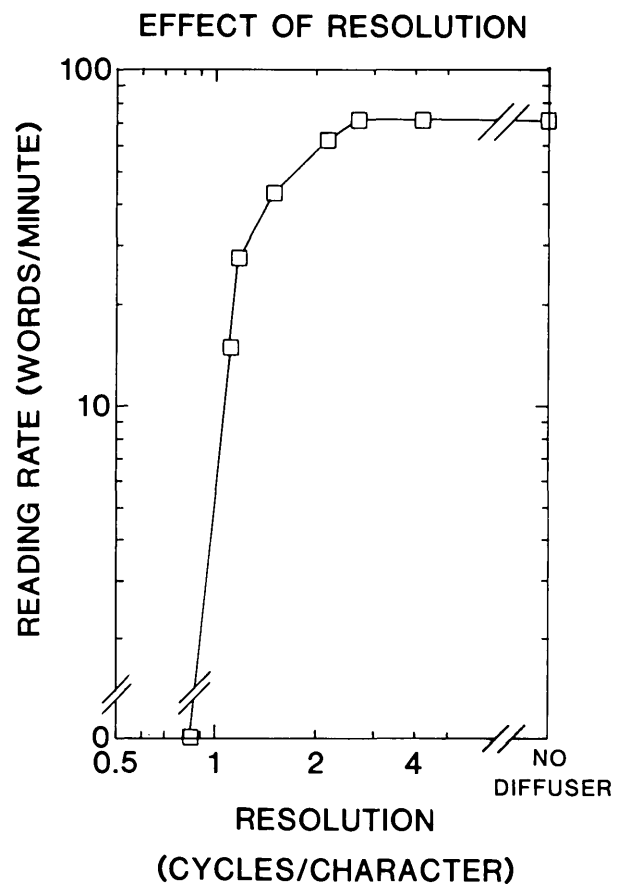
EFFECT OF RESOLUTION

Fig. 5. Fiberscope reading rate as a function of resolution. The vertical scale is fiberscope reading rate (average of four 1-min trials) by a normal reader. The horizontal scale is the resolution of the fiberscope in cycles/character, as defined in Figure 4. Reading rate increases with resolution only up to a resolution of about 2 cycles/character.

diffuser blurs the matrix display formed by the image guide, any excess resolution of the matrix display beyond what the diffuser will resolve is wasted. Therefore, we made a side-by-side comparison of fiberscopes with different numbers of fibers but the same resolution, determined by a diffuser. First we measured a baseline reading rate of 60 ± 4 words/min with 125 × 125 fibers and no diffuser. With a 0.04-inch thick ground glass diffuser producing a 4.2 cycle/character resolution, reading rate was still 60 words/min with 125 × 125 fibers, but fell to 50 words/min with 75 × 75 fibers. With a 0.02-inch thick ground glass diffuser producing a 2.2 cycle/character resolution, reading rate was still 60 words/min with 125 × 125 fibers, but fell to 50 words/min with 38 × 38 fibers. We think that the small reduction in performance, from 60 words/min to 50 words/min, is not due to the lower number of fibers per se in the 38 × 38 fiber image guide, but rather to the inferior quality of manufacture of the these low-resolution image guides. Their fibers are irregular, giving the image a blotchy appearance. This makes reading more difficult, probably as a result of masking. This irregularity and resulting blotchiness is present to a lesser degree in the 125 × 125 image guide and is apparent in Figure 3A, B. Unfortunately, there is only one manufacturer of large-diameter low-resolution image guides. Even so, our comparison shows that if a diffuser is used to reduce the continuous resolution down to about 2 cycles/character, then the image guide resolution may be reduced down to 38 × 38 fibers and still provide nearly the same performance. For the clinical evaluation reported in the following subsection, all the fiberscope reading rates were made with a 125 × 125 image guide with no diffuser, ie, a matrix display with 31 × 31 samples/character, as in Figure 2A.

Clinical Evaluation

The results appear in Table 1 in three sections, within which they are ordered by fiberscope reading rate. Low-vision readers (A–G) with central field loss appear in the top section. Low-vision readers (H–M) with intact central fields appear in the middle section. Normal readers (N–P) appear in the bottom section. The low-vision readers read with the fiberscope at rates between 12 and 95 words/min. Those with central field loss read at a median rate of only 18 words/min. Those with intact central fields read at a median rate of 67 words/min, not far short of the normal readers' median rate of 73 words/min.

Three of the low-vision readers (G, J, M) read about 200 ± 20 words/minute with reading spectacles (despite having acuities of only 2 M to 2.5 M, about

20/100 Snellen), greatly exceeding their fiberscope reading rates of 65 to 95 words/min. However, all three of these readers said that they would like to use the fiberscope to read fine print.

The visual properties of the fiberscope are quite similar to those of a black-on-white CCTV. Both provide a large-field high-magnification bright display of a small part of the page, and this text drifts across the display as a result of manual scanning of either the fiberscope objective over the page, or the page under the CCTV camera. The CCTV allows electronic enhancement of contrast to about 94%, only slightly better than the fiberscope contrast which is typically 90%.

Unlike the fiberscope, CCTV can also provide reversal of contrast polarity, producing white-on-black text from a black-on-white original. Table 1 lists reading rates for both contrast polarities on CCTV. Our previous study[5] found that readers with clear ocular media had equal reading rates with black-on-white and white-on-black text, whereas readers with cloudy media usually read slightly faster with white-on-black text. In the present study the median ratio for those with cloudy media was 1.14, while only one (B) of the 11 readers with clear media showed any difference between the two contrast polarities.

Figure 6 is a scatter diagram in which each letter represents one subject's reading rate with the fiberscope (the vertical scale) and with the black-on-white CCTV (the horizontal scale). The solid diagonal line represents equal reading rates on the two devices. The fiberscope reading rate never significantly exceeded the CCTV rate; all the points are at or below the solid line.

Discussion

The low-vision readers used only the version of the fiberscope with 125 × 125 fiber resolution and no diffuser (ie, a matrix display). Thus, the conclusions regarding the suitability of the fiberscope as a low-vision reading aid are properly confined to this version of the fiberscope. However, our prior work[4] and the above results with normal readers indicate that a continuous display with a resolution of only 2 cycles/character would work nearly as well at a substantially lower cost.

In a previous study,[5] we found that the best predictor of low-vision reading rate under optimal conditions was the state of the central fields. In that study, the median reading rate was 25 words/min if there was central field loss, and 90 words/min if the central fields were intact. This study confirms the predictive value of central field loss. The corresponding
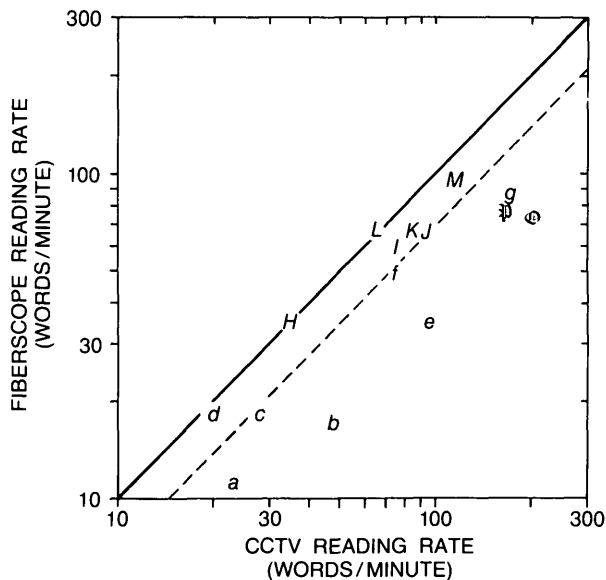
Fig. 6. Reading rates with fiberscope vs black-on-white CCTV. Each point represents one reader's reading rate with the fiberscope (on the vertical scale) and with the black-on-white CCTV (on the horizontal scale). The lower case letters *a–g* represent the low vision readers with central field loss. The upper case letters *H–M* represent the low vision readers with intact central fields. The Gothic letters O and P represent normal readers. Normal reader N could not be plotted, since no CCTV rate was measured. The standard errors were about 2%, about one fifth of the size of the plotted symbols. The solid diagonal line represents equal reading rates with the two devices. The dashed line represents fiberscope reading rate equal to 69% of the CCTV reading rate.

median reading rates in this study were 54 and 90 words/min for CCTV, and 18 and 67 words/min for the fiberscope.

There is some indication that central field loss is particularly bad for fiberscope reading. The dashed diagonal line in Figure 6 represents fiberscope reading rate equal to 69% of the CCTV reading rate. About half the points are above the dashed line and about half are below it. All but one (d) of the low vision readers with central field loss (a–g) fall below the dashed line in Figure 6, indicating a fiberscope rate less than 69% of the black-on-white CCTV rate, while all of the low-vision readers with intact central fields (H–M) are at or above the dashed line.

Thus for low-vision readers with intact central fields the fiberscope is nearly as successful as black-on-white CCTV in satisfying the visual requirements for fast reading. They read 82% as fast (median) with the fiberscope as with black-on-white CCTV. Low-vision readers with central field loss read only 52% as fast (median) with the fiberscope as with black-on-white CCTV but may still prefer it when portability or cost matters.

The primary purpose of this research was to determine whether the fiberscope is useful. Thus we sought a practical trial which would test the performance of diverse readers with limited training. However, there are several limitations to the study.

Our study included a limited sample of subjects, mostly in their twenties and thirties. Most of the low-vision population is elderly and some may experience coordination problems—as 71-year-old reader A apparently did—that would made the fiberscope difficult to use. Indeed the fact that normal readers could only attain about 73 words/min suggests that reading with the fiberscope poses a challenging manual task. Our readers read only loose sheets of paper, avoiding the mechanical problems of small books with springy bindings.

We allowed the readers only half an hour of practice. It is possible that their reading rates on both the fiberscope and CCTV would increase with further practice,[11] though not necessarily in equal proportion. Only one reader (L) had extensive experience with both devices, and his reading rates with the fiberscope (68 words/min) and the black-on-white CCTV (65 words/minute) were similar.

Conclusions

1. In a prior study of reading of scanned text we found that the visual requirements of reading are modest: a four-character field and 2 cycle/character resolution. The fiberscope design was based on this principle, and its success confirms the soundness of the principle.

2. Our prior work has shown that the state of the central fields is the single most important factor affecting the reading rates attainable by a low-vision reader. Thus, it is not surprising that this factor is also predictive of fiberscope reading rates. The low reading rates attained by readers with central field loss may still be useful when an inexpensive or portable aid is required.

3. There is some indication that reading with the fiberscope requires some dexterity.

4. Although the fiberscope does not offer contrast reversal, this factor is significant only for readers with cloudy media, and even for them only increases reading rate by 14%.

5. In sum, we believe the fiberscope will be most useful to readers who require high magnification for reading, and have intact central fields and some dexterity. Our results indicate that such people will typically read at 67 words/min with the fiberscope.

Acknowledgments

Appendix

Construction of the Fiberscope

Figure 7 is an exploded diagram of the fiberscope. All parts that fit into one another should be machined for a slip fit. The threads of the threaded aluminum tube are standard Royal Microscope Society threads, and taps are commercially available (eg, Rolyn 80.3750, Rolyn Optics Co.; Covina, CA). All the aluminum parts should be black anodized (both for appearance and to minimize internal reflection). The spring should be painted black.

The sources of electrical power for the light bulbs are not shown. The bulbs are rated at 5 volts, 0.3 or 0.4 amps each. To connect power to the bulbs we use two-pin Jones sockets (TRW/CINCH S-302-CCT, TRW/CINCH Connectors; Elk Grove, IL). For portable use, we recommend the lighting of just one bulb. A pair of plastic battery holders (eg, Radio Shack), each holding two 1.5-volt AA alkaline batteries (in series) may be attached to either side of the long aluminum tube by Velcro strips. They should have a 2.5-inch cable terminated by a two-pin Jones socket. This allows easy removal or replacement of the batteries. The four batteries will power the bulb for about 4 hr. For extended use, both bulbs may be powered by a wall-mounted 6-volt transformer with a 10-ft cable terminated by two Jones sockets. The transformer we used (Edmund Scientific D33,406; Barrington, NJ) provides only 0.5 amp, so we use two, one for each bulb.

The image guide (Poly-Optical Products Inc., 3062; Santa Ana, CA) has 125 × 125 fibers. Image guides with fewer fibers—75 × 75 and 38 × 38—and the same outer dimensions are available from the same source, at lower cost (Poly-Optical Products, 3162 and 3262, respectively). Unfortunately the fibers in the lower resolution guides tend to be quite irregular, resulting in a blotchy appearance once the diffuser is in place, which seems to reduce reading rates somewhat. Order the image guide without any sheath. Sheath it with a thin inner sleeve of lightproof plastic (eg,

from a plastic garbage bag), and an outer sleeve of sewn cloth, such as black satin (largely for appearance). Make the inner sleeve by cutting out a 6″ by 24″ piece of plastic, fold it in half lengthwise twice, making it 1.5″ by 24″, and seal one edge with hot air. The image guide itself should never be exposed to temperatures exceeding 82°C.

The appropriate ground-glass disk to use as a diffuser depends on which image guide is used. We recommend a 0.02″ thick disk with the 125 × 125 and 75 × 75 fiber image guides and a 0.04″ thick disk with a 38 × 38 fiber guide. However, the glass disk is fragile, so it may be worth trying plastic.

For spectacle-mounting, mount the eyepiece in an opaque-plastic spectacle blank. Comfort may be improved by tying back the image guide to the eyepiece so the image guide drops from a point closer to the spectacle frame, reducing the pressure on the user's nose. For stand-mounting, use a laboratory support stand and a two-prong clamp (eg, Fisher Scientific, 14-670A, 05-731, and 05-754; Pittsburgh, PA) to hold the eyepiece.

Assembly of the fiberscope is straightforward. The plastic stand holds two light bulbs and supports a microscope objective (held by a set screw) at its focal length above the page. The threaded aluminum tube holds another microscope objective, upside down, on top of the first. Upon this second microscope objective is mounted a long aluminum tube (fixed by the lower set screw of the long tube). Inside is a sliding aluminum tube supported by a spring, and fixed by the upper set screw of the long tube. The sliding tube serves only to support the image guide at the correct height for optimal focus. One end of the image guide slides into the top of the objective until it reaches the stop (the sliding tube). The image guide is held in place by the tongue cut into the side of the long tube. Slide the nylon tube over the other end of the image guide, and slide both into an eyepiece until the image guide hits the field stop of the eyepiece. If a ground-glass disk is to be used, it should be inserted into the eyepiece before the image guide. Tighten the set screw in the nylon tube to hold it onto the image guide. Tightening the set screw further will deform the nylon tube enough to hold the eyepiece in place (Note: Poly-Optical Products has changed the diameter of the image guide fitting twice during development of this device and may do so again. Thus it may be necessary to use a lathe to reduce the diameter of the image guide fitting to fit the other parts specified here).

To focus the objective, assemble the entire fiberscope (without the ground-glass disk) and place a high contrast edge underneath the objective, well-illuminated. Loosen the upper set screw of the long tube of the objective. Looking through the eyepiece, slide the objective end of the image guide up and down until the image is in best focus, and then tighten the set screw. At best focus, the edge will appear slightly jagged due to a moiré effect produced by the discrete sampling of the image guide. Now, if desired, insert the ground-glass disk.

Changing the objective to read different text sizes simply requires pulling the image guide out of one objective and

Eyepiece power	Microscope eyepiece
▶20X	American Optical 157
15X	American Optical 184
10X	Swift W10X

Objective power	Dimension A	B	C	D	Part E	F	Dimension G	H
2X	2.8	1.05	.45	1.4	2:1	4:1	1.000	46°
▶1X	1.7	.9	.32	.4	4:1	4:1	1.000	46°
.5X	1.7	.9	.32	.4	4:1	2:1	2.000	67°

Microscope objectives	
2:1	Rolyn 80.3020
4:1	Rolyn 80.3040

ALL DIMENSIONS ARE IN INCHES

FIBERSCOPE READING AID

DENIS G. PELLI   JULY 1983
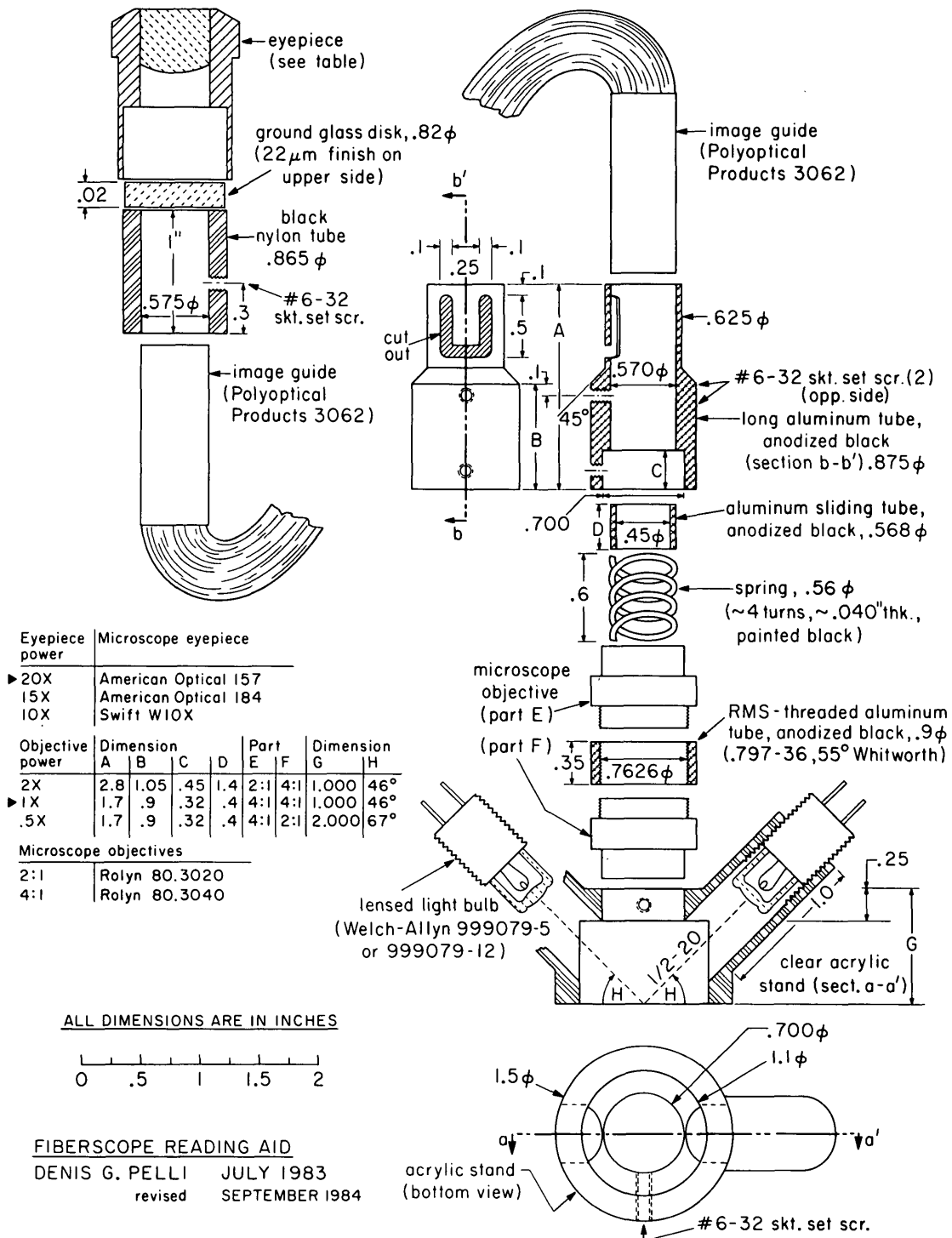   revised   SEPTEMBER 1984

Fig. 7. An exploded diagram of the fiberscope. All parts are shown except the sleeve for the image guide, and the batteries and connectors for the light bulbs. The parts not commercially available may be made in a machine shop in about 30 hr. The figure is drawn showing a 20X eyepiece, and a 1X objective. The tables indicate alternate eyepieces and the changes in dimension to build 2X and 0.5X objectives. Each user of the fiberscope will require only one eyepiece (determined by his or her acuity) and both the 1X and 2X objectives (to read text of different sizes).

pushing it into another until it hits the stop (the sliding tube fixed by the set screw).

Since the eyepiece has no provision for focus adjustment,

the user should first try the fiberscope with his normal refraction in place. However, the eye relief of the 20X eyepiece is too short for use with spectacles. Eye relief is

the maximum distance from the back of the eyepiece to the observer's eye which allows the whole field to be seen. The eye reliefs of the recommended eyepieces are approximately 22 mm (10×), 13 mm (15×), and 8 mm (20×).

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