A NOVEL FIBER OPTIC READING MAGNIFIER FOR LOW VISION READING

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INTRODUCTION

Stand magnifiers are popular reading aids prescribed by vision rehabilitation services or frequently purchased by patients over the countrie. Therefore, they serve as the only aids for many of the visually impaired who do not have access to low vision services. The popularity of stand magnifiers may be attributed to the fact that they provide higher magnification than hand held magnifiers yet are easy and simple to learn to use. The fixed object to lens distance provides a stable and focused image at all times. Despite these benefits optical lens stand magnifiers have numerous disadvantages_ The main shortcoming of existing stand magnifiers is the need to bend over the magnifier in order to be able to read through it (Spitzberg et al 1989), which may be tiring and difficult for elderly users. The postural problems associated with stand magnifiers also complicate the attainment of proper illumination. The user's head tends to block light from above, while the need for light access through the sides of the magnifier makes for an uncomfortable and difficult grip. As is the case with all other optical magnifiers, stand magnifiers are also limited by distortions and vignetting. Typically their field of view is smaller than other devices with equivalent power (Cohen & Waiss, 1991), preventing binocular use in most cases.

We are developing fiber optics technology to provide stand magnifiers with improved optical and ergonomic properties specifically designed for use as low vision reading aids, The fiber optic reading magnifier eliminates, or reduces, all of the limitations listed above. Fiber optic magnifiers provide bright, uniformly illuminated, distortion free images. In the magnifiers we have developed the magnified image may be seen without bending directly over the magnifier, while the magnifier is scanned over a large portion of the page. The contrast and brightness provided by our tapers are significant improvements over previous designs while simplifying production and lowering costs.

OPTICAL, CHARACTERISTICS OF TAPERS AS READING MAGNIFIERS

Fiber optic tapers consist of a large number of optical fibers fused together to form a coherent bundle that can transmit an image from one end to the other. The bundle is heated in the center and stretched. forming an hourglass shape. In this process, each individual fiber is stretched and tapered as well. The bundle is then cut into two tapermagnifiers. When such a fiber optic taper is placed with its small face in contact with an object, an enlarged image appears on the larger **upper face. The** magnification in simply the ratio of the diameters of the end faces. Magnifications of 3x-5x are practical, and larger magnifications are possible, but are not likely to be useful as reading aids. Because the magnified image is real and appears at the top face, the effective magnification as related to retinal image size is much larger than equivalently rated lens magnifiers (Fig. 1).

A taper used as a magnifier also efficiently gathers ambient light from the surroundings (such as ceiling lights). The illumination thus obtained often exceeds the illumination reaching the same object (the printed page) without the taper. This light concentration capability is proportional to the square of the magnification of the taper (Peli & Siegmund, 1995). The effect is similar to the converging of light by a lens magnifier. All the light falling on the large upper face of the taper is concentrated on the smaller area covered by the small face. The advantage of a taper over lens magnifier in this regard is that the condensed taper illumination is uniformly distributed over the field of view. In a lens magnifier a bright local condensed highlight usually produces a glare source that masks the visibiliy of nearby letters.

The numerical aperture (N.A.) of optical fibers is a measure of the angular width of the cone of light which is captured by the fibers. This is also a measure of the angle of obliquity at which an image is still observable on the face of the bundle. Beyond this angle, the image fades off. The nominal or intrinsic numerical aperture is determined by the refractive indices of the glasses which comprise the fiber core and the cladding. It is given, for a fiber of uniform diameter, by:

$$\text{N.A.} = \sin\alpha = \sqrt{n_1^2 - n_2^2}$$

where n_1 is the refractive index of the fiber core, and n_2 is the refractive index of the cladding. The angle α is the half angle of the cone of light <<captured>> by the fiber. This parameter is important in the use of a taper as a magnifier because it determines both the light gathering capability and angular field of viewing by the observer (i.e., the vignetting).

In a taper the ***effective*** numerical aperture ($\text{N.A.}_{\text{large face}}$) is influenced by the tapering of the fibers. The $\text{N.A.}_{\text{large face}}$ in such a fiber is proportional to the nominal N.A. and inversely pro portional to the magnification:

$$\text{N.A.}_{\text{large face}} = \frac{\text{N.A.}_{\text{small face}}}{M}$$

where M is the magnification. Thus the larger the magnification the smaller the cone in space from which the enlarged text can be viewed, and the smaller is the cone from which light can be captured to increase illumination. This is why tapers with magnification higher than 5x are not practical as reading aids.

The ***object field*** is the width or diameter of the small end of the taper, and is expressed in linear terms (e.g., 1.0 in) or characters. Typical newsprint is about 15-17 letters/inch. thus the size of the bottom face is determined by the number of letters that need to be displayed simultaneously. Results of an experiment carried out to determine the optimal object field for reading standard test are described in the next section.

As a magnifier is scanned across a page of text, one can measure the total field of text that can be read through the magnifier without change in body posture. This ***scannable field*** is very small for a typical optical stand magnifier. In the case of the fiber optic reading magnifier, it is determined by the effective N.A. The patented innovation described below, of tilting the face of the taper towards the observer, allows for a doubling of the scannable field. The large scannable field is one of the main advantages of the Taper over an optical lens magnifier.

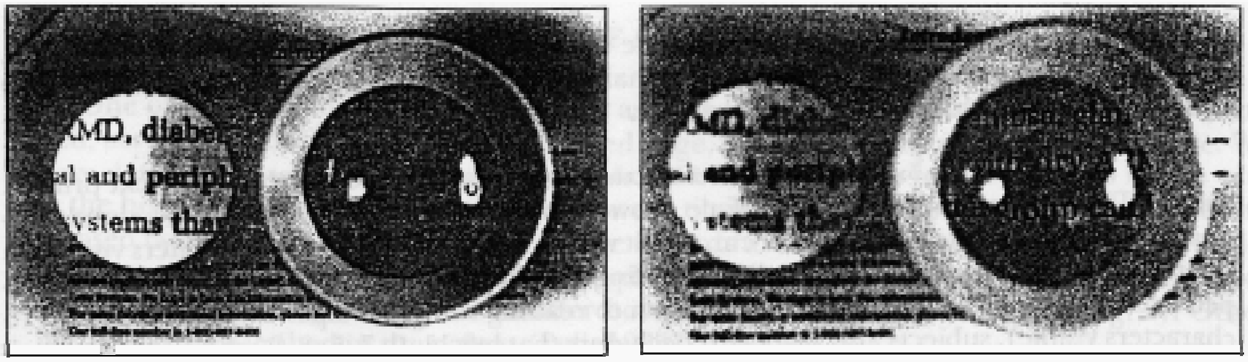

Figure. 1. **Side by side comparison of fiber optic taper (SBIR 1) to lens magnifier (Eschenback 2627). Photographs were taken from approximately 25 cm above the lens with one light source above the two magnifiers. (A second light source was aimed from the right to maximize the illumination of the lens magnifier). The camera's focus was adjusted (a) for the real image on top of the taper, and (b) for the virtual image of the lens magnifier, which is approximately 20 cm below the lens. The 2.5x, low-resolution taper provides an image size equal to, or larger than, the lens magnifier rated as 4.0x. The distortion fo the aspheric magnifier is evident as compared with the flat image of the taper. The next is better illuminated by the taper than the lens magnifier. Furthermore, specular reflections of the over-head light source are not reflected by the taper, but could not be eliminated from the curved surface of the lens, resulting in reduced visibiity. Note that the glare-producing highlight formed by the lens was not captured in these photographs.**

Image resolution in fiber bundles is determine by the fiber size. Typical tapers produced for medical and military applications have very high resolution with fiber diameters of 6-10 µm at the large end. For persons with low vision, the image resolution of the magnifier need not be as high, and thus tapers of lower resolution (that is, larger fibers) may be used to reduce the cost of the device. For low vision observers, even the resolution obtained with 250 µm fibers may be unnecessarily high. We have constructed tapers with fibers of 240 to 300 µm diameter. Such tapers require as few as 1/1000th of the number of fibers required for high resolution tapers of the same size and thus permitted significant reduction in manufacturing costs.

Each fiber in the taper is composed of a high optical index core glass ($n = 1.7$ to 1.8) covered by a lower index cladding glass ($n = 1.49$). Only the cores transmit imaging light.The imaging light transmission of a fiber optic taper is given in terms of the internal transmittance of the core glass of the fibers, the Fresnel reflection losses at the faces, and the packing fraction (P.F.). The Fresnel factor is a function of the refractive index of the core glass n. For $n = 1.8$ light transmission in reduced by as much as $1-0.92^4 = 29\%$. Light transmission may be increased if anti-reflection coating is used. The P.F. is the ratio of core area to the total taper face area (i.e., core + cladding)_ The thinner the cladding is the higher the P.F. The P.F. of commonly used tapers is on the order of 50% to 75%. The non-imaging light transmited by the cladding in turn limits the contrast transferred through the taper. Due to the lower resolution requirements of the low vision reading magnifier, the fiber may be quite large, while the actual cladding thickness can be maintained, and thus the packing fraction can be high (> 90%), resulting in a concomitant improvement in contrast ratio transfer through the taper. We describe below such improvement obtained in experimental tapes.

THE NUMBER OF CHARACTERS NEEDED FOR MAXIMUM READING RATE

The field of view (the number of characters visible simultaneously through the tapers) is determined simply by the diameter of the small face. Increasing the small face size while maintaining magnification requires increasing the top face size. Such an increase, however, is very expensive due to the increased amount of material needed ($\propto$ diameter^3), and results in excessive weight. It is therefore, important to determine the effect of field of view on reading rate with the taper. Covering the top face of the taper with an annular occluder results only in a change in the number of letters visible, while all other parameters -magnification, weight, brightness, contrast, illumination, etc.— remain unchanged. Thus the effect of field of view can be measured separately (Peli *et al.,* 1996).

A 5.3 cm top face, 2.5x taper was used for the reading task. When placed over text printed using a Times 10 pt font, the bottom face allowed for 13 adjacent 'e's to be viewed simultaneously. The height of the taper was4,7 cm, and it weighed 9.5 oz. The number of letters visible on the upper face of the magnifier was limited using a white adhesive vinyl cut into doughnut-shaped occluders using a laser plotter. In addition to reading using the taper with no occluder (13 characters visible), subjects also read with occluders that left 11, 9, 7, 5, 3, 2, and 1 characters visible. Passages were printed with a laser printer on white paper. The passages were printed in a 2 in. (5.1 cm) column format. This layout was chosen to mimic the layout of a newspaper column.

Subjects read using their habitual reading correction. All subjects silently read at least 12 passages selected from elementary level reading primers: three with an unocclude taper (13 characters) and three with each fo three occluder sizes (9, 5, and 3 characters visible). Normally sighted younger (YN) and older subjects (ON), and those visually impaired (VI) subjects who were able, also read three passages without the taper. In addition, the younger subjects read with 11, 7, and 1 characters visible.

Figure 2 shows reading rates (in wpm) by window size. As expected, the YN group read faster than the ON group, who in turn read faster than the VI group. Reading rates continued to increase for all window sizes, and never reached the reading rates possible without the taper. For the YN group, the slope of the reading rate by window size function does tend to become more shallow with seven or more characters visible. For the ON and VI groups reading rates have not begun to level-off even with as many as 13 characters visible.

Rates continue to increase with as many as 13 characters visible, well beyond the 5 characters needed to read scrolled text or to read with CCTV. These additional characters may be needed for navigation. Since much of the reading time is lost in locating the beginning of the next line of text, a magnifier that provides a full column field of view would be desirable. Such a magnifier will require only vertical movement down the column and should increase reading rates substantially. Lens optical magnifiers with such large fields of view are limited to low magnification (usually rated at less than 2.0x). Although taper magnifiers of higher effective magnification can be made in this size (2 in. bottom face) they would be very large, heavy, and currently too expensive.

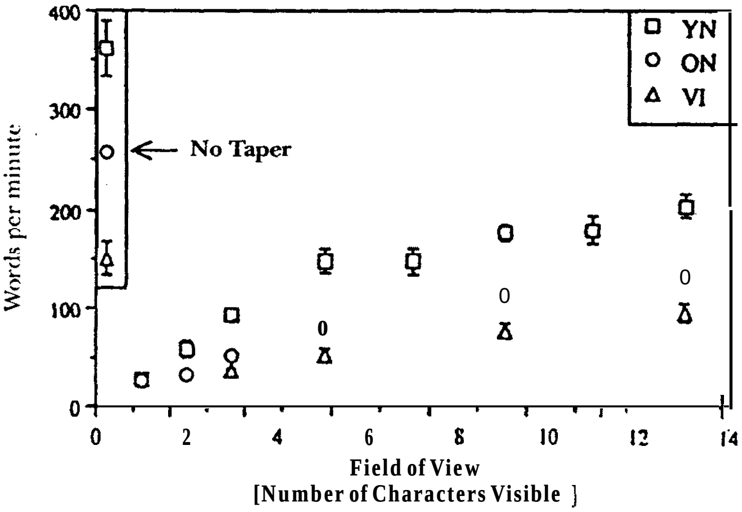

figure 2. **Reading rate in wpm by window size** for the YN, **ON, and VI groups. Reading rate continues to increase, even with the largest window size, and neverreaches reading rates without thetaper.**

INCREASING THE SCANNING FIELD OF A TAPER MAGNIFIER

One of the main advantages of the taper as a reading aid is its ability to be moved, i.e. scanned, across a relatively large area of a printed page, and still display a bright, sharp image. We have defined the scanning field as the distance the magnifier can be moved (L in Fig. 3) while the head is fixed in one position (head or eye tilt is allowed). The scanning field can be increased by slanting the taper to tilt the image towards the observer. Such slanting can be. achieved in a variety of ways (Peli, 1995). The simplest method of tilting the upper face of the taper toward the users is by cutting the smaller bottom face of the taper at a bias (Fig. 2). Other methods are described in the patent (Peli, 1995).

From fig. I it can be shown that

$$L=H\ [\tan(\theta+\alpha)-\tan(\theta-\alpha)]$$

where $\sin\alpha = N.A._{\text{large face}}$ and θ = tilt angle of taper. For the nominal case when D = 0 and the taper is scanned from just under the eyes and away from the observer, the optimal tilt angle is $\theta = \alpha$. Smaller tilt angles ($0 < \alpha$) will result in a loss for of scanning range, and larger angles are possible but will force the scanning range away from the user (D > 0). Table 1 gives the calculated and measured scanning fields for a number of the tapers we have developed, both with and without the tilt (Peli & Siegmund, 1995). As can be seen, the agreement between the calculated and measured values is quite good.

The scanning ranges of the two tilted tapers measured were compared with the scanning, range of 4 commercially available, commonly used, lens stand magnifiers. The tapers' effective magnification as measured by the equivalent viewing distance (EVD) were 12.5 and 8.3 cm, for the 2.0x and the 3.0x magnifications, respectively, and for an eye to lens distance of 25 cm (Bailey *et al.*, 1994). The lens magnifiers tested had EVDs (for the same distance) similar to the EVD of the tapers (see Table 2). The advantage of the taper over the lens magnifiers is apparent (compare Tables 1 & 2). Note that the range of the tilted 2.0x taper (bold entry in Table 1) is almost double that of the equivalent lens magnifiers even though a cut of less than half the optimal angle was used. Similarly the 3.0x taper's range is about 50% wider than that of the stand magnifier. The actual benefit of the tapers is even larger than that indicated by the numerical results since the image through the lens magnifiers becomes highly distorted even at distances much less than the scanning range.

In addition to providing an increased scanning range, these tilted tapers also provide better control of illumination. Control of illumination is achieved both in collecting the ambient light and in avoiding the glare resulting from specular reflections from the upper face of the taper. Due to the tilt of the upper face, rotation of the taper around a vertical axis permits the user to include within the taper's admittance cone an off-axis light source (a window or a ceiling light fixture) which would otherwise be outside the admittance cone of the same taper without the tilt (Peli & Siegmund, 1995). Once a source lies within the admittance cone its light is concentrated by the taper and results in a brighter image. Specular reflections from bright light sources which would be reflected from the polished upper surface of the taper can also be redirected by the same slight rotation of the taper away from the user's eyes. Such reflections are almost impossible to remove from the curved surface (or surfaces) of a lens magnifier. An additional design we proposed (Peli & Siegmund, 1995) and implemented results in a taper with flat upper face parallel to the desk surface, while the admittance cone is still tilted as desired. This is achieved by cutting both surfaces on a bias each at half the calculated optimal angle. With this design, specular reflections from any source positioned behind the user's shoulders will be reflected away from the user's eyes, providing comfortable and controlled illumination.

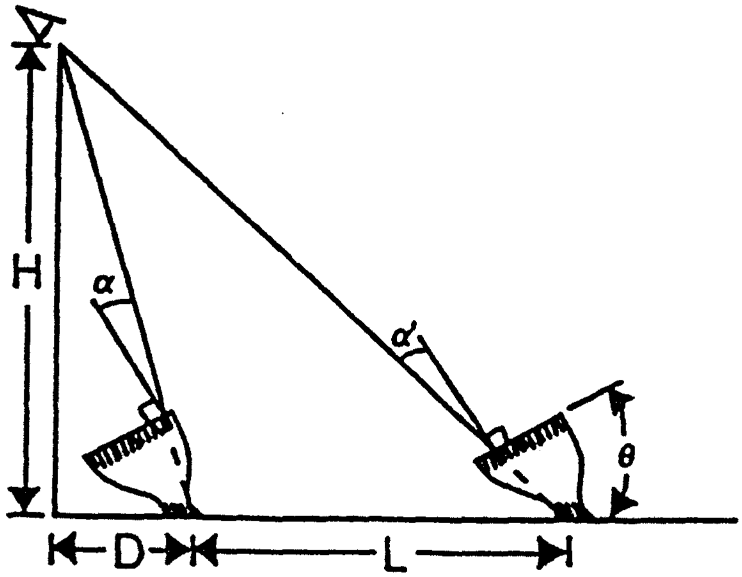

Figure 3. Parameters associated with the calculation of scanning field.

Table 1. Calculated and Measured Scanning Fields of Tapers

NA (nominal)	Mag (M)	EVD (@25 cm)	Admittance (α)	Tilt (θ)	Measured Range [cm]	Calculated Range (L+D) [cm]
1.0	2.0x	12.5	30.0°	0°	17.2±1.5	14.7
1.0	2.0x	12.5	30.0°	13°	25,0±1,7	23.7
1.0	3.0x	8.3	19.5°	0°	8.3±0.6	9.0
1.0	3.0x	8.3	*19.5°*	*12°*	*15.4±0.6*	15.5

Table 2. Measured Scanning Fields of Lens Stand Magnifiers
Bold and **italic entries** should be compared with the corresponding **entries in Table 1.**

Type	Mag (Marked)	EVD (@25 cm)	Measured Range [cm]
Eschenbach 2627	4.0x	13.3	11.4±1.3
COIL 52 14 tilted	4.0x	12.3	14.6±1.1
Sesi #402 Jupiter	4.0x	11.1	11.0±0.7
COIL 62 79 (Illum.)	*5.4x*	**8.1**	*10.9±1.4*

CONTRAST TRANSFER

The most important factor in contrast transfer is the non-image forming light transmitted by the cladding. The cladding material occupies about 30% of the area of commonly made

high resolution tapers. This large amount of non-imaging (scattered) light limits the ratio of contrast transferred through the taper. The lower resolution requirements of the **taper for use by the** visually impaired allows us to improve this situation. The fiber size may be quite larger than in a conventional taper, while the absolute cladding thickness can remain small, and thus the packing fraction can be quite high (exceeding.90%), resulting in a concomitant improvement in contrast transfer through the taper.

To evaluate the contrast transmittance of tapers used as magnifiers, we measured the contrast of a square wave grating through 4 different types of fiber optic bundle materials used in tapers. The material, a parallel (non tapered) bundle slab of about 1/2 in. was cut from the large end of tapers of various types. Parallel slabs were used to avoid the confounding effects of luminance changes associated with the taper magnification. The conventional material had hexagonal shaped fibers of 20 pm with clad fraction of 30%. The SBIR la and lb materials, we designed for use as reading magnifiers for the visually impaired, were made from the same material having a clad fraction of 17% and round fibers in hexagonal packing of 240 pm and 300 pm, respectively. The SBIR 2 material had hexagonal fibers of 300 µm and clad fraction of 7%.

The luminance of the bright and dark stripes of the gratings printed with a Laser Printer on white paper where measured with a Minolta LS100 luminance meter (1 desg spot). The minimum and maximum luminances were then measured through the various tapers placed over the printed gratings. The Michelson contrast was found to be 0.83 for the paper «target» alone. The luminance values measured through the various tapers and the contrasts calculated from them are given in Table 3. The contrast transfer was calculated as the ratio of the contrast through the fiber optic bundles to the contrast measured without the bundles (0.83). The contrast transfer increases from a low of 0.72 with conventional Tapers up to 0.94 with our large fiber Tapers.

The contrast transfer increases we measured are consistent with the increases in core-to-cladding ratio implemented. Other factors, such as fiber diameter may have an efect as well, as is evident from the difference in contrast transfer through tapers marked SBIR la and lb. These two materials had identical core fractions (made from the same batch of fibers) and differ only in the fiber diameter. It is clear that using the low resolution fibers needed in a low vision reading aid, the increase in contrast that can be achieved over smaller fibers is substantial.

Table 3: Measured Contrast Transfer of Bundles of Various Materials.

Taper Type	l_{max}[cd/m^2]	L_{min}[cd/,m^2]	Contrast	Contrast Transfer
Target (no taper)	108	9.9	0.83	NA
Conventional	107	26.8	0.06	0.72
SBIR la	90	15.6	0.70	0.85
SBIR lb	96	20	0.66	0.79
SBIR 2	100	12.4	0.78	0.94

Anti-reflection coating increased contrast transfer more for the coating of the bottom face than for the top face (Peli & Siegmund, 1995). Coating both faces increases the contrast transfer substantially from 0.67 up to 0.87. The use of coating on the bottom surface is unlikely since the continuous friction of the taper against the reading materials may result in fast stripping of the coating even if a hard, scratch resistance coating is used. Furthermore, the increase in contrast afforded by the increase in core-to-clad ratio, limits the additional value afforded by the coating. Further increase in contrast can be achieved by a method called *end blocking* in which the clad portion at the top face is removed and replaced by a black material.

CONCLUSION

The outstanding performance of tapers as reading magnifiers is selfevident. The improvements that we introduced by increasing the scanning range and the control of illumination via the bias cut of the small face or both faces, and the improved contrast transfer we demonstrated with low resolution fibers will make them an even better choice as reading aids. The real image on the large face of the taper makes for a convenient and easy to use device that can be readily combined with any existing spectacle or head mounted aid, using binocular vision. We believe that the only obstacle to wider use is the current high cost of production ($400 for a 2 inch taper) and relatively low contrast transfer. Therefore, we are working to produce low resolution, high contrast tapers of useful magnification using materials and production designs that will bring the price into an affordable range.

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