The Effect of Light Level and Small Pupils on Presbyopic Reading Performance

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Purpose. To examine the impact of small pupils and light levels on reading performance of distance-corrected presbyopes. To determine whether small pupils would enable presbyopes to read at near even at low light levels.

Methods. To establish the lower range of text luminances, we quantified the space-averaged luminance of text in nine different artificially lit interior environments, and examined the impact of the text characters on space-averaged luminance of electronic and printed displays. Distance and near reading speeds of 20 presbyopes (ages 40–60 years) were measured while viewing through artificial pupils (diameters 1–4.5 mm), natural pupils, or with a multifocal contact lens. Space-averaged text luminance levels varied from 0.14 to 140 cd/m^2 (including the range of measured environmental text luminances).

Results. Adding black text to a white computer display or paper reduces luminance by approximately 15% to 31%, and the lowest encountered environmental text luminance was approximately 2 to 3 cd/m^2. For both distance and near reading performance, the 2- to 3-mm small pupil yielded the best overall reading acuity for space-averaged text light levels $\geq$ 2 cd/m^2. The 2- to 3-mm artificial pupils and the multifocal contact lenses both enabled maximum or near-maximum reading speeds for 0.5 logMAR characters at distance and near, but with natural pupils, reading speeds were significantly reduced at near.

Conclusions. Although photon noise at low luminance reduces the visual benefits of small pupils, the benefits of 2- to 3-mm artificial pupils are sufficient to enable >80% of distance-corrected presbyopes to read proficiently at near, even at the lowest text luminances found in interior environments.

Keywords: presbyopia, retinal illuminance, small pupil, reading, low light

For a young, well-focused eye, objects at various distances can appear equally clear because the optical power of the eye can actively adjust.[1] However, with loss of lens elasticity,[2,3] accommodation typically drops to zero beyond 50 years and below 2 diopters (D) at approximately 40 years.[4] This presbyopia affects approximately half of the population in the United States and more than 1 billion people worldwide.[5,6] These patients typically employ extra plus power in their optical correction to focus near targets, which can take the form of reading glasses, progressive lenses,[7–9] bifocal and multifocal contact lenses,[10–12] and intraocular lenses.[13–17] Alternatively, a fixed small pupil inserted into the spectacle plane,[18,19] or a contact lens,[20–22] or directly into the cornea, also known as a corneal inlay,[23–29] can expand the eye's depth of focus, thus reducing the need for accommodation.[24,25,29]

Photopically, small pupils have been shown to significantly expand the objective[26,27] and subjective[30,31] depth of focus, distance,[24,25,29,32] and near visual acuity[24,25,29,33] and reading performance.[23] However, at mesopic light levels, the gains in objective image quality for near targets,[34] near visual acuity,[34] and subjective near visual task satisfaction [23,35] associated with pupil miosis are reduced. Except at high photopic light levels, human spatial vision is considered to be photon limited,[36–38] and the elevated photon noise effects at lower light levels reduce contrast sensitivity. Also, computer modeling and visual acuity experiments both indicate that the pupil size required to maximize visual acuity becomes larger as light levels fall.[34,39–41] Because small pupils lower retinal illuminance, which leads to decreased contrast sensitivity and visual acuity, there is concern that small pupils, although perhaps ideal for presbyopes at high photopic light levels, will compromise visual performance at low photopic or mesopic light levels.[34]

Reading at near is the most difficult visual task for presbyopes,[42] motivating patients to seek a near add in their prescription.[43] Consequently, many studies of bifocal/multifocal optics[44] and corneal inlays[23–25] have evaluated their efficacy by quantifying the reading performance or lack of need for additional reading aids. We have examined the impact of small pupils on this critical visual task as a function of light level. We first measured the luminance of text found in interior environments, and then examined the impact of light level on the ability of small pupils to facilitate reading performance in distance-corrected presbyopes over the range of text luminances observed in the environment.

Methods

Patients and Lenses

The study enrolled 20 healthy presbyopes (ages 40–60 years, mean age 51 years) with no ocular or systemic diseases, and

FIGURE 1. Scaled schematic diagrams of the tinted artificial pupil contact lenses used in our study.

monocular corrected distance visual acuity of 0.0 logMAR (equivalent to 20/20 Snellen acuity) or better in the tested right eye (the left eye was covered). Each subject's refraction was confirmed with a subjective refraction and the Grand Seiko autorefractor.[45] All 20 subjects were tested with 2.1- and 3.2-mm artificial pupils (AP); half of these were also tested with 3.6-mm AP and with natural pupils with or without a multifocal contact lens. Two subjects were tested with a wide range of pupils and light levels. Experimental protocols were approved by the Indiana University institutional review board, adhered to the tenets of the Declaration of Helsinki, and required informed consent from each subject.

To measure the monocular reading performance achieved with different small pupils, we chose not to employ the typical optical telescope system that images a fixed AP into the subjects' pupil plane[34,46] because of the significant eye movements associated with reading lines of text.[47] Instead we placed different AP into contact lenses with zero optical power (Alden Optical, Lancaster, NY, USA; http://www.aldenoptical.com). Lens designs contained an opaque black iris with an outer diameter of 11.5 mm and five inner diameters of 1.0, 2.1, 3.2, 3.6, and 4.7 mm (Fig. 1). Lenses were nominally plano with a center thickness of 0.19 mm. Contact lenses contained 49% water and 51% Hioxifilcon B, with a base curve radius of 8.60 and a 14.5-mm lens diameter. The contact lens pupil diameters, powers, and aberrations were confirmed on and off the eye with COAS and Clearwave aberrometers.[48,49] For comparison, we also measured the reading performance with natural pupils and a plano Air Optix AQUA multifocal high-add lens (center-near aspheric/bi-aspheric design) (Alcon, Fort Worth, TX, USA). After 20 minutes of dark adaptation, natural pupil size of the nontest eye was measured with a Neuroptics (VIP-200) Pupilometer[50] while the test eye viewed the stimulus display. The power profile of the Air Optix multifocal was documented in Figure 4 and the Table of Plainis et al.[51]

Reading Test Measurements

Foveal reading speed was measured with two target vergence levels (0 and −2 D) in a random order. The zero target vergence condition used trial lenses to make the text display conjugate with the retina for the unaccommodated eye, and thus replicated the optical conditions faced by a distance-corrected presbyope viewing a distance target. We then added a −2-D lens to simulate target vergence for a 50-cm stimulus when viewed by a distance-corrected presbyope. After the initial dark adaptation, light levels were tested in an ascending order to ensure that the retina was progressively light adapting during the experiment. Light levels were controlled with neutral density filters placed in front of the subject's right eye. Subjects viewed the screen through an opening in a black card that occluded the peripheral field ($>\pm 45°$). Room lights were turned off during the experiment.

High-contrast black-on-white characters were presented on either an iPhone5S or iPad (Apple Store, Bloomington, IN, USA) displays with a white background of 200 cd/m^2. Reading speed was measured with two paradigms, both using the validated IURead test.[52] First, reading speed was measured as a function of letter print size in two presbyopes (ages 60 and 54). Letter sizes ranged from −0.38 (font size 9 points displayed on iPhone5S at 70 cm) to +1.11 (font size 57 points displayed on iPad at 40 cm) logMAR, equivalent to 20/8 to 20/260 Snellen acuity. These data reveal maximum reading speed achieved with the larger letters, and the rapid decline in reading speed as text approached the acuity limit. A second experiment measured reading speed for presbyopic subjects (age: 40–60 years) with a fixed 0.5 logMAR angular size (font size 50 points on iPhone 5S viewed from 50 cm), equivalent to 20/60 Snellen acuity. This font size was chosen because approximately 75% to 80% of American adults use a cell phone or computer to message or surf networking sites (the Pew Research Center's Internet & American Life Project, http://www.stateofthemedia.org; in the public domain), and 0.5 logMAR is not only the mean font size of the cellphone text message,[53] but also the minimum font size of computer workstations required by National Standards Institute ANSI/HFES100-2007 (https://www.hfes.org/web/Standards/standards.html; in the public domain). As soon as each sentence appeared on the screen, subjects were instructed to read each sentence aloud "as fast as possible" without making significant errors. Free downloadable digital recording software (Audacity version 2.0.5, http://audacity.sourceforge.net; in the public domain) was used to record the duration of each spoken sentence (timing accuracy of 0.001 second).[52] Reading speed in words per minute (wpm) was derived from reading time (in seconds) by the following equation[52,54]:

$$\text{Reading Speed} = \frac{60 \times (10 - \text{Errors})}{\text{Time}} \qquad (1)$$

where errors represent total unread or incorrectly read words in each sentence.

Text Luminance Measurements

Impact of Text Characters on Display Luminance. Establishing the luminance of text is complicated by the fact that text includes two light levels, one for the background and one for the text characters (e.g., black text on a white background). Therefore, we defined the luminance of all our text stimuli by integrating photons over multiple lines of text to get a space-averaged measure of stimulus luminance that included characters and background. Also, rather than testing at some arbitrarily selected high and low luminance levels, we sought to identify representative text luminance levels present in the interior urban environment to guide our psychophysical testing. All luminance levels were measured with a photometer (Konica Minolta Sensing Americas, Ramsey, NJ, USA) calibrated to National Institute of Standards Technology (NIST) standards.

To quantify the impact of text on mean luminance of a display, we measured the luminance of our displays either with no text or with maximum-contrast black-on-white characters sampled from 10 famous English language texts (Dickens, Lincoln, F. Scott Fitzgerald, Steinbeck, Hemmingway, Austin, Bronte, Joyce, Twain, and Rowling) displayed on a Macintosh Thunderbolt Display (Apple Store, Bloomington, IN, USA) in the commonly used 8-point (most common font in U.S. newspapers[55]) and 12-point type (default font size in Microsoft Word; Microsoft, Indianapolis, IN, USA), bold or unbold, and using the most common serifed Times New Roman and nonserifed Helvetica fonts[56] with single space or 1.5-line spacing. The luminances of the black levels used in the text were also recorded. The same text materials were also printed out with a Cannon printer (iR-ADV C5045/5051; Canon, Bloomington, IN, USA). The photometer was set to integrate

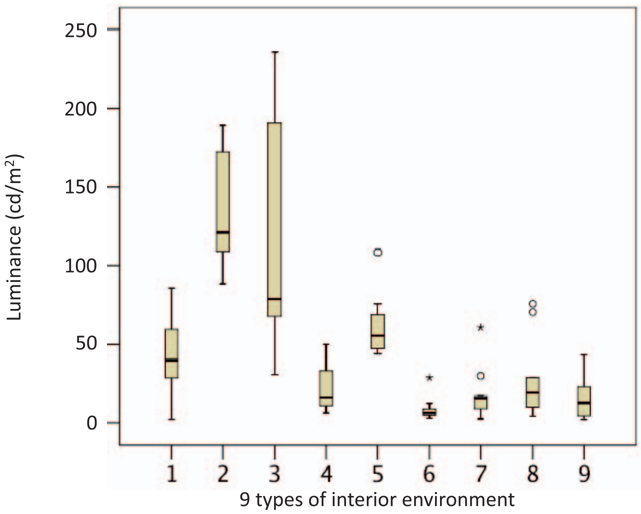

Figure 2. Box-and-whisker plot of space-averaged luminance in cd/m^2 from nine types of interior environment. The median, interquartile range, and the range of the data are indicated by the *thick black line* inside each box, the height of each box, and the separation between the upper and lower whiskers, respectively. *Circles and stars* are the outliers that are greater than 1.5 (*circles*) or 3 (*stars*) times the interquartile range away from the 25th or 75th percentile. Text in nine types of interior environment was documented: 1. Public buildings (signage in corridors, elevators, lobby); 2. office desktops (printed text on white paper); 3. libraries (book text held horizontally at reading height); 4. shopping mall (product labels, signage); 5. supermarket/box store (product labels); 6. history/culture museums (exhibit signage); 7. art museums (exhibit signage); 8. restaurants with dim hanging bar lamp lighting (menus, signage); and 9. hotels (lobby, corridor, elevator signage).

over a 3-cm-diameter circle, and these measures of text luminance included between 3.5 and 8 lines of text.

The % reduction of luminance produced by adding text to the display was derived from Equation 2:

$$\text{Decrease of Luminance}\ (\%) = \frac{100 \times (\text{White Screen Luminance} - \text{Text Luminance})}{\text{White Screen Luminance}} \qquad (2)$$

The percentage of the display covered by text was computed from Equation 3:

$$\text{Area of Display Covered by Text}\ (\%) = \frac{100 \times (\text{White Screen Luminance} - \text{Text Luminance})}{\text{White Screen Luminance} - \text{Black Screen Luminance}} \qquad (3)$$

Luminance of Text in Interior Environments. Charness and Dijkstra[57] measured large samples of the blank region (lacking text) of reading materials from the home, office, and public places, and found that the lowest light level was 11 cd/m^2. However, the printed or electronic text mostly employs dark ink or dark text pixels and therefore lowers the overall space-averaged luminance levels, which are routinely employed by contrast sensitivity studies when defining stimuli. Thus, we repeated the Charness and Dijkstra study by measuring the luminance levels of actual text samples.

We measured the space-averaged luminance for text found in nine types of interior urban environments (Fig. 2). Our motivation was to explore the lower range of light levels at which humans read. We therefore avoided measuring high-luminance computer displays or well-illuminated printed text during daylight. Luminance data were all collected in the absence of natural lighting either in spaces lacking any windows (e.g., museums) or at night (e.g., restaurants) in either Bloomington or Indianapolis, Indiana. These measurements are the space-averaged luminance or the area-weighted luminance averages of both the text characters and background. For each category of stimulus (see Fig. 1), we sampled 10 different environmental locations. In most cases, the text was black or darker than the background, but we also sampled examples of white or lighter text on dark backgrounds.

Results

Impact of Added Text on Display Luminance

The impact on space-averaged luminance of adding text to a display was highly consistent across our 10 text samples (e.g., SD <1% or <2% of the mean for the computer-displayed or printed text, respectively), and means from all 10 samples are shown in the Table. For example, single-spaced and unbold 8-point black (maximum contrast) Times New Roman text displayed on a white computer screen, with a white luminance of 76.5 cd/m^2 and a black luminance of 0.2 cd/m^2, dropped the mean luminance to 58 cd/m^2 (a 24.6% reduction), which is consistent with 24.7% of the screen being covered with text pixels. Displaying bold Times New Roman text decreased the screen luminance by 28.7%, whereas increasing line spacing to 1.5× character height reduced the luminance by 16.6% and 19.1% with the unbolded and bold text, respectively. Changing font to Helvetica reduced screen luminance by an additional 2%. In our print-on-paper examples, the white background and black text luminances were 150 and 15 cd/m^2, respectively. The higher luminance of the printed black letters produced, on average, a slightly smaller reduction in space-averaged luminance when adding text, but the impact of font and spacing was basically the same.

When converted to percentage area covered by text (Equation 3), our data confirm Scharff and Ahumada's[58] calculations that text coverage for single-spaced unbold Times New Roman text was between 22% and 25% of the text area. We found that this percentage area increased to 27% to 29% with bolding, and decreased to approximately 15% (unbolded) or 18% (bold) when line spacing is increased to 1.5. The highest percentage coverage we observed was for Helvetica bold, single spaced, which covered approximately 31% of the page (Table). Changes in font, bolding, and line spacing produce matching changes in the proportion of the display covered by text for both printed and computer-displayed text, with R^2 of 0.96. Because character and line spacing do not scale perfectly with font size, we generally observed slightly lower (<5%) text luminance with the 8-point font.

Luminance Measurements of Text in the Natural Environment

Because text can reduce display background luminance by 15% to 31% (see columns 2 and 3 in the Table), we measured the luminance of all our environmental text stimuli by integrating characters and background to get a space-averaged mean light level. In Figure 2, we plot the luminance for our 90 text samples from the nine text sources. The median text luminances in the office and library, 121 and 79 cd/m^2, respectively, were the highest, while text in the shopping mall, hotels, art museum, and restaurants was generally between 20 and 30 cd/m^2. Mean text in the history/culture museum had the lowest luminance, approximately 9 cd/m^2. Most of the text in this museum was, however, light text on a dark background, causing mean text (space average) luminance levels to be

TABLE. The Decrease of Luminance in Percentage Caused by Adding Different Types of Text to Either Computer-Displayed Text (Column 2) or Printed Text (Column 3). The Percentage of Each Display Covered by Text Is Calculated for a Computer Display and a Printed Sheet of Paper in Columns 4 and 5, Respectively

	Luminance Drop %		Text Coverage %	
Text Feature	Computer	Print	Computer	Print
Times New Roman, unbold, single space, 8 pt	24.6	24.1	24.7	26.7
Times New Roman, unbold, single space, 12 pt	22.4	20.7	22.5	22.5
Helvetica, unbold, single space, 8 pt	26.3	26.9	26.4	30.0
Helvetica, unbold, single space, 12 pt	24.6	23.7	24.7	26.6
Times New Roman, bold, single space, 8 pt	28.7	26.8	28.8	29.3
Times New Roman, bold, single space, 12 pt	26.9	25.4	27.0	28.6
Helvetica, bold, single space, 8 pt	31.0	30.1	31.1	34.1
Helvetica, bold, single space, 12 pt	30.7	28.8	30.8	31.4
Times New Roman, unbold, 1.5 space, 8 pt	16.6	16.8	16.6	18.6
Times New Roman, unbold, 1.5 space, 12 pt	15.3	14.5	15.3	15.9
Helvetica, unbold, 1.5 space, 8 pt	17.7	17.9	17.7	19.9
Helvetica, unbold, 1.5 space, 12 pt	16.6	16	16.7	17.4
Times New Roman, bold, 1.5 space, 8 pt	19.1	19.1	19.2	21.1
Times New Roman, bold, 1.5 space, 12 pt	18.1	17.8	18.1	20.0
Helvetica, bold, 1.5 space, 8 pt	20.6	21	20.6	23.8
Helvetica, bold, 1.5 space, 12 pt	20.8	20.3	20.8	22.0

lower because the background generally covers between 69% and 85% of the text field (Table). Therefore, switching from dark text on white background to white text on a dark background will approximately reduce light level by a factor of 2 and therefore increase photon noise problems by a factor of $\sqrt{2}$ (square root law[34,36]). For this reason, as shown previously,[59] contrast reversal of text has a trivial impact on reading performance. The lowest and highest encountered luminances were 2.1 and 215.2 cd/m^2, respectively, with only 3 out of 90 samples in the lowest 2- to 3-cd/m^2 range. Our measured light levels were generally lower than previously reported interior light levels[57,60] because our measurements included the impact of dark characters in the text, which lowers space-averaged luminance by 15% to 31% (Table); and we avoided interior environments that included daylight illumination and specifically sought out low-light environments, for example, museums and restaurants, and took most of our measurements at night.

These results emphasize that humans read over the full photopic range, with the lowest text luminances being at the boundary between photopic and mesopic light levels. For example, if a person reads 1.4 cd/m^2 text with a large natural pupil of, say, 7-mm diameter, retinal illuminance will be $1.4 \times 3.5^2 \times \text{pi} = 53$ Trolands, generally considered to be the lower bound of photopic (cone only) vision.[61] Of course, if the same text is read with a small AP, for example, 1.6-mm diameter, retinal illuminance will drop to <3 Trolands, well within the mesopic range.

Our text luminance measurements were used to define the light levels tested in the psychophysical portion of this study. We measured reading performance with space-averaged text luminances varying from 140 to 1.4 cd/m^2, which is a 31% drop (Table) from the white background luminances (200–2 cd/m^2). We also tested reading performance at 0.14 cd/m^2 to include a light level low enough to prevent the fovea from being used to perform the reading test.

Reading Speed and Reading Acuity

We measured reading speed for focused and −2-D defocused text (Figs. 3, 4, respectively) as a function of print size (incremented in 0.1 logMAR steps) for two presbyopic subjects (ages 60 and 54 years) with no residual accommodation,[4] at four different light levels (140, 14, 1.4, and 0.14 cd/m^2). Within each panel, we plot data for four AP diameters and the eye's natural pupil. Most of the data conform to the familiar pattern[52,62,63] in which reading speed increases with text size over approximately a 0.3 logMAR range (or a doubling in size), at which point maximum speed is achieved.

Noticeably, once text is large enough, varying pupil size or further increases in letter size have no effect on maximum oral reading speed, which is consistent at approximately 200 wpm for subject 1 and approximately 250 wpm for subject 2 at all light levels and both defocus levels. However, pupil size can significantly affect the reading acuity. Basically, pupil size and light level affect the horizontal, but not the vertical, position of these reading speed plots. We define reading acuity as the smallest text for which subjects could read, admittedly at a slow rate.

For both subjects, with a well-focused retinal image (Fig. 3), a 2.1-mm AP provides best reading acuity at all light levels except at 0.14 cd/ m^2, where the natural pupil or a 4.7-mm-diameter AP was best. At the highest light levels, reading speed with a 2.1-mm pupil drops to zero with −0.3 logMAR text, and has already reached maximum speed with text between 0.00 and 0.20 logMAR. The 1-mm AP produced the worst acuities, being approximately 0.4 logMAR worse than those achieved with the 2.1-mm AP at 140 cd/m^2, and decreasing even further as light level dropped; and reading with the 1-mm AP was unmeasurable at 0.14 cd/m^2. This complete failure to read at 0.14 cd/m^2 with the 1-mm AP reflects the low mesopic retinal illuminance of $0.14 \times 0.5^2 \times \text{pi} = 0.1$ Trolands, which is below the cone threshold.[61,64] Therefore, we expect that the fovea cannot respond to the text at 0.14 cd/m^2 with a 1-mm pupil diameter and thus reading foveated text is impossible. Increasing light levels from 0.14 to 140 cd/m^2 shifts all pupil size data sets to the left, affirming the value of higher lighting levels for reading acuity with all pupil sizes. The reduction in reading acuity associated with reduced light levels was greatest for the smallest 1-mm-diameter pupil (0.4 logMAR per log drop in luminance). With natural pupils, which expanded from approximately 4 at 140 cd/m^2 to 7 at 0.14 cd/m^2, reading acuity dropped by only 0.13 logMAR per log unit drop in luminance.

The expected gain in visual performance associated with small pupils is much larger in the presence of large amounts of defocus (Xu R, Wang H, Thibos LN, Bradley A, manuscript

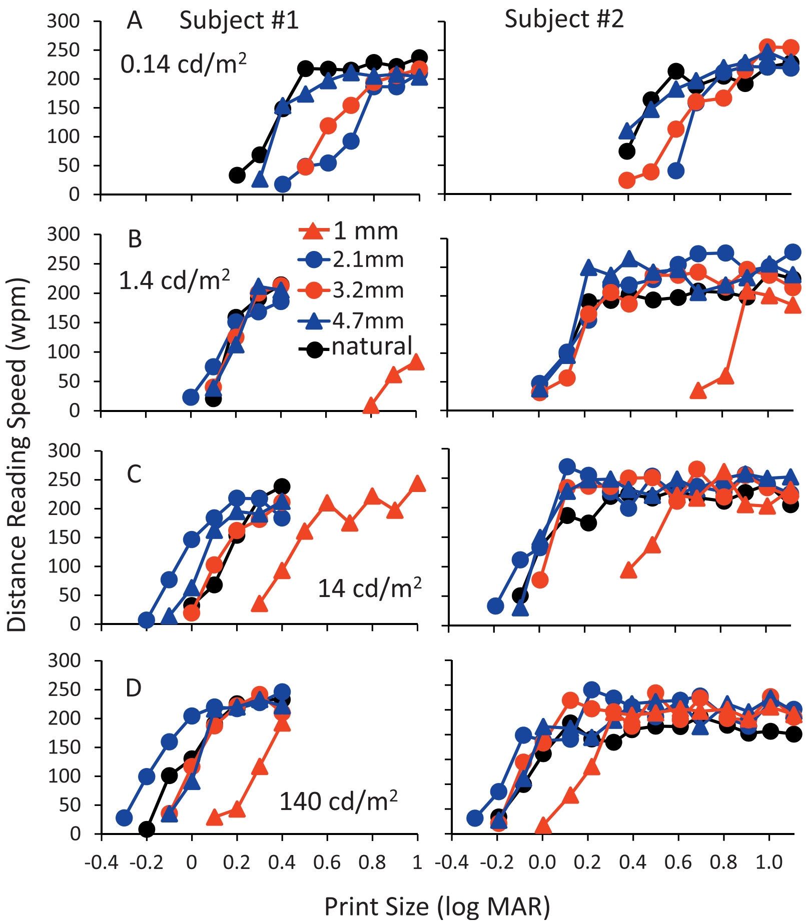

FIGURE 3. Distance reading speed (with 0-D defocus) as a function of print size for 0.14 (**A**), 1.4 (**B**), 14 (**C**), and 140 (**D**) cd/m^2 text for presbyopic subjects 1 (*left column*) and 2 (*right column*). *Different symbols* inside each part of the figure indicate different pupil diameters (see key).

submitted, 2016).[34,65] This trend can be seen in the −2-D reading data (Fig. 4). For example, in the presence of −2-D target vergence, the 1-mm AP proved best for subject 1 and almost best for subject 2 at 140 cd/m^2. This superiority of the very small pupils gradually declines such that at 1.4 cd/m^2, the 1-mm AP produced the worst reading acuities. The increased vulnerability of small-pupil vision at low light levels can again be quantified by the drop in logMAR acuity as a function of decrease in light level, being approximately 0.35 logMAR per log unit drop in luminance for the 1-mm pupils and only 0.1 for the natural pupils. With a 1-mm AP, as light levels drop from 140 cd/m^2, reading acuity declines from 0.1 to 0.4 logMAR at 14 cd/m^2 and to 0.8 logMAR at 1.4 cd/m^2, for both subjects. At 0.14 cd/m^2, reading was impossible with a 1-mm AP, because light levels are below cone threshold.[61,64] Also, with −2-D target vergence, the 2.1-mm AP outperforms the natural pupil by up to 0.4 logMAR and on average 0.3 and 0.1 logMAR for subjects 1 and 2, respectively. Unlike the 1-mm AP, the 2- and 3-mm AP provided best reading acuity in presence of −2 D of defocus for all light levels except 0.14 cd/m^2, where the natural and or 3.2-mm AP provided best reading performance.

These results, therefore, reveal that the improved reading acuity for defocused text afforded by 2- to 3-mm pupil diameters is generally achievable over the full range of text light levels experienced in our natural environment (≥2 cd/m^2, Fig. 2), but not at the very low light levels encountered while night driving.[66] The smaller 1-mm AP provided improved reading acuity at the highest photopic light level, but at the low end of the text luminance range, the 1-mm AP produced a significant drop in reading performance, even with −2-D target vergence (Fig. 4).

Our first experiment confirms, therefore, that reducing pupil size to around 2 to 3 mm improves presbyopic reading acuity at near even at the anticipated lower range of lighting expected in artificially lit natural indoor environments (2 cd/m^2). We next examined reading speeds for a sample of presbyopes with pupil sizes of 2.1, 3.2, and 3.6 mm at space-averaged text luminance levels of 2, 7, and 140 cd/m^2 for a fixed 0.5 logMAR text size. The results were compared to the natural pupil with either monofocal or multifocal corrections at the same target vergence and light levels. Consistent with the previous literature,[67] the average natural pupil diameters for 20 subjects were 5.83 ± 0.57, 5.41 ± 0.53, and 4.25 ± 0.76 mm for 2, 7, and 140 cd/m^2, respectively. Figures 5A and 5B show the mean distance (zero target vergence) and near (−2-D target vergence) reading speed data as a function of light level for 20 distance-corrected presbyopes (age range, 40–60 years). As predicted from the data in Figure 3, with a well-focused retinal image, maximum reading speeds around 200 wpm are observed for all pupil sizes and with the lens at all three light levels (Fig. 5A). However, when reading with −2-D of uncorrected target vergence, subjects exhibited slower reading speeds at all three light levels when using their larger natural pupils (black circles), failing on average to reach a 100-wpm criterion at 7 and 2 cd/m^2.

Between-subject variability in reading speed doubled (from a mean SD of 33 wpm at distance to 70 wpm at near), likely revealing the impact of different levels of defocus generated by

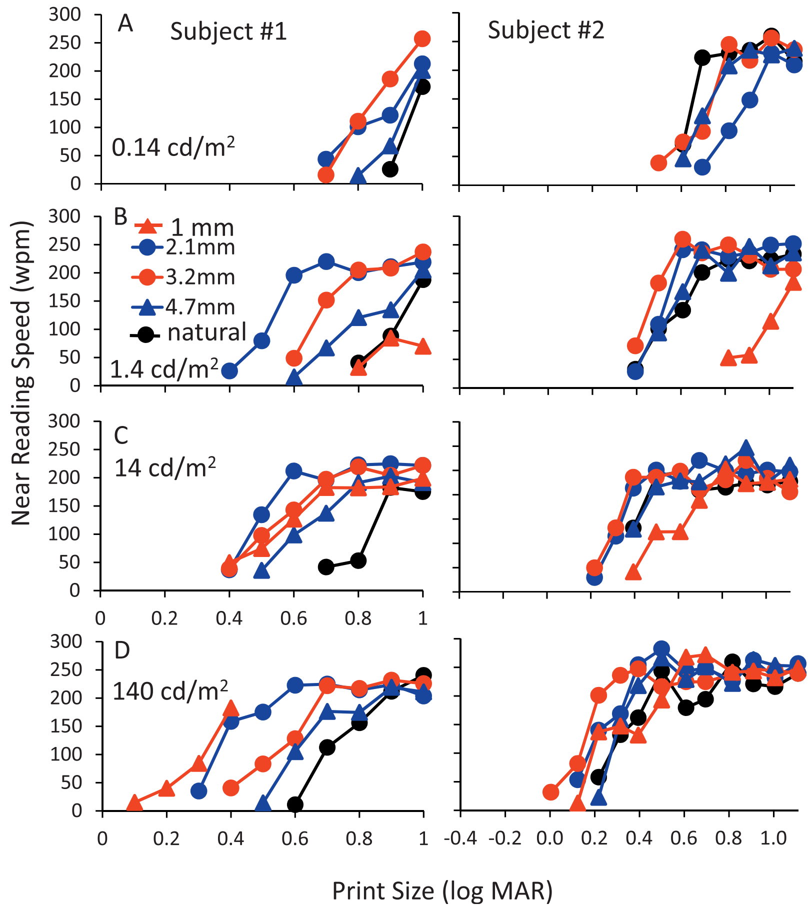

FIGURE 4. Near reading speed (with −2-D of target vergence) as a function of print size for 0.14 (**A**), 1.4 (**B**), 14 (**C**), and 140 (**D**) cd/m^2 text for presbyopic subject 1 (*left column*) and subject 2 (*right column*). *Different symbols* inside each part of the figure indicate different pupil diameters.

the −2-D target vergence due to varying levels of residual accommodation. At near, reading speeds with the 3.6-mm pupil (blue squares) were better than those achieved with a natural pupil, but the 2.1- and 3.2-mm small pupils and the multifocal contact lens enabled subjects to successfully maintain maximum reading speed at near with 7 and 140 cd/m^2 text, and speeds were only slightly lower at 2 cd/m^2. Our data confirm that for all text light levels, 100% of distance-corrected presbyopes can read at >100 wpm with focused retinal images with all pupil sizes and multifocal optics. However, in the presence of −2 D of uncorrected target vergence (50-cm near target distance), only 40% of eyes with natural pupils can read at this speed at the lower light levels, whereas with the 2- to 3-mm APs, >90% of distance-corrected presbyopes can achieve proficient reading speeds at near, even at the lowest text light levels experienced in interior environments and the smallest text routinely encountered.

If the increased between-subject variability seen in the −2-D target vergence data sets of Figure 5 reflects differences in retinal image defocus due to varying levels of residual accommodation over the 40- to 60-year-old age range, we anticipate seeing declining near reading performance associated with increasing age. We examine this in Figure 6, where we plot reading speed normalized to the distance (well-focused) reading speed observed with natural pupils. These data clearly show that distance reading speed is unaffected by age or light level, whereas near reading speed in these distance-corrected presbyopes declines with increasing age, and the impact of age becomes more exaggerated at lower light levels. Notably, with the 3.2-mm AP (red triangles in Fig. 6A), all but the oldest subject were able to read at their maximum speed at near when light level was 140 cd/m^2, but at this light level only 3 of 10 were able to read at their maximum speed with their natural pupils (black triangles in Fig. 6A). At 2 cd/m^2 (Fig. 6B), only the two youngest (46 and 48 years) achieved their maximum reading speed with near targets with natural pupils (black triangles), while six of eight subjects 48 years or older had measured speeds of zero to 33% of their maximum. Significantly, all but one of the older subjects could read >50% of their maximum when viewing near text through a 3.2-mm AP (red triangles) even for the lowest luminance text present in our environment.

Since reading comprehension is related to the proportion of correctly read words rather than speed,[68] we plot the percentage of the words of each sentence that were correctly read at near (Fig. 7A). The average percentage of words read is >90% for all pupil conditions except the natural pupil, for which the mean values are 60% and 80% for 2 and 7 cd/m^2, respectively. Also, although the maximum percentage of words accurately read by some subjects is 100% for all AP, multifocal, and natural pupils, variability was very large, as indicated by the error bars (range of data) in Figure 7A, which shows that with natural pupils, some subjects read less than 25% of the text.

In a related graph (Fig. 7B), we plot the percentage of subjects who could read whole sentences at near (although speed might be slow) for the five AP groups listed in Figure 5. At 140 cd/m^2, all pupils enabled ≥90% of subjects to read the whole sentence at near. With APs and the multifocal lens, this result remains even when reducing light levels to 7 cd/m^2 and only slightly drops at 2 cd/m^2. However, with natural pupils, at

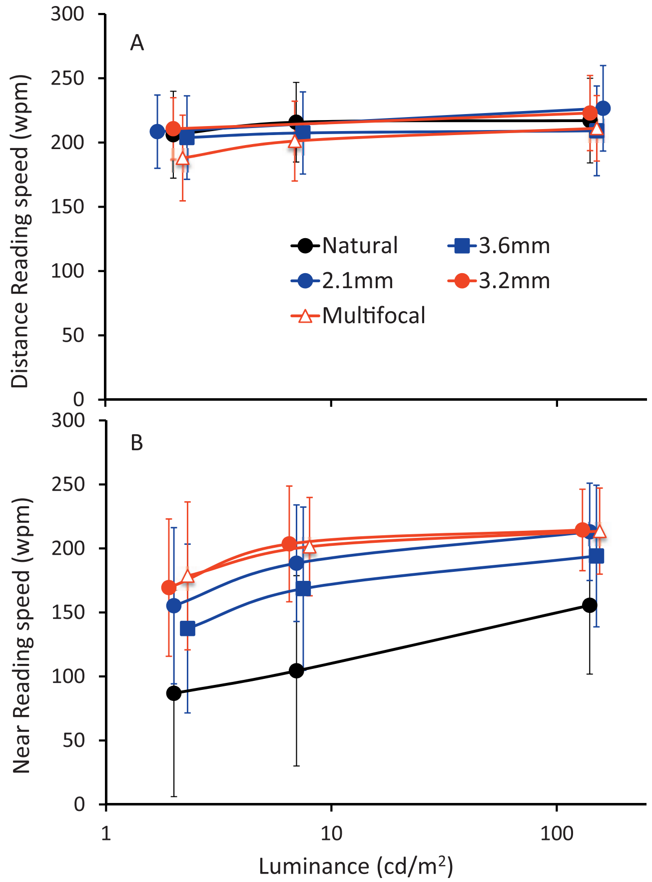

Figure 5. The mean reading speed for 0.5 logMAR text is plotted as a function of space-averaged text luminance (2, 7, and 140 cd/m^2) for either focused (**A**) or defocused (–2 D of target vergence) (**B**) images. *Different symbols* inside each part of the figure show reading acuities obtained with artificial pupils, a natural pupil (*black circles*), and a multifocal contact lens (*red triangles*) and were shifted horizontally to avoid symbols and error bars overlapping. *Error bars* indicate ±1 SD.

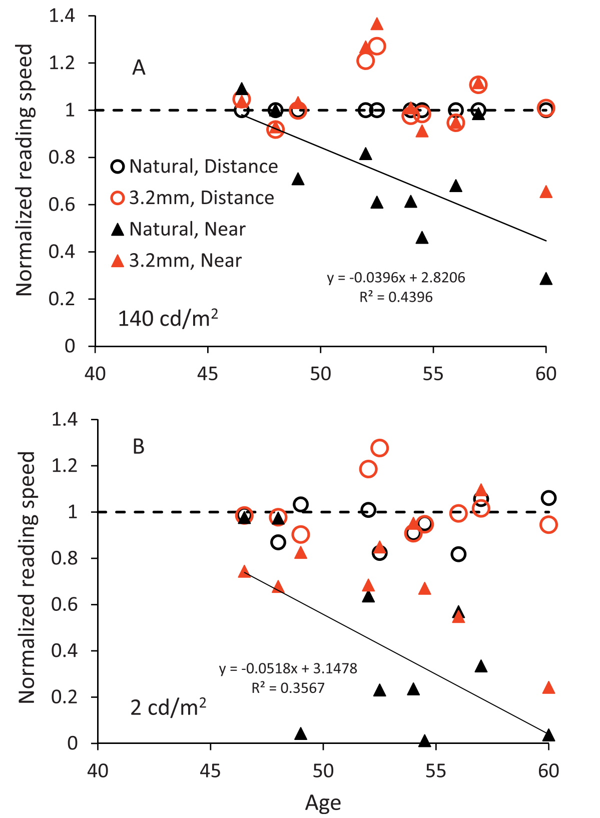

Figure 6. Reading speed, normalized to the distance reading speed observed with natural pupils at 140 cd/m^2, is plotted as a function of subject age in years for high (**A**; 140 cd/ m^2) and low (**B**; 2 cd/ m^2) light levels. Regression lines were fit to the near reading speed data obtained with natural pupils.

7 and 2 cd/m^2, only 40% and 30% of subjects, respectively, could read whole sentences with no error at near.

Discussion

We asked a simple question: Can small pupils enable proficient reading at near for distance-corrected presbyopes even when light levels fall? Our data emphasize that low light levels are detrimental to reading at near for the majority of presbyopes, which can be significantly alleviated with either APs between 2.1 and 3.6 mm, multifocal treatments, or increasing light levels. This result, however, does not hold true when a 1-mm AP is used, which tended to produce the worst reading acuities (Figs. 3, 4), especially at low light levels. The age plots (Fig. 6) reveal the common experience of emerging presbyopes: They can read near text at high light levels, but not at low light levels, and therefore it is the poor low-light-level reading performance that likely motivates emerging presbyopes to employ specific near reading aids. Employing a 1-mm AP only exacerbated this low-light-level challenge. Our data (Figs. 3–7) convincingly show that presbyopes can read with a small-pupil diameter around 2 to 3 mm at maximum or near-maximum speeds with text luminances between 140 and 1.4 cd/m^2 without any significant loss in best focus (distance) vision. This result is significant, because we also found that the lowest encountered environmental text luminances are at or above 2 cd/m^2. Because lens optical density increases monotonically with age,[69] we recommend pupil miosis for early presbyopes. Actually, pupil miosis might worsen vision if patients had age-related nuclear cataract.

Previous studies have shown that the 1.6-mm central clear zone corneal inlay can improve photopic distance[24,25,29,32] near visual acuity[24,25,29] and near reading performance.[23] A 1.6-mm AP, which transmits 2.5× more light than a 1-mm-diameter pupil but 1.7× less light than a 2.1-mm-diameter pupil, likely produces reading performance in between the results we observed with 1- and 2.1-mm APs, and therefore elevated photon noise problems may explain the reduced subjective near visual task satisfaction reported for patients with a 1.6-mm AP at dim (exact luminance level is unknown) light levels.[23,35] It is important to emphasize that corneal plane small pupils will produce even larger reduction in retinal illuminance in the peripheral retina.[70,71]

The reduced retinal illuminance associated with small pupils elevates contrast thresholds due to photon noise.[37,38] Similarly, multifocal optics lower retinal image contrast[10] and therefore also raise contrast thresholds.[72] Consequently, although these two approaches employ very different optics, patients using either approach will exhibit elevated contrast thresholds. Therefore, at the low end of the text luminance range (Fig. 2), both types of presbyopic correction are vulnerable to the elevated neural contrast thresholds caused by increased photon noise. It is not surprising, therefore, that reading speed with both small pupils (between 2.1 and 3.6 mm) and multifocals (Fig. 5) shared a similar drop (an approximately 25% decrease from maximum) at the lowest tested light levels (2 cd/m^2).

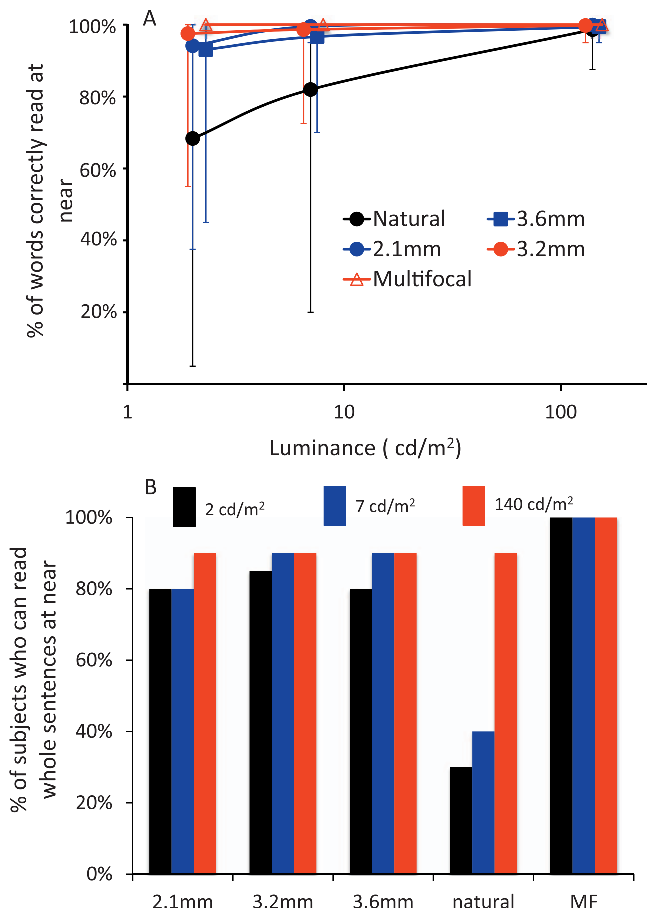

Figure 7. The percentage of words correctly read (**A**) and the percentage of subjects who could read the complete sentences at near (**B**) are plotted for a series of light levels for the same AP and multifocal conditions employed in Figure 5B. *Upper and lower bars* (Fig. 7A) are the maximum and minimum % read.

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