Effects of Lighting on Reading Speed as a Function of Letter Size

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OBJECTIVE. We sought to determine under what conditions brighter lighting improves reading performance.

METHOD. Thirteen participants with typical sight and 9 participants with age-related macular degeneration (AMD) read sentences ranging from 0.0 to 1.3 logMAR under luminance levels ranging from 3.5 to 696 cd/m².

RESULTS. At the dimmest luminance level (3.5 cd/m²), reading speeds were slowest at the smaller letter sizes and reached an asymptote for larger sizes. When luminance was increased to 30 cd/m², reading speed increased only for the smaller letter sizes. Additional lighting did not increase reading speeds for any letter size. Similar size-related effects of luminance were observed in participants with AMD.

CONCLUSION. In some instances, performance on acuity-limited tasks might be improved by brighter lighting. However, brighter lighting does not always improve reading; the magnitude of the effect depends on the text size and the relative changes in light level.

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Increased lighting is a recommended intervention for many clients with low vision (Brilliant, 1999; Faye et al., 2011; Jackson & Wolffson, 2007). Beginning with Tobias Mayer in 1754, the effects of lighting on visual acuity have frequently been studied (Bowers, Meek, & Stewart, 2001; Eldred, 1992; Eperjesi, Maiz-Fernandez, & Bartlett, 2007; Ferree & Rand, 1921; Haymes & Lee, 2006; Sloan, 1969; Tinker, 1954). This body of work has repeatedly demonstrated that, under some conditions, visual acuity can be improved by increasing illumination. However, the effects of lighting on detection and processing of large text have not been considered clinically. The data of Campbell and Robson (1968) and De Valois, Morgan, and Snodderly (1974) suggest that the relationship between light level and threshold tasks may not hold for performance on suprathreshold tasks, such as reading. Thus, it is important to determine under

which conditions additional light should be recommended; specifically, the purpose of this study was to delineate the conditions under which increased light levels improve reading performance because reading goals are common in people seeking low-vision rehabilitation (Brown, Goldstein, Chan, Massof, & Ramulu, 2014; Owsley, 2011). Data showing the relationships among luminance, letter size, and reading speed will help vision rehabilitation practitioners predict the amount of increased lighting that could be expected to provide a benefit.

Method

Participants

Thirteen participants with typical vision and without ocular disease (median age = 61 yr) and 9 participants with nonexudative age-related macular degeneration (AMD; median age = 77 yr) were enrolled. All

participants signed written informed consent. The research adhered to the tenets of the Declaration of Helsinki (World Medical Association, 2013) and was approved by the institutional review board of the Lighthouse Guild.

Stimuli

Two-line sentences were printed on separate pages in the Calibri font. Sentences were adapted from the Woodcock Johnson III—Tests of Achievement Reading Fluency (Woodcock, McGrew, & Mather, 2001). We used a total of 65 sentences, and each sentence was read only once by each participant. Sentences were printed at letter sizes ranging from 0.0 (0.4M) to 1.3 logMAR (8M).

Light Levels

The light source was an incandescent tungsten lightbulb in a cone-shaped reflector lamp placed 50 cm above the desk-top. In separate conditions, the light was attenuated using neutral density filters. The luminance levels of the paper were 695 cd/m², 250 cd/m², 65 cd/m², 35 cd/m², and 3.5 cd/m² (Minolta Luminance Meter LS-110; Konica Minolta Sensing Americas, Inc., Ramsey, NJ). To make the lighting values relevant to real-world situations, we calculated the equivalent lightbulb wattages required to produce these luminance levels, assuming 15 lumens/watt (W) efficiency for incandescent lightbulbs. The equivalents were 250W, 90W, 30W, 17W, and 10W incandescent lightbulbs at 50 cm from the paper. The physical contrast of the text was constant under all lighting conditions.

Procedure

Participants used their dominant eye (control) or the eye with the better visual acuity (AMD) and wore their habitual near refraction. The contralateral eye was patched. The paper was illuminated from above, in front of the participants. The participants held their heads approximately 40 cm from the pages; a 40-cm “measuring string” was used to keep the reading distance constant. Participants were instructed to read the sentences aloud as quickly and accurately as possible. Testing began at the lowest light level, and the participants adapted to this light level for 2 min before testing. At the

start, the paper was placed so that the printed side was against the table. When a participant verbally indicated that he or she was ready, the page was flipped to reveal the text, and the participant read the sentence aloud. Sentence readings were recorded using GoldWave digital audio software (GoldWave, Inc., St. Johns, Newfoundland, Canada). Reading times were derived from the audio waveform, and reading speeds, in correct words per minute (WPM), were calculated. At each illumination level, the participants started reading at the largest letter size (1.3 logMAR) and read sentences of progressively smaller letter sizes until all of the sentences in the set were read, or until two consecutive sizes could not be read. Then the next brighter light level was tested. Near acuity (Lighthouse Near Acuity Test, 2nd ed.; Lighthouse Guild, New York) and Mars contrast sensitivity (Mars Perceptrix Corp., Chappaqua, NY) were measured at each illumination level.

Data Analyses

We used a within-subject repeated-measures design, which allowed comparisons of the relative effects of lighting within a participant and controlled for factors such as age, education, acuity, and so on. A sigmoidal equation provided the best fit to the log reading speed (log WPM) as function of letter size (logMAR):

$$y = a / \{1 + \exp [-(x - b)/c]\}. \quad (1)$$

The advantage of fitting a mathematic function is that all of the points are used to describe the data, which reduces the influence of individual noisy data points. In addition, changes in the data as a function of lighting can be quantified by changes in the parameters of the fit function. For example, if reading speeds increase, the value of parameter *a* of this function will increase. If increased lighting improves reading acuity, the value of parameter *b* will decrease.

Results

Level of Illuminance

Visual function is related to (1) the amount of light incident on the paper (illuminance: lux), (2) the reflection of light by the paper (luminance: cd/m²), and (3) the pupil area,

which restricts the amount of light impinging on the retina (retinal illuminance). We calculated the amount of light falling on the retina (retinal illuminance) in trolands (td) by multiplying the luminance of the pages (in cd/m²) by the pupil area under each lighting condition.

Near Visual Acuity and Near Contrast Sensitivity Charts

Near visual acuity improved by an average of five letters (one line) when the level of retinal illuminance was increased from a dim mesopic¹ level (1.9 log td is equivalent to a 10W bulb) to a photopic level of 2.8 log td (17W bulb; Figure 1A). However, when the illuminance was further increased from 2.8 to 3.0 log td (17W–30W bulb), acuities increased by only one additional letter; there was no further improvement in acuity between 3.0 and 3.9 log td (30W–250W bulb). Post hoc comparisons revealed significant differences only between the mean acuity measured at 1.9 log td and the mean acuities at the other light levels. MARS letter contrast improved slightly when light was increased from 1.9 to 2.8 log td, with no further improvement at higher light levels (Figure 1B). Lighting had an insignificant effect on chart contrast sensitivity over the range of light levels tested, $F(3, 9) = 2.2$, $p = .16$.

Effects of Illuminance

For control participants, mean reading speeds as a function of letter size are plotted in Figure 2A. The lines drawn through the data are the best fits of Equation 1 to the data for each illuminance level. At each light level, reading speeds increased with increasing letter size, but the improvement in speed declined with larger text size. As illuminance was increased, reading speeds at small letter size increased, but there was little change at large letter sizes. In other words, reading speeds reached an asymptote at larger letter sizes for all levels of illuminance, as demonstrated by a significant interaction between illuminance level and letter size, $F(3, 9) = 4.8$, $p < .03$.

¹Mesopic refers to a low but not dark illumination level at which both rod and cones are functioning. Photopic refers to an illumination level at which only cones are active.

Figure 1. Effects of increasing light.

(A) Mean near-vision acuity (*SDs* are smaller than the symbols for means) is plotted against the level of retinal illuminance. Equivalent light levels and letter sizes are shown on the additional axes. (B) Mean near-vision contrast sensitivity (*SDs* are smaller than the symbols for means) is plotted against the level of retinal illuminance. (C) The mean values of parameter *b* derived from the fits of Equation 1 to the control participants' data are plotted against retinal illuminance (filled circles). The values of all of the individual AMD participants with eccentric PRLs are plotted as open symbols. Those with central fixation are filled symbols. The dotted and dashed lines are the best fits to the average of the AMD central and eccentric fixation subgroups, respectively. (D) Reading speeds at threshold are plotted as a function of illuminance level. The average speeds of controls are plotted as filled circles; the mean reading speeds of Participants 1 and 8 are plotted as open symbols and those of Participant 6, as filled diamonds. (E) Average reading speeds at >0.5 logMAR above threshold are plotted as a function of illuminance level; symbols are the same as in Panel D.

Note. AMD = age-related macular degeneration; PRL = preferred retinal locus; *SD* = standard deviation; td = trolands; WPM = words per minute.

To show more clearly how the gains in reading speed varied as a function of light level and letter size, we replotted the data for two letter-size ranges. At the smallest letter size near threshold (0.0 logMAR; Figure 2B), mean reading speed more than doubled (0.38 log WPM) when illuminance was increased from 1.9 to 2.8 log td. However, using brighter lighting (up to the equivalent of a 250W bulb) did not result in further increases in reading speed. In contrast, reading speeds at letter

sizes larger than 0.5 logMAR were relatively independent of light level (Figure 2C).

In Figure 1C, the mean values of parameter *b* of Equation 1 are plotted for the control participants for each light level (small circles, solid line). Parameter *B* reflects the position of the curves along the letter-size axis and can be related to reading acuity. The values of parameter *b* as a function of light level were best fitted with an exponential decay function:

$$y = a + b(-x/c), \quad (2)$$

where *a* determines the vertical position in logMAR, *b* determines the horizontal position in log td, and $-x/c$ is the exponential factor. This function is a mathematical way of describing that the gain in acuity is reduced by the exponential term for each increment in illuminance.

Participants With Nonexudative AMD

The AMD participants' demographics are presented in Table 1. Fixation locations

Figure 2. Control participants.

(A) Mean (± 1 SD) reading speeds (log WPM) are plotted as a function of letter size (logMAR) for each level of retinal illuminance (log td). Equivalent light levels and letter sizes are shown on the additional axes. The best fits of Equation 1 to the data are drawn as lines through the data points (detailed in the legend). (B) Mean reading speeds at 0.0 logMAR letter size are plotted as a function of retinal illuminance. (C) Reading speeds averaged for all sizes >0.5 logMAR are plotted as a function of retinal illuminance.

Note. SD = standard deviation; td = trolands; WPM = words per minute.

were identified using an OCT SLO Imaging System for Retinal Analysis (OPTOS; Touch Ophthalmology, Goring-on-Thames, England). Three of the 9 participants retained central fixation; 6 had eccentric fixation. All AMD participants with eccentric viewing had unifocal dense central lesions greater than 1-disk diameter. All were pseudo-phakic. The mean logMAR acuity for the eccentric-viewing group was higher (0.88 logMAR) than that for the central-viewing group (0.39 logMAR). Maximum reading speed for each participant was calculated from his or her data at 3.5 log td and 1.3 logMAR letter size.

Results for Participants With AMD

All of the AMD participants' values of parameter B are plotted as a function of light level (Figure 1C). Individual AMD

participants' data are plotted as symbols. The dotted line is the fit to the average of the centrally fixating participants (filled symbols); and the dashed line, to the eccentrically fixating participants (open symbols). Although the positions of the participants' curves were shifted to larger letter sizes (vertical shift), the relative effects of lighting were similar to those observed in the control participants' data (small dots); that is, there was the same exponentially decreasing gain with increasing illuminance.

Three patterns were observed in the AMD participants' data. Examples of each pattern are presented in Figure 3. In each panel, the control participants' data are plotted as dashed lines.

Pattern 1. For AMD Participant 1 (Figure 3A), reading speeds at the lowest

light level were below the control participants' data at the smaller letter sizes, but not at larger letter sizes. Reading speeds at the brighter light levels were within the range of the control participants' reading speeds. AMD Participant 9 also had this pattern of results. Both of these participants fixated foveally and had relatively good visual acuity ($\geq 20/30$).

Pattern 2. For AMD Participant 8 (Figure 3B), all of the curves were shifted to larger letter sizes, but the maximum reading speeds were within normal values (albeit at larger letter sizes). Participants 4 and 5 also followed this pattern of results. All of these participants fixated eccentrically and had reduced visual acuity.

Pattern 3. For AMD Participant 6 (Figure 3C), the reading speeds at asymptote were slower than the control participants'

Table 1. AMD Participants' Demographics

Participant	Sex	Age	Eye	Acuity	logMAR	Fixation	PRL Distance/Quadrant	WPM
1	F	75	OD	2/2.5	0.10	C	0°	2.1
2	F	77	OD	2/12	0.78	E	7° S	1.7
3	F	94	OS	2/16–	0.90	C	0°	2.0
4	F	92	OD	2/16+	0.90	E	10° T	1.7
5	F	78	OS	2/20	1.00	E	5.5° S	1.4
6	F	77	OD	2/16–	0.90	E	6° S	1.6
7	M	84	OD	2/20	1.00	E	6° S	1.3
8	F	74	OD	2/10	0.70	E	4° T	2.0
9	M	72	OS	2/3	0.18	C	0°	1.6

Note. AMD = age-related macular degeneration; C = central; E = eccentric; OD = oculus dexter (right eye); OS = oculus sinister (left eye); PRL = preferred retinal locus; S = superior; T = temporal; WPM = words per minute.

speeds, and her functions were shifted to larger letter sizes. At the sizes tested, we did not observe saturation of the lighting effect; however, a diminishing effect of increased lighting was still observed. Participants 2, 3, and 7 also followed this pattern of results.

Figure 3. Participants with AMD. (A) AMD Participant 1. (B) AMD Participant 8. (C) AMD Participant 6. *Note.* Reading speeds for representative AMD participants are plotted as a function of letter size for each level of retinal illuminance. Size and reading speed equivalents are shown on the axes. The best fits of Equation 1 to the data are drawn through the data points (detailed in the legend). Best fits to the control participants' data are plotted as dashed lines. AMD = age-related macular degeneration.

All but Participant 3 fixated eccentrically, and all had reduced visual acuity.

Reading speeds at each AMD participant's threshold letter size are plotted as a function of retinal illuminance in Figure 1D. The corresponding control data are plotted as filled circles. The speeds for the AMD participants with Patterns 1 (Participant 1) and 2 (Participant 8) are drawn as open symbols; the data from Pattern 3 (Participant 6), drawn as filled diamonds. All of these data show an overall shift to slower speeds. For all participants, increasing illuminance had the same decreasing gain in reading speed as found for the control participants.

The average reading speeds at letter sizes >0.5 logMAR above each participant's thresholds are plotted in Figure 1E. For the control participants (filled circles), illuminance level had little effect on reading speed at these letter sizes. The same was true for the reading speeds of AMD participants with Patterns 1 and 2 (open symbols). The data from Pattern 3 (diamonds) showed an overall shift to slower speeds, but again, there was little change with increasing illuminance.

Discussion

We found that, for the control participants, the effects of lighting on reading speed depended on letter size and on the relative change in illumination level. At threshold letter sizes, increasing illuminance from a mesopic level into the photopic range increased reading speed (Figure 2B) and reading acuity (Figure 1C). Further light level increases above $2.8 \log td$ ($>17W$ bulb) did not greatly increase reading speed and had only a small effect on reading acuity; that is, the effects of increased lighting were exponentially smaller as letter size increased. At letter sizes of >0.5 logMAR above threshold, none of the increases in light level resulted in faster reading speeds. The observed reading speed gains at smaller letter sizes when light levels were increased from mesopic to photopic are consistent with previous studies on the effects of luminance on visual acuity. In general, these studies have reported an increase in foveal acuity over a luminance range from approximately 0.03 to 32 cd/m^2 ; above this range, increasing luminance had a diminishing effect on acuities (Eldred, 1992; Eperjesi, Fowler, & Kempster, 1995; Fosse & Valberg,

2004; Haymes & Lee, 2006; Sloan, 1968) and reading (Bullimore & Bailey, 1995; Fosse & Valberg, 2004; Sloan, Habel, & Feiock, 1973; Tinker, 1954).

For some AMD participants, reading speed functions were shifted to larger letter sizes and slower reading speeds compared with control participants. Despite the absolute losses in acuity and reading speed, the relative effects of light level were similar to those observed in control participants; that is, the largest effect of increased illuminance was observed at letter sizes near the participant's threshold. At larger letter sizes there was essentially no gain with increased lighting. AMD did not alter the basic effects of lighting; it affected only the size and speed ranges over which these effects operated.

Our data and the published literature show a facilitative role of increasing lighting for threshold tasks and little or no role for suprathreshold tasks. Are these findings relevant to other, everyday tasks? There are published reports concerning the role of lighting for functional measures. Brunnström, Sörensen, Alsterstad, and Sjöstrand (2004) found that changing kitchen lighting from an average of 239 cd/m² to 658 cd/m² positively affected self-reported assessments of performance on tasks involving acuity/depth perception (e.g., slicing bread, pouring liquids). However, self-reported performance on tasks involving larger objects did not significantly improve with an increase in luminance (e.g., finding objects in a cupboard). Cornelissen, Bootsma, and Kooijman (1995) measured recognition and identification of 25 objects in a naturalistic setting. The objects were of various sizes and contrasts. For many of the participants, detection and recognition performance increased as the light level was increased from 0 to approximately 100 cd/m²; however, with further increases in light level, performance saturated. The authors concluded that performance was best predicted by a measure that evaluated the area under the contrast sensitivity function rather than by only threshold acuity or contrast sensitivity measured at a single spatial frequency.

Our small sample of participants with AMD does not provide an exhaustive survey of the patterns of changes with disease. It does, however, provide a framework for examining the interactions of disease and lighting in participants with eye disease. Although media

opacities could cause increased glare at higher light levels that might reduce acuity and reading rates at brighter light levels, all of the AMD participants were aphakic.

Our findings emphasize the importance of measuring performance at threshold and at suprathreshold levels, determining the relevant parameters of the visual task (e.g., size and contrast), and assessing the participant's typical level of illumination for the task to estimate potential gains from brighter lighting.

Implications for Occupational Therapy Practice

This study has several implications for occupational therapy practice:

- Our data do not support the broad generalization that providing a brighter light to low-vision participants will always increase performance.
- If a client is attempting to read small text (near his or her acuity threshold) in relatively dim light, one could suggest either magnification or increased lighting: Increased light would be preferred because it does not have the field restriction of most magnifiers.
- If a client is attempting to read small text under light levels equivalent to a 30W bulb or brighter, increased lighting will have less effect, and magnification should be considered.
- If a client is attempting to read large text (relative to his or her acuity), increased lighting would have little benefit, and magnification should be considered.

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