

New Definition of Legibility Index to Examine Off-Axis Viewing of Text and Graphics

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Abstract

Reading text and graphics is a common issue in lighting design and practice. Legibility of text and graphics is often measured using the Legibility Index, conventionally defined as the distance at which material can be read with perfect accuracy (the legibility distance) divided by the character height. The ratio equals to the inverse tangent of the visual angle V . This definition assumes the material to be read is perpendicular to the viewer, which is always not true. Off-axis viewing of text and graphics is common in reality, yet rarely researched.

To examine off-axis legibility, this paper has developed a new definition of the Legibility Index, defined as the inverse square root of solid angle ω subtended by the target, based on a hypothesis that the three-dimensional solid angle, rather than the two-dimensional visual angle, captures how people recognize text and graphics.

This hypothesis has been verified in light of how retinal images activate cones. When viewed, text or graphics form a retinal image that activates the underlying cones in the center fovea of viewer's eyes. Legibility is then determined by the spatial distribution of these activated cones. For linear targets, their retinal images have only one dimension. Their activated cones are linearly distributed. Thus, visual angle is sufficient to examine the legibility of linear targets. For common nonlinear targets, their retinal images usually have two significant dimensions (width and height) and activate a two-dimensional collection of cones. Solid angle should be used to examine the legibility of these real viewing targets.

Keywords: definition, equation, legibility index, off-axis viewing, text and graphics, solid angle, visual angle

1 Introduction

Reading text and graphics is common visual task in lighting research and practice. Text and graphics can be presented on a wide variety of displays: instrument panel displays, maps, billboards, warning placards, signs, computer screens, classroom projection screens, blackboards, books, magazines, etc. For all of them, their purpose is not served if the text and graphics presented are not legible to the intended viewer. To be legible, the text and graphics must be large enough to be discriminated, and with enough contrast to activate the cones in fovea of the viewer's eyes. The legibility level of text and graphics is measured in practice using the Legibility Index (LI), or the affiliated minimum visual angle that the text or graphics subtend.

Geometric, viewer, and lighting-related factors all affect the legibility level of text and graphics as well as the viewing duration. Geometric factors include viewing distance, image size (width, height, stroke width of text, or detail of graphics), and image orientation (perpendicular or off axis). Viewer related factors include age and visual acuity level of observer, color deficiencies, and so forth. Lighting-related characteristics include image luminance and color, background luminance and color, adapting luminance, and combinations of them such as luminance contrast and color contrast. When these factors have been examined in the literature, it is commonly assumed that the image is oriented perpendicular (on axis) to the viewer. However, off-axis viewing of text and graphics commonly occurs. For example, when driving, driver's line of sight to a navigation screen in the center console is not perpendicular to the display surface. When way finding, road signs, architectural signs, etc. are invariably viewed off axis. In classrooms, the viewers' lines of sight are rarely perpendicular to the blackboards and projection screens. Although off-axis viewing is common, this situation has not received much attention in the research literature.

2 Research Problem

The Legibility Index (LI) (equation 1) has been conventionally defined as the ratio of the distance at which material can be read with perfect accuracy (the legibility distance) to the character height, as illustrated in Figure 1 (United States Sign Council, 1998). The ratio equals to the inverse tangent of the two-dimensional visual angle V that text or graphics subtend. This conventional definition assumes the image being examined is perpendicular to the viewer.

$$LI = \frac{D}{H} = \frac{1}{\tan(V)} \quad (1)$$

Where:

LI = Conventional definition of the Legibility Index

D = Legibility distance

H = Normal height of the character

V = Visual angle subtended by the height of character

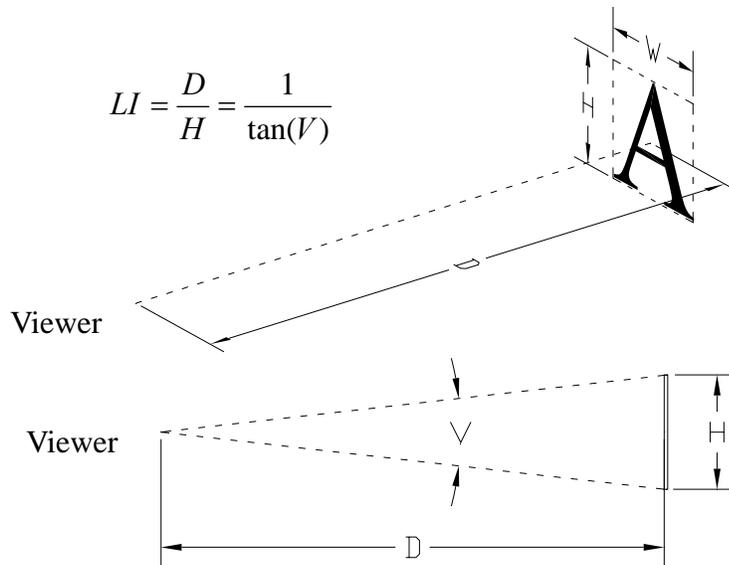


Figure 1. Conventional definition of the Legibility Index (LI)

As illustrated in Figure 2, when text or graphics are read off axis, their projected image, which is perpendicular to the visual line, rather than themselves, forms an inverted retinal image in the center fovea of the viewer's eyes. This projected image is often with decreased size compared to the normal text or graphics. Accordingly, if extending the conventional definition for off-axis situations, the projected height, rather than the normal height of text or graphics, should be used to calculate the Legibility Index.

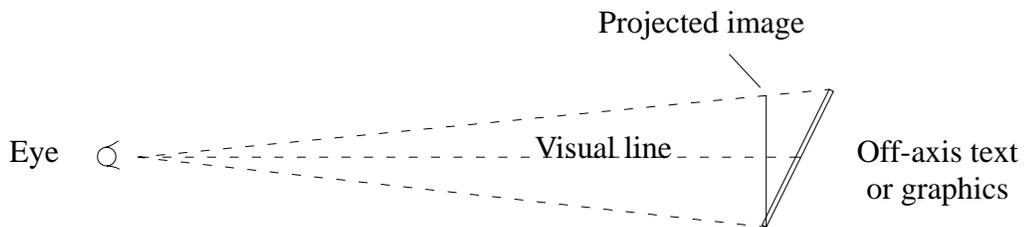


Figure 2. Projected image of off-axis text or graphics

Given this, why not replace the normal height with the projected height to redefine the Legibility Index? Unfortunately, this replacement works only for: linear targets, such as line which has no substantial width. For non-linear targets where both height and width are substantial, width cannot be ignored.

3 New Definition of Legibility Index

To examine off-axis viewing of text or graphics, a new definition of the Legibility Index is considered necessary to replace the insufficient conventional one (equation 1 previously). This new definition has been developed in this paper, defined as the inverse square root of solid angle ω subtended by the viewing target (equation 2), based on the hypothesis below.

Hypothesis. The three-dimensional solid angle ω subtended by text and graphics, rather than the two-dimensional visual angle V subtended by text and graphics, captures how people recognize text and graphics.

$$LI' = \sqrt{\frac{1}{\omega}} \quad (2)$$

Where:

LI' = New definition of Legibility Index for both on- and off-axis viewing
 ω = Solid angle subtended by any text and graphics to the retina

The proposed definition of the Legibility Index in equation 2 is the essential form to examine off-axis viewing of text or graphics, which can be further developed by substituting the definition of the solid angle ω . The solid angle is defined as equation 3 (Rea, 2000, IESNA handbook), and illustrated in Figure 3.

$$\omega = \frac{A}{D^2} \cos \xi = \frac{W \cdot H}{D^2} \cos \xi \quad (3)$$

Where:

ω = Solid angle subtended by character to the retina
 ξ = Incident angle
 A = Normal character area,
 $A = W \cdot H$, for characters using width and height to define area
 D = Viewing distance
 W = Character width
 H = Character height

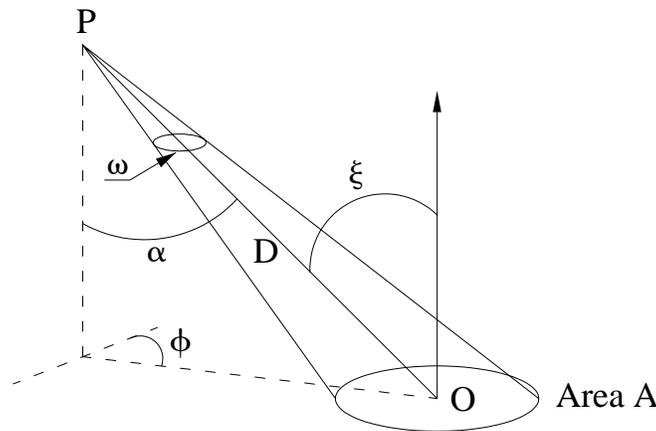


Figure 3. Definition of solid angle ω (Based on Figure 9-1, IESNA handbook)

Based on the geometrical relationship shown in Figure 4, the incident angle ξ can be further substituted by the horizontal off-axis viewing angles ϕ and the vertical off-axis viewing angle α , as equation 4.

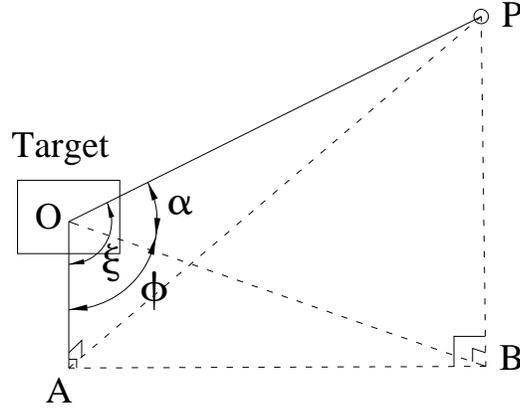


Figure 4. Off-axis viewing of target and the incident angle ξ
 Incident angle $\xi = \angle AOP$;
 Horizontal viewing angle $\phi = \angle AOB$;
 Vertical viewing angle $\alpha = \angle BOP$;
 $\cos \angle AOP = OA/OP$; $\cos \angle AOB = OA/OB$; $\cos \angle BOP = OB/OP$

$$\cos \xi = \cos \phi \cos \alpha \quad (4)$$

Where:

ξ = Incident angle

ϕ = Horizontal off-axis viewing angle

α = Vertical off-axis viewing angle

Substitute equation 3 and 4 into equation 2, get equation 5, which is the developed definition of the Legibility Index for both on- and off-axis viewing, primarily off-axis viewing, of text or graphics.

$$LI' = \frac{D}{\sqrt{A \cdot \cos \phi \cos \alpha}} = \frac{D \cdot \sqrt{r}}{H} (\cos \phi)^{-0.5} (\cos \alpha)^{-0.5} \quad (5)$$

Where:

LI' = New definition of Legibility Index for both on- and off-axis viewing

D = Legibility distance

A = Normal character area,

$A = W \cdot H$, for characters using width and height to define area

H = Character height

W = Character width

r = Height-to-width ratio of character, $r = H/W$

ϕ = Horizontal off-axis viewing angle

α = Vertical off-axis viewing angle

Based on equation 5, when $\phi = 0$, $\alpha = 0$, the Legibility Index for on-axis viewing is calculated using equation 6 below.

$$LI'_{on-axis} = \frac{D}{\sqrt{A}} = \frac{D}{H} \cdot \sqrt{r} \quad (6)$$

Where:

$LI'_{on-axis}$ = New definition of Legibility Index for on-axis viewing only

D = Legibility distance

A = Normal character area,

$A = W \cdot H$, for characters using width and height to define area

H = Character height

W = Character width

r = Height-to-width ratio of character, $r = H/W$

Comparing equation 6 and 1, apparently the conventional definition (equation 1 previously) of the Legibility Index assumes the height-to-width ratio of any text or graphics viewed equals to 1, which is always not true in reality.

4 Verification of the Hypothesis

Using the solid angle ω subtended by the viewing target to replace the visual angle V to redefine the Legibility Index has the physiological foundation, in light of how retinal image activate cones. When viewed, text or graphics form a retinal image in center fovea of viewer's eyes. The retinal image then activates the underlying cones to fire signals to the cortex nerves in brain. These foveal cones are very tightly packed and form a two-dimensional triangular array, without any strong orientation dependencies, as illustrated in Figure 5 (Wandell, 1995). The dense representation of the foveal cones suggests that the spatial mosaic of the cones must be important to the visual encoding (recognition) of text and graphics (Wolken, 1966; Hende, 1993; Wandell, 1995; Boff, et al, 1986).

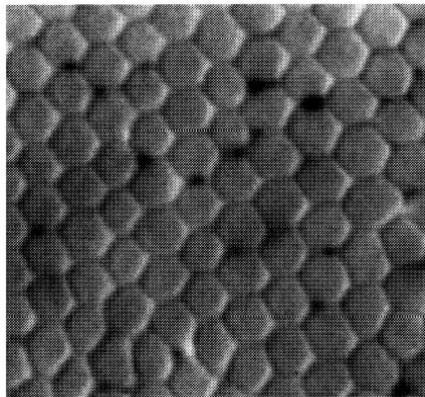


Figure 5. Spatial mosaic of cones in the fovea (Figure 3.4, Wandell, 1995)

Legibility of text or graphics viewed on or off axis is eventually determined by the number and spatial distribution of the activated cones in center fovea. Viewer's eyesight, light levels of target and its environment, contrasts and geometries of the characters jointly determine the number of activated cones and the intensity of the signals fired, which, in turn, determine the brightness of the retinal image. Whereas, different text or graphics being viewed are discriminated by the different spatial distribution of their activated cones in center fovea.

The conventional definition of the Legibility Index has been developed based on the two-dimensional visual angle V , as shown in equation 1 previously. According to this definition, only one dimension (usually height) of the text or graphics viewed is used to calculate their legibility level, while the other dimension is irrelevant. The reasonable explanation to this assumption is that the activated cones must be linearly distributed in the center fovea of the viewer's eyes. In reality, this is true only for line or other linear targets, which has no width, as illustrated in Figure 6. Thus, the conventional definition of the Legibility Index is applicable only for linear targets, where visual angle V is sufficient to examine their legibility.

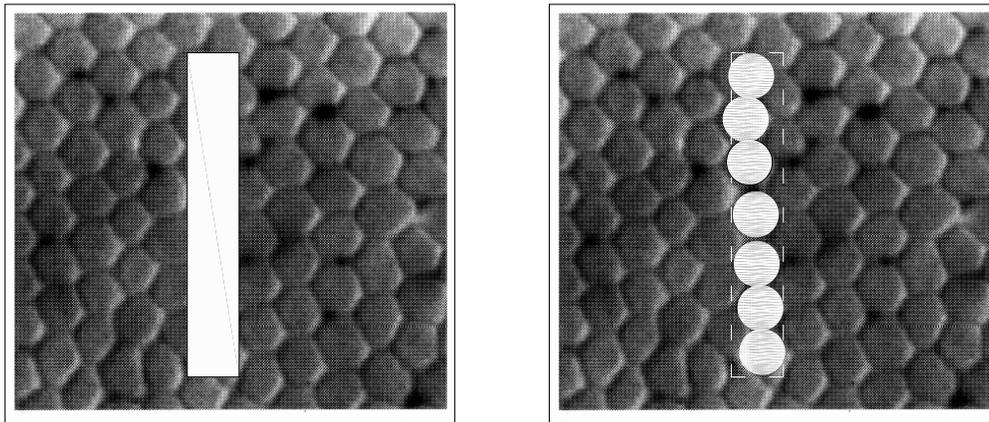
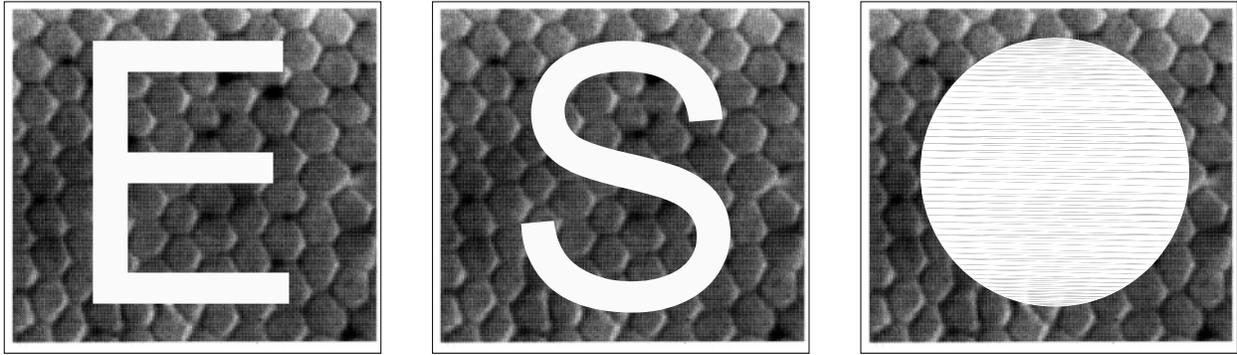


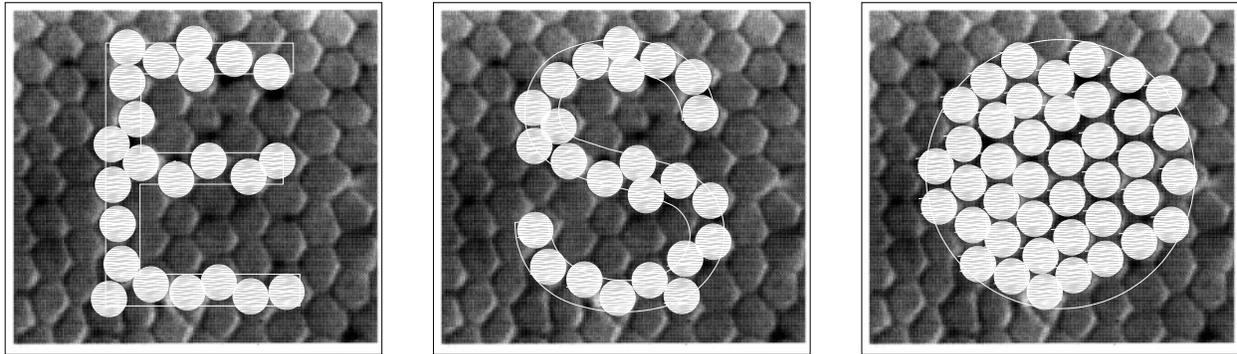
Figure 6. Linearly distributed cones activated to recognize a tiny bar (based on Figure 3.4 from Wandell, 1995)

However, linear viewing target is uncommon. For wide variety of nonlinear targets in reality, their retinal images usually have two significant dimensions (both width and height) and activate a two-dimensional collection of cones. Such an area of activated cones is supported by the two-dimensionally oriented and distributed limbs or strokes of text, or details of graphics of the retinal images, as illustrated in Figure 7.

For nonlinear targets, the two-dimensional visual angle V , which examine only one dimension of text or graphics (usually height), is insufficient to examine the two-dimensional collection of activated cones. Instead, the three-dimensional solid angle ω should be used to replace it for this purpose. This is the physiological foundation of the new definition of the Legibility Index developed in this paper (equation 2 or 5 previously).



(a) Retinal images of letter E, S and a disc



(b) Two-dimensional distribution of the activated cones

Figure 7. Retinal images of text (E, S) and a disc in the fovea with underlying activated cones (based on Figure 3.4 from Wandell, 1995)

5 Application of the New Definition to Examine Off-Axis Legibility

The new definition of the Legibility Index (equation 2 or 5 previously) can be used to calculate the legibility levels (measured using the Legibility Index) of text or graphics viewed off axis. For targets using width and height to define their area, the height H and width W are conveniently used to calculate the Legibility Index using equation 5. For other viewing targets without clear width and height to define area, like disc, the general area A is used to calculate the Legibility Index.

When the legibility levels of text or graphics (measured using the Legibility Index) are already known or assigned in a scenario, this new definition can also be used to predict the size and orientation of text or graphics that will be legible when viewed off axis across the scene, using equation 7 or 8, which are re-expressed from equation 5. Likewise, equation 8 is used for alternative viewing targets without clear width or height to define area, such as disc, etc.

$$H = \frac{D \cdot \sqrt{r}}{LI'} (\cos \phi)^{-0.5} (\cos \alpha)^{-0.5} \quad (7)$$

$$A = \frac{D^2}{(LI')^2 \cdot \cos \phi \cos \alpha} \quad (8)$$

Where:

LI' = New definition of Legibility Index for both on- and off-axis viewing

D = Legibility distance

H = Character height

W = Character width

A = Normal character area,

$A = W \cdot H$, for characters using width and height to define area

r = Height-to-width ratio of character, $r = H/W$

ϕ = Horizontal off-axis viewing angle

α = Vertical off-axis viewing angle

6 Conclusion

Capturing how people recognize text and graphics, a new definition of the Legibility Index based on the three-dimensional solid angle ω has been developed in this research, as $LI' = \sqrt{\frac{1}{\omega}}$.

This new definition is capable to interpret and measure the legibility levels of any viewing targets viewed either on or off axis more accurately.

After substituting the definition of solid angle ω , this new definition can be further expressed

as: $LI' = \frac{D}{\sqrt{A \cdot \cos \phi \cos \alpha}} = \frac{D \cdot \sqrt{r}}{H} (\cos \phi)^{-0.5} (\cos \alpha)^{-0.5}$. With both horizontal and vertical

off-axis viewing angles (ϕ , α) examined, this equation has offered researchers a new measure to calculate the Legibility Index of off-axis text or graphics, or to predict their geometries and orientations when legibility levels (measured using Legibility Index) are assigned, using

$$H = \frac{D \cdot \sqrt{r}}{LI'} (\cos \phi)^{-0.5} (\cos \alpha)^{-0.5}, \text{ or } A = \frac{D^2}{(LI')^2 \cdot \cos \phi \cos \alpha}.$$

This new definition can examine text and graphics viewed on axis, by setting the incident

angle to zero: $LI'_{on-axis} = \frac{D}{\sqrt{A}} = \frac{D}{H} \cdot \sqrt{r}$.

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