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# Computational Assessment of Text Legibility in Lecture Halls

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## Key Words

Computer program · Lecture halls · Ideal viewing area · Text · Legibility

## Abstract

Text presented in lecture halls often simultaneously appears on multiple visual displays (e.g., blackboards, projection screens, video monitors), which should be legible to the entire audience seated in an ideal viewing area. Existing guidelines identify this area as fan-shaped, but the origin of those guidelines and the data on which they are based are not specified. To supplement the guidelines, this paper describes the development of a computer program (available online) to compute locations in which all displays are legible to the audience, which considers the height, width, location and orientation of each display, text geometries (height, height-to-stroke width ratio) and its lighting conditions (background luminance, luminance contrast percent), as well as the observer's visual acuity. This program was validated in a small experiment involving

21 subjects looking at text in a lecture hall, and further examined for two other test cases.

## Introduction

Instructional spaces to date include, in the order of the capacity of seats, seminar rooms ( $\leq 19$ ), small standard classrooms (20–49), large classrooms (50–100), small lecture halls (75–149), large lecture halls (150–299) and lecture theatres ( $\geq 300$ ) [1–6]. Small and large lecture halls and theatres (here collectively referred to as lecture halls) became relatively more common in the 1960s as teaching venues due to the large increase in enrolments and the shortage of faculty and facilities [1]. Lecture halls have five characteristics that distinguish them from smaller instructional spaces [1–6]:

1. large capacity ( $\geq 75$  seats);
2. teaching activities, which are not tied to a specific subject or discipline;

3. large scale use of visual displays, including blackboards, whiteboards, marker boards, projection screens, video monitors, etc., in the front of the room;
4. fixed and compact (minimum 1.1 m<sup>2</sup> (12 ft<sup>2</sup>) per seat required by the code) seating arrangement in the audience area;
5. Fan-shaped, with sloped or tiered floor. Small lecture halls may be rectangular and use a flat floor when their capacity is less than 100 seats.

A carefully designed lecture hall will provide good viewing and acoustic conditions for visual and auditory materials, encourage presenter–audience interaction and retain interior environmental quality, all at minimum cost [4,6]. Among these requirements, good viewing conditions are primary, since most of the information audience receives is visual. Then, how can favourable viewing conditions in lecture halls be achieved? Theoretically, good viewing conditions occur when: (1) view of the materials to be read is unobstructed, (2) glare does not interfere with viewing and (3) the contrast ratio, scene luminance and character size combinations lead to text that is easy to read for the entire audience. In lecture hall design, the audience is always assumed to have average good vision (with or without correction). The size and contrast of the viewing materials presented in lecture halls are also assumed to be within a reasonable range, and out of control of architects, though the size is often not adequate. What architects can do is to provide sufficient lighting to assure visual displays can be read and limit seating placement to where that will occur. Lighting could be easily improved after a lecture

hall has been built up, but an ideal viewing area for seating arrangement is subject to the size and shape of the lecture hall, which is determined at the very beginning of lecture hall design.

To estimate where text displayed in lecture halls can be seen, guidelines have been available in the literature since the 1960s. Hauf et al. [1,7] conducted a research project on new spaces for learning and illustrated the ideal viewing areas in lecture halls for seat arrangement. Aschoff (1966) carried out a research in the Association for Research of North Rhine-Westphalia, Germany, on planning large lecture halls and summarised the ideal plans and section profiles in a paper, which was translated and collected in literature [2]. Allen et al. [4,5] developed a manual for reducing the impact of technology on classroom and lecture hall design, and addressed the optimal view of projection screens and video displays. Conway [8] suggested the ideal viewing distances of projection screens when she outlined the emerging technologies in master classrooms. McGowan and Kruse [9] illustrated the optimal cone view of projection screens and video monitors used in lecture halls in their interior graphic standards. There is also an online calculator [10] well prepared for computing the throw distance of projection projectors and the recommended seating distances from the screen, data available for most existing projector models. Unfortunately, no experimental evidence was cited as a basis for these recommendations.

Table 1 summarises these guidelines for defining an optimal cone area in lecture halls for locating seats with

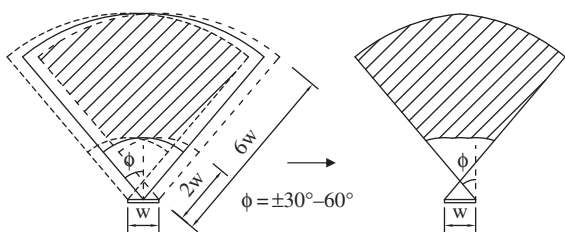
**Table 1.** Fan-shaped ideal viewing area defined using the existing guidelines

Display types	Sources	Fan-shaped ideal viewing area ( $d$ is the viewing distance, $\phi$ horizontal viewing angle and $w$ display width)	Recommendation basis
Projection screens	Aschoff [2]	$2w \leq d \leq 6w$ , $\phi = \pm 30^\circ$ , with maximum elevation angle of $35^\circ$ , and depression angle of $12^\circ$	DIN108
	Hauf et al. [1,7]	$2w \leq d \leq 6 - 10w$ , $\phi = \pm 30^\circ - 60^\circ$ , with maximum elevation angle of $15^\circ$	No experimental evidence
	Conway [8]	$1.5 - 2w \leq d \leq 6w$	None given
	McGowan and Kruse [9]	$1.5w \leq d \leq 4 - 5w$ , $\phi = \pm 45^\circ$	None given
Video monitors	Online projection calculator [10]	$1.3w \leq d \leq 4.5 - 6w$	Manufacturer supplied data
	Hauf et al. [1]	$4w \leq d \leq 12w$ ( $14w$ for less optimum condition), $\phi = \pm 35^\circ - 40^\circ$ ( $\pm 45^\circ$ for less optimum condition), with the maximum elevation angle of $15^\circ$ to the bottom of image ( $30^\circ$ for less optimum condition)	No experimental evidence
	Allen et al. [4]	$1.5w$ (optimum $2w$ ) $\leq d \leq 6w$ (or $4w$ for electronic projection), $d_{\max} \leq 0.12 \text{ m cm}^{-1}$ ( $1 \text{ ft in.}^{-1}$ ) of TV diagonal size; a maximum elevation angle of $35^\circ$	None given
	McGowan and Kruse [9]	$2 - 2.5w \leq d \leq 6 - 7w$ , $\phi = \pm 45^\circ$	None given

legible view of images presented on projection screens and video monitors. The horizontal fan-shaped areas were defined using a viewing angle  $\phi$ , which is the angle between the display normal and the edge of the optimal view cone, and an optimum viewing distance  $d$ , which is in proportion to the display size (usually the width is used) [1,2,4,7–10]. In Table 1, note that the size of characters is not used by the guidelines for prediction, neither lighting, nor viewers' acuity, which are essential for legibility. In addition, the guidelines cannot predict an oblique two-dimensional (2D) viewing area, such as one parallel to the sloped floor, which is of great interest to architects, and do not include conventional displays such as blackboards or whiteboards. Careful review of Table 1 shows that often the recommendation is that viewers should be no more than six screen widths away from it and no closer than two, but the source of that recommendation is not given.

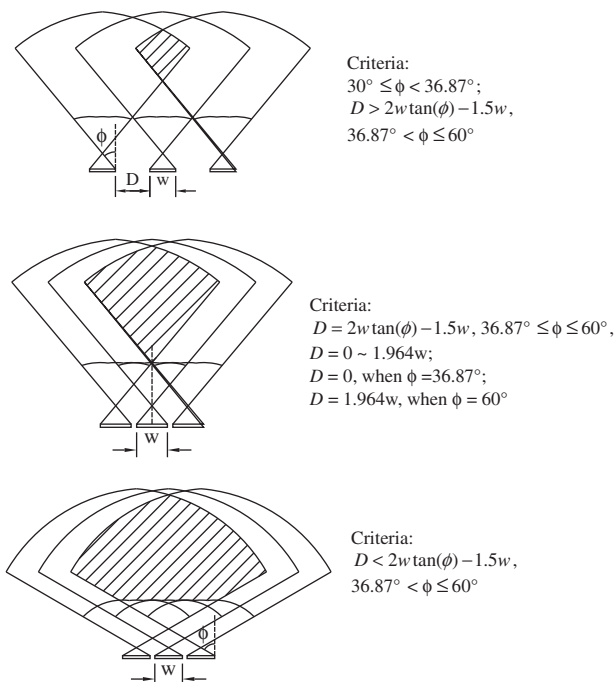
Combining the recommendations listed in Table 1, an ideal view area of projection screens or video monitors can be illustrated in figures with regard to the following five cases:

1. A single matte projection screen. The ideal viewing area is overlapped at three critical points: middle point, left edge and right edge, as illustrated in the shaded area in Figure 1.
2. Three coplanar equally spaced matte screens mounted in the front of the hall. The shape and size of their overlapped ideal viewing area vary with the viewing angle  $\phi$  and the spacing  $D$ , as illustrated in Figure 2.
3. Three non-coplanar equally spaced matte screens mounted in the front of the hall. Likewise, the overlapped ideal viewing area depends on the viewing angle  $\phi$ , the spacing  $D$  and the rotating angle  $\theta$  of side screens, as illustrated in Figure 3.
4. A single video monitor. Due to greater brightness of the specular surface, the ideal viewing area has larger dimensions (optimum  $4w - 12w$  or less optimum  $4w - 14w$ ), but smaller horizontal viewing angles (optimum  $\pm 35^\circ - 40^\circ$  or less optimum  $\pm 45^\circ$ ), as illustrated in Figure 4: (a) Optimum horizontal

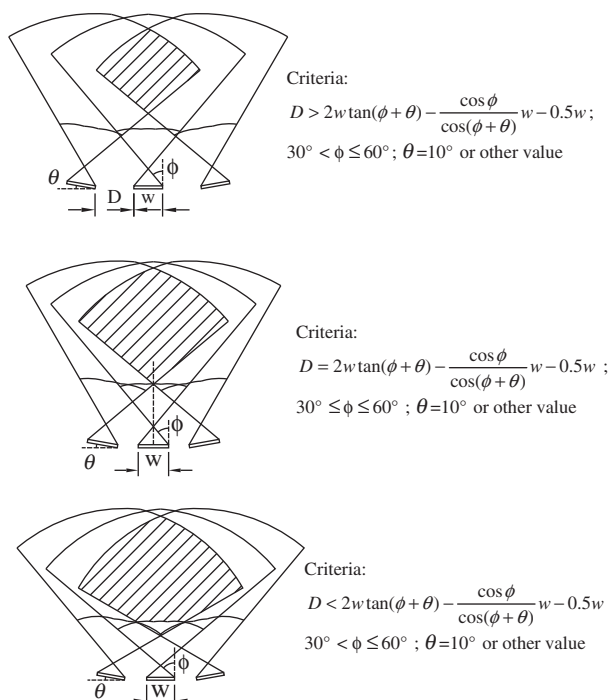


**Fig. 1.** Overlapped horizontal ideal viewing area (shaded) of a single projection screen (Hauf et al. [1], the fold-out diagram, after pp. 11–14).

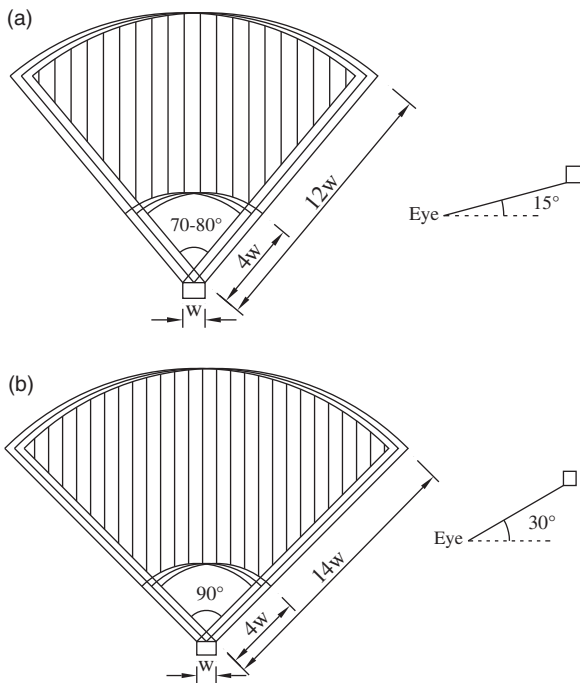
viewing area of video monitor with viewing distance  $4w - 12w$ , horizontal viewing angle  $\pm 35^\circ - 40^\circ$  and maximum elevation angle  $15^\circ$  to the bottom of image; (b) less optimum horizontal viewing area of



**Fig. 2.** Overlapped horizontal ideal viewing area (shaded) of three coplanar equally spaced matte screens (Hauf et al. [1], the fold-out diagram, after pp. 11–14).



**Fig. 3.** Overlapped horizontal ideal viewing area (shaded) of three non-coplanar equally spaced matte screens (Hauf et al. [1], the fold-out diagram, after pp. 11–14).



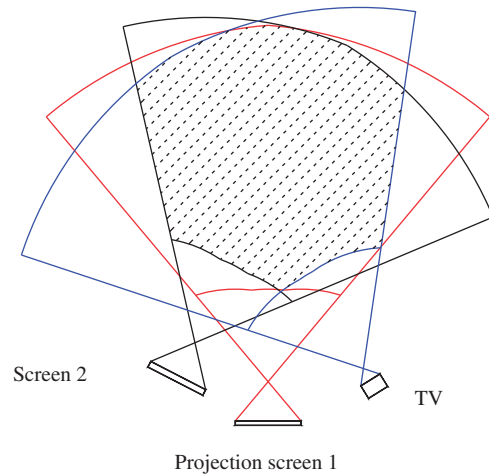
**Fig. 4.** Ideal viewing area of video monitors with different mounting heights: (a) optimum and (b) less optimum (Hauf et al. [1], no Figure number, pp. 11–19, 11–20).

video monitor with maximum distance increased to  $14w$ , horizontal angle to  $\pm 45^\circ$  and maximum elevation angle to  $30^\circ$ .

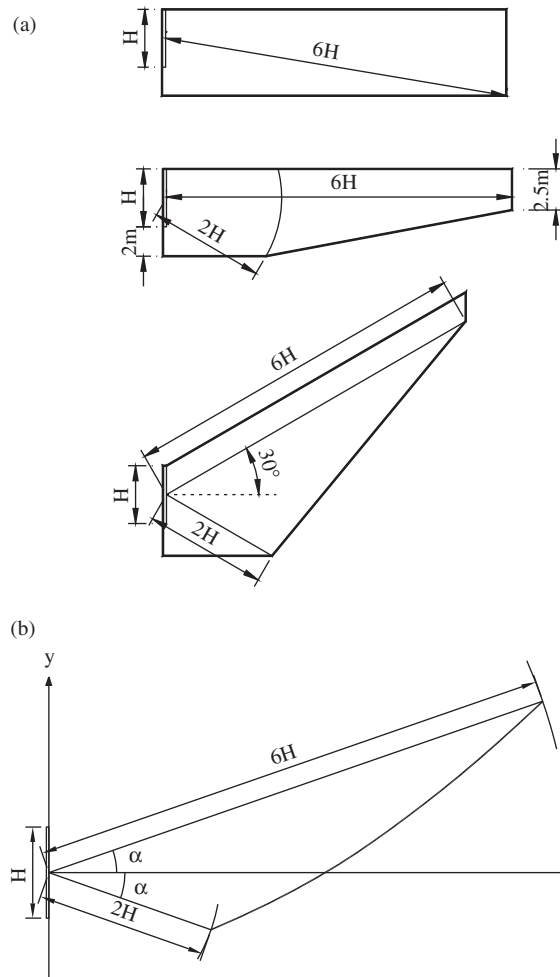
- Multiple displays (projection screens and video monitors), randomly mounted in the front of the room. Their overlapped ideal viewing area is illustrated in Figure 5.

In addition to the horizontal plane, lecture halls have an ideal longitudinal section profile for best viewing as well. As illustrated in Figure 6(a), the recommended viewing distance is two to six times the height of displays, with a maximum vertical viewing angle  $30^\circ$  to the centre line of screen [2]. For a clear viewing of the projection screen without obstruction by previous seats, the floor of lecture halls with a capacity greater than 100 should be stepped or sloped to some degree [1,11]. Aschoff [2] also quantified the ascending profile of lecture halls, as shown in Figure 6(b).

On the other hand, the upgraded information technologies have been largely applied in recent decades [6]. In modern lecture halls, multiple types of visual displays (e.g., blackboards, whiteboards, projection screens, video monitors) with different sizes are commonly used in the front space at different locations with different mounting heights and orientations. Materials are simultaneously presented on these displays and observed by the entire



**Fig. 5.** Overlapped ideal viewing area (shaded) of multiple projection screens and video monitors randomly installed in the front space of a lecture hall (for demonstration purpose, not to scale, no unit).



**Fig. 6.** Ideal longitudinal section profiles of lecture halls defined using: (a) viewing distance and viewing angle and (b)  $x$ - $y$  curve for ascending profile (Aschoff [2], Figures 4 and 9, pp. 18, 20).

audience. Lighting is also frequently dimmed to multiple levels for different presentation modes. To handle these complicated viewing situations, the existing guidelines need a review in light of legibility of text viewed across lecture halls. To evaluate the efficiency of the floor plan of lecture halls for ideal viewing, an index  $\eta$  could be used, which is the ratio of usable area (the area within the ideal viewing limitations) to total area ( $\eta = \text{usable area}/\text{total area}$ ); the larger, the better [2].

In contrast to what these guidelines suggest, the legibility of text has been studied extensively. In fact, since 1898, human factors researchers have published almost 100 equations that predict the legibility of Roman characters based on experimental evidence [12]. Some legibility equations could be used for calculating optimum viewing distances at which materials presented in lecture halls are legible to a viewer. In prior research [12], authors of this paper developed an equation that determines if text will be legible as a function of its size, contrast, background luminance, viewing angle visual acuity of observers, etc. Therefore, this paper describes the development of a computer program, which uses that equation, to determine the ideal viewing areas for single letters of text presented on all types of displays inside lecture halls, including projection screens, video monitors and blackboards/whiteboards. The legibility of entire words and sentences, and graphics are not covered, but are anticipated to be examined in the near future. The program was validated in a field experiment and then further examined for two test cases in which the legibility estimated by the computer program was compared with existing architectural guidelines.

## Research Problems

Thus, existing guidelines do not consider the size of characters, their contrast and luminance, visual acuity of observers and conventional displays such as chalkboards in their predictions. In addition, in lecture hall design, seating arrangement is often compromised by practical considerations, such as acoustics, space efficiency and cost, which may also cause the farthest or most off-axis seats located outside the fan-shaped ideal viewing areas [9], something the existing guidelines do not consider.

What shape, if not exactly a fan, must the ideal viewing area of a display or multiple displays take? The answer lies in the spatial legibility of text viewed across lecture halls. The spatial legibility means the 3D distribution of the legibility levels of characters viewed in a space, or their 2D

distribution along an interested viewing plane. In lecture halls, materials are viewed at incident angles possibly from  $0^\circ$  to  $90^\circ$ . Such off-axis characters are not as legible as those viewed perpendicularly. The larger the incident angle, the more difficult it is to recognise the seemingly distorted characters. To maintain the legibility level, either the size or contrast, or both, of the characters needs to be increased. Alternatively, the observer could approach the materials to decrease the viewing distance. The larger the viewing angle, the shorter the viewing distance. At  $90^\circ$ , the viewing distance would have to be zero. In lecture halls, text is commonly viewed by observers randomly sitting in a 3D space. Correspondingly, there is a 3D ideal viewing sphere of text. Although the 3D sphere gives architects a good feeling about its size and shape, architects tend to prefer a 2D area along an interested viewing plane where audience is located, such as the horizontal plane (for an ideal plan shape of lecture halls), the vertical plane (for an ideal section profile), or, most of the time, a plane parallel to the sloped floor at eye height level (for an ideal seating area). Geometrically, a 2D ideal viewing area can be obtained by slicing the 3D ideal viewing sphere with the interested 2D viewing plane. The task for defining an ideal viewing area of text presented on multiple types of displays viewed by observers with different acuity levels sitting along an oblique 2D plane under uneven lighting conditions, apparently, goes beyond the existing guidelines.

## Solutions

This study adopts Equation (1), a legibility equation developed in Cai [12], to predict the ideal viewing areas in lecture halls of multiple displays under uniform fluorescent lighting conditions without glare. Though uniform, glare-free lighting may be a very optimistic situation, it is a useful starting point for design. Geometrically, Equation (1) defines 3D legibility threshold contours whose surface is sphere-like. Note that Equation (1) does not examine incident angles  $82.8^\circ < \xi \leq 90^\circ$ , as letters are extremely distorted at those angles and the recognition mechanisms at those extremes are likely to be different than for normal viewing. To make this research useful to architects, Equation (1) is rewritten as Equation (2), to compute a complete 3D ideal viewing sphere of text. Keep in mind that in Cai's work, Equation (1) was mathematically derived from Howett's equation [12] based on a constant-solid-angle hypothesis, which was validated in experiments using rotated Snellen Es as prototype viewing targets.

Although Howett's equation, thus Equation (1), can predict legibility of letters A–Z, it is presumed that the ideal viewing area of real letters could be a little larger or smaller than those estimated by Equation (2), due to the difference in legibility between Snellen Es and letters A–Z. Thus, the authors believe the shape predicts the legibility of real text, but the exact area is not specified.

$x_0, y_0, z_0 = x, y$  or  $z$  coordinate of original point  $O'$   
 $D'_0$  = modified legibility distance of text viewed at zero incident angle  $\xi = 0^\circ$   
 $H$  = normal text height  
 $Sw$  = stroke width of text  
 $S_d$  = denominator in the Snellen ratio of observer's acuity level

$$D = \begin{cases} 2443.5H\left(\frac{H}{Sw}\right)^{-1}S_d^{-1}L_b^{0.213}C_{\%}^{0.532}(\cos\xi)^{0.5} & 0^\circ \leq \xi \leq 65.7^\circ \\ 2443.5H\left(\frac{H}{Sw}\right)^{-1}S_d^{-1}L_b^{0.213}C_{\%}^{0.532}(\cos\xi)^{0.5}(0.024\xi - 0.577)^{-1} & 65.7^\circ < \xi \leq 82.8^\circ \end{cases} \quad (1)$$

$$D = \begin{cases} 2443.5H\left(\frac{H}{Sw}\right)^{-1}S_d^{-1}L_b^{0.213}C_{\%}^{0.532}(\cos\xi)^{0.5} & 0^\circ \leq \xi \leq 65.7^\circ \\ 2443.5H\left(\frac{H}{Sw}\right)^{-1}S_d^{-1}L_b^{0.213}C_{\%}^{0.532}(\cos\xi)^{0.5}(0.024\xi - 0.577)^{-1} & 65.7^\circ < \xi \leq 82.8^\circ \\ 0 & 82.8^\circ < \xi \leq 90^\circ \end{cases} \quad (2)$$

where

$D$  = legibility distance when text is viewed at any incident angle  $0^\circ \leq \xi \leq 90^\circ$   
 $H$  = normal text height  
 $Sw$  = stroke width of text  
 $S_d$  = denominator in the Snellen ratio of observer's acuity level  
 $L_b$  = background luminance  
 $C_{\%}$  = luminance contrast percent  
 $\xi$  = incident angle between the display normal and the sightline of the observer,  $0^\circ \leq \xi \leq 90^\circ$ .

Using Equation (2), many consecutive viewing spots, from which text is viewed at a threshold legibility level – just readable with 100% accuracy – can be located on  $x$ – $y$ – $z$  coordinates to confine the 3D ideal viewing sphere. To compute the 3D ideal viewing sphere of text in MatLab, Equation (2) is re-expressed on  $x$ – $y$ – $z$  coordinates as Equation (3), where text is presented at an original point  $O'$  ( $x_0, y_0, z_0$ ) with initial orientation ( $\Delta\phi, \Delta\alpha$ ), and recognised by an observer at viewing spot  $P$  ( $x, y, z$ ) with orientation ( $\phi, \alpha$ ) to  $O'$ .

$L_b$  = background luminance  
 $C_{\%}$  = luminance contrast percent  
 $\xi$  = incident angle between the display normal and the sightline of the observer,  $0^\circ \leq \xi \leq 90^\circ$ ,  $\cos\xi = \cos\phi\cos\alpha$   
 $\phi$  = horizontal viewing angle,  $-90^\circ \leq \phi \leq 90^\circ$   
 $\alpha$  = vertical viewing angle,  $-90^\circ \leq \alpha \leq 90^\circ$   
 $\Delta\phi$  = initial horizontally rotated angle of the visual displays, positive for clockwise  
 $\Delta\alpha$  = initial vertically tilted angle of the visual displays, positive for clockwise.

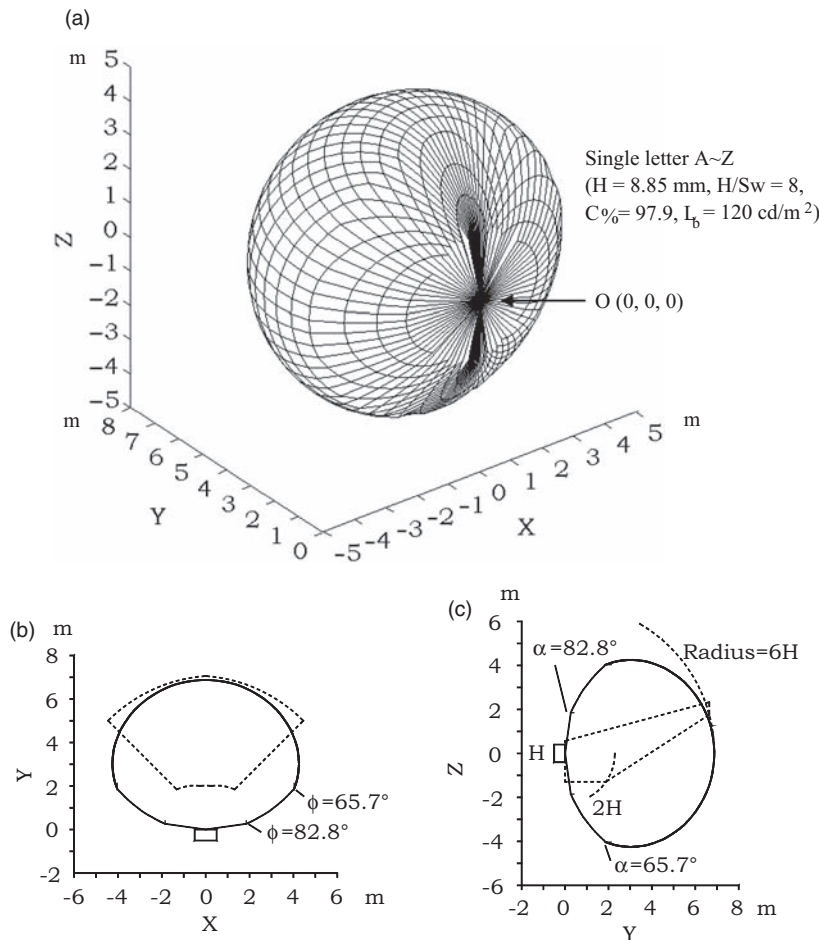
What does the 3D ideal viewing sphere look like? As an example, Figure 7(a) shows the 3D ideal viewing sphere from MatLab for a single letter (A–Z) illustrated on a video monitor (width = 1 m, height = 0.8 m) centred at  $O$  ( $0, 0, 0$ ) with normal orientation ( $\Delta\phi = 0, \Delta\alpha = 0$ ) and recognised by a young observer with 20/20 acuity. Of interest to architects, its plan ( $x$ – $y$  coordinates) and section views ( $y$ – $z$  coordinates) are also plotted as the solid contours in Figure 7(b) and (c), by assuming  $\alpha = 0$  and  $\phi = 0$ , respectively, in Equation (3). For comparison, the fan-shaped ideal plan ( $d = 2$ – $7$  m,  $\phi = 45^\circ$ ) and ideal

$$\begin{cases} x = x_0 + D'_0 \cdot (\cos\phi)^{0.5} \cdot (\cos\alpha)^{1.5} \cdot \sin(\phi + \Delta\phi) \\ y = y_0 + D'_0 \cdot (\cos\phi)^{0.5} \cdot (\cos\alpha)^{0.5} \cdot (\cos\alpha \cos(\phi + \Delta\phi) \cos(\Delta\alpha) - \sin\alpha \sin(\Delta\alpha)) \\ z = z_0 + D'_0 \cdot (\cos\phi)^{0.5} \cdot (\cos\alpha)^{0.5} \cdot (\cos\alpha \cos(\phi + \Delta\phi) \sin(\Delta\alpha) + \sin\alpha \cos(\Delta\alpha)) \\ D'_0 = 2443.5 \times H \cdot \left(\frac{H}{Sw}\right)^{-1} \cdot S_d^{-1} \cdot L_b^{0.213} \cdot C_{\%}^{0.532} & 0^\circ \leq \xi \leq 65.7^\circ \\ D'_0 = 2443.5 \times H \cdot \left(\frac{H}{Sw}\right)^{-1} \cdot S_d^{-1} \cdot L_b^{0.213} \cdot C_{\%}^{0.532} \cdot (0.024\xi - 0.577)^{-1} & 65.7^\circ < \xi \leq 82.8^\circ \\ D'_0 = 0 & 82.8^\circ < \xi \leq 90^\circ \end{cases} \quad (3)$$

where

$x, y, z$  = legibility distance of text projected on  $x, y$  or  $z$  coordinate

sectional profile ( $d = 2$ – $6$  m) for viewing the video monitor, by following the guidelines of McGowan and Kruse [9], are also shown in Figure 7(b) and (c) in dash line.



**Fig. 7.** The 3D ideal viewing sphere of a single letter illustrated on a video monitor: (a) 3D view, (b) plan view ( $\alpha=0$ ) and (c) section view ( $\phi=0$ ). For comparison, areas in dash line are the optimal cone view of the video monitor defined using the existing guidelines.

As shown in Figure 7(b) and (c), the letter may be illegible to observers sit at the off-axis back seats, while the front space good for close-up view of the monitor is not used by the guidelines.

Figure 7 illustrates only a simple case. In lecture halls, however, text is actually presented anywhere with random orientations. The interested viewing plane is often oblique. Observers may also have different acuity levels. For such complicated cases, a computer program developed based on (3) is needed for defining a 2D ideal viewing area by slicing the 3D ideal viewing space of text with the interested plane.

### A Computer-Program-Aided Design Method

The computer program was developed in MatLab [12], which is also available online <http://www.umich.edu/~driving/publications/publications.html>. This program calculates an overlapped 2D ideal viewing area of text

presented on multiple types of visual displays with different sizes, locations, mounting heights and orientations, under different lighting conditions, and viewed by observers located along any viewing plane. This program assumes: (1) text is viewed by an identical observer each time to compute a 2D ideal viewing area; (2) text presented on the minimum calculating unit area of each display is identical in geometries, typefaces and under uniform lighting conditions; and (3) visual displays are rectangular without depth. Though this program can handle different acuity levels of observers, typically 20/20 far acuity (with or without correction) is assumed for a young population, but good design should assume reasonable worst cases, such as 20/30 or 20/40. If necessary, please refer to Weale [13] for the age-related variation of visual acuity for calculation purposes. Further, keep in mind the predictions specify what the viewer can just see with 100% accuracy, their legibility threshold, not what they can see easily. In practice, even on the same visual display, text may be of different sizes and the lighting may be uneven.

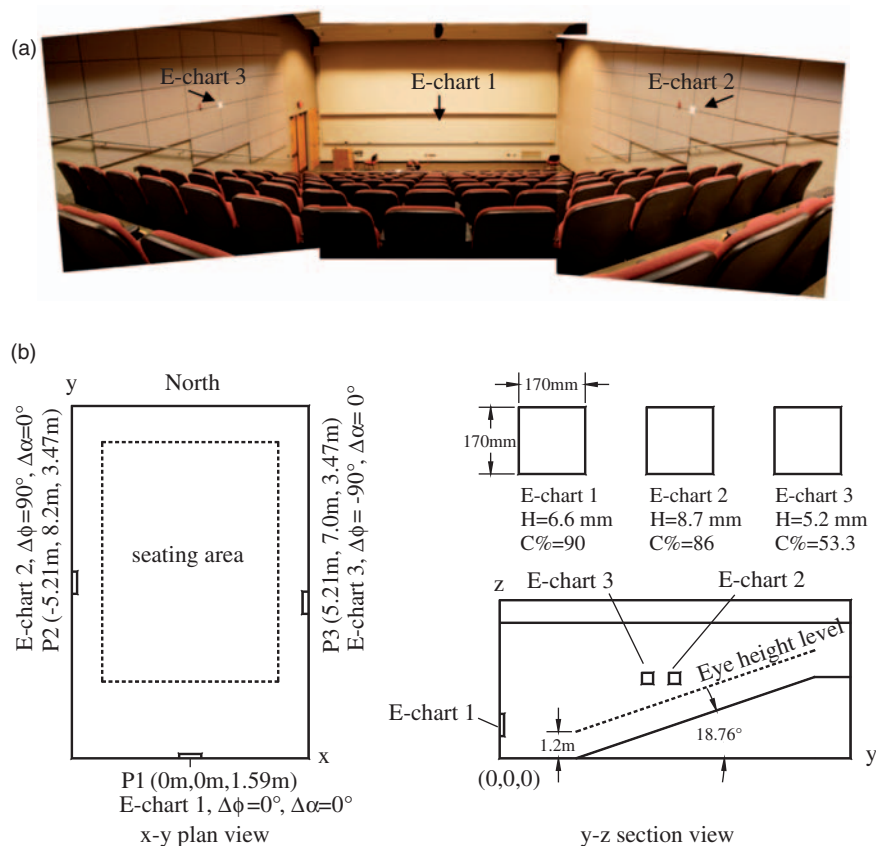
In such cases, the visual display is divided into smaller quasi-uniform sections and then individually calculated in the program.

The flow of this computer program is listed below:

1. Enter the number of visual displays.
2. Enter the observer's visual acuity.
3. Enter the text geometries (height, height-to-stroke width ratio), and its lighting conditions (background luminance, luminance contrast percent).
4. Calculate the on-axis legibility distance of text presented on each visual display.
5. Enter the geometries (heights, widths, locations on  $x$ - $y$ - $z$  coordinates) and initial orientations ( $\Delta\phi$ ,  $\Delta\alpha$ ) of each visual display.
6. Find the  $x$ - $y$ - $z$  coordinates of the nine calculating points on each display.
7. Define the viewing plane where the observer's eyes are located.
8. Draw the 3D ideal viewing spaces of text presented on each calculating point on each visual display, and then slice them all with the specified viewing plane.
9. Plot the overlapped 2D ideal viewing area of text presented on all visual displays.

10. Show the parameters of the 2D ideal viewing area.

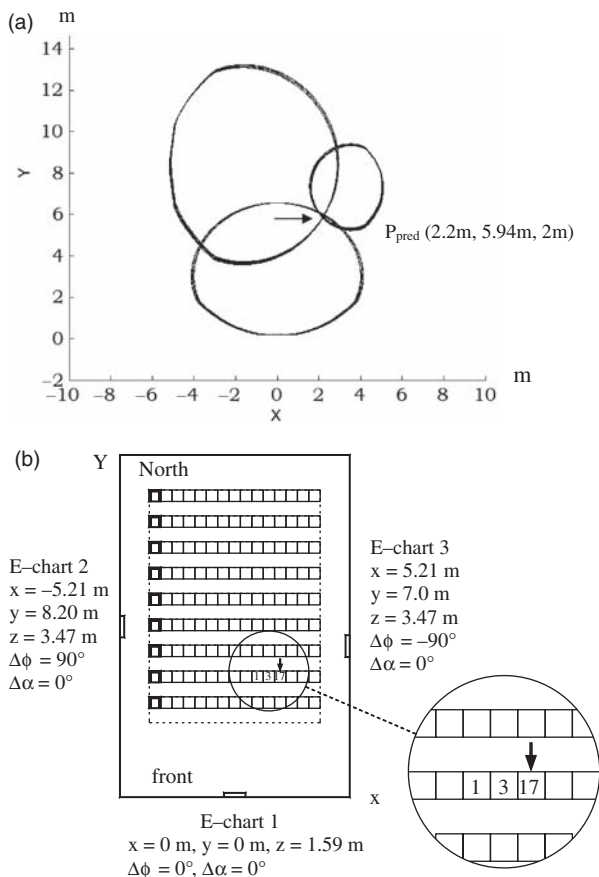
This computer program predictions were verified in a field experiment carried out in a lecture hall in the Art and Architecture building at the University of Michigan, Ann Arbor. The lecture hall (Room 2104) has seating for 135 and is  $10.70 \times 15.85 \text{ m}^2$  with a sloped floor. There is a blackboard and a projection screen in the front of the room. Typical T8 fluorescent lighting is used. A total of 21 subjects participated, aged 20–29 years old, with binocular eyesight 20/12.5 (with or without glasses) and normal colour vision. Viewing materials include three E-charts (four lines of letter Es with the same height but random orientations) printed on matte paper, and mounted at different locations with different orientations, as illustrated in Figure 8. Different E-charts have different letter sizes and different contrasts. Each E-chart, including letter Es and margins, is 170 mm wide by 170 mm high, and subtends about  $1.5^\circ$  to the observer's eyes within the centre fovea when viewed at about 6.7 m [14]. Subjects were asked to find the seat(s) where they could clearly read all three E-charts with threshold 100% accuracy. The experiment took about 20 min per subject. Each subject tried at least one, at most four and on the average



**Fig. 8.** Settings of the field experiment: (a) picture of the lecture hall and (b) experimental arrangement and dimensions.

three intermediate seats before they find the final seat location.

Using the computer program, the predicted seat is pointed by an arrow in Figure 9(a), centred at  $P_{pred}$  (2.2, 5.94 and 2m) with an overlapped small area  $0.2 \times 0.2 \text{ m}^2$ . The predicted area is so small that it can be occupied within only one seat – the fourth seat counting from the east side wall in the second row. Figure 9(b) shows the distribution of selected seats by all subjects. Of the 21 subjects, 17 (81%) chose the predicted seat, while three other subjects (14%) chose the immediately adjacent seat. Only one subject (5%) insisted that he could see all three E-charts the best in the sixth seat counting from the east wall in the second row. The outcome that 17 of 21 subjects chose the predicted seat indicates a majority of the audience will confidently pick the predicted seat ( $p=0.0023$ ). Given error allowance of one seat, which might still be acceptable in lecture hall design for seating arrangement, 20 of 21 subjects chose the predicted seat or its immediately adjacent one.



**Fig. 9.** Predicted and observed seat locations: (a) predicted ideal seat location as the overlapped small area and (b) final seat locations chosen by the 21 subjects (unit in metres).

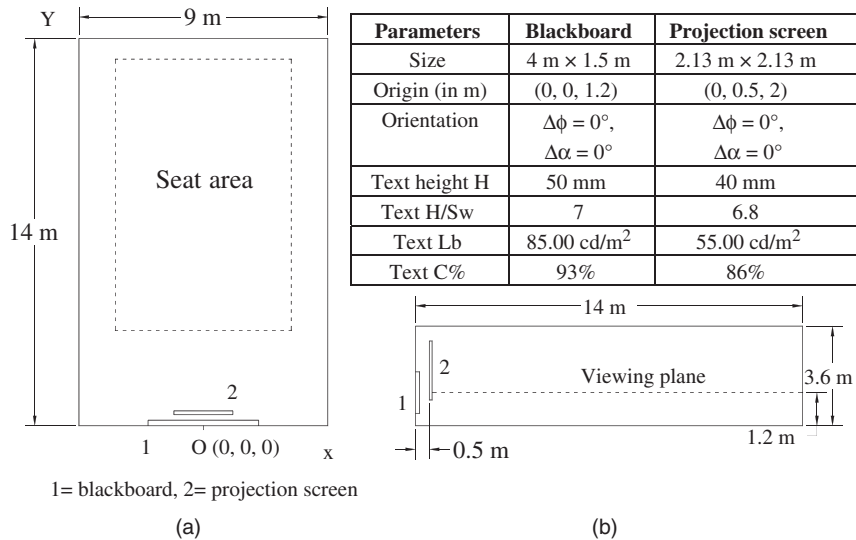
## Two Additional Test Cases

Specifications for two hypothetical lecture halls were developed to represent those commonly found in universities. Those specifications were based on a field survey carried out at the University of Michigan of 16 small lecture halls, 15 large lecture halls and 7 lecture theatres [12]. The surveyed 38 lecture halls are carefully chosen from the list on the University of Michigan Postsecondary Education Facilities Inventory and Classification Manual, based on the five characteristics of lecture halls. To provide some perspective, of the public universities in the US, the University of Michigan is 14th in terms of enrolment [15]. Because of its relatively large size, there are probably more lecture halls than at most universities. Among the 38 lecture halls, 24 have two visual displays installed (often a projection screen plus a blackboard/whiteboard), whereas 9 lecture halls use three displays and 5 lecture halls use four displays. Ten lecture halls have flat floors; the other 28 have sloped floors. In addition, the maximum viewing distance from off-axis seats to the centre of front displays in each of the 38 lecture halls varies from 10.0 to 25.7 m, with a mean 15.5 m. The maximum horizontal viewing angle from off-axis seats to the edge of front displays is  $43.5^\circ \leq \phi_{max} \leq 80.4^\circ$ . To span the range of typical lecture halls, a small flat-floor lecture hall ( $9 \times 14 \times 3.6 \text{ m}^3$ , 99 seats) and a large sloped-floor lecture hall ( $16 \times 20 \times 8 \text{ m}^3$ , 280 seats) were selected as test cases. To reflect the typical use of visual displays, the small lecture hall has a blackboard and a projection screen, while the large one has a whiteboard, a projection screen and a video monitor. In terms of lighting levels, the surveyed surface luminance of displays in all 38 lecture halls is in a range of  $2.81 \pm 4.73 \leq L_b \leq 86.00 \pm 102.28 \text{ cd m}^{-2}$ . Therefore, the range  $55.00\text{--}85.00 \text{ cd m}^{-2}$  was selected in the two test cases as the background luminance of text.

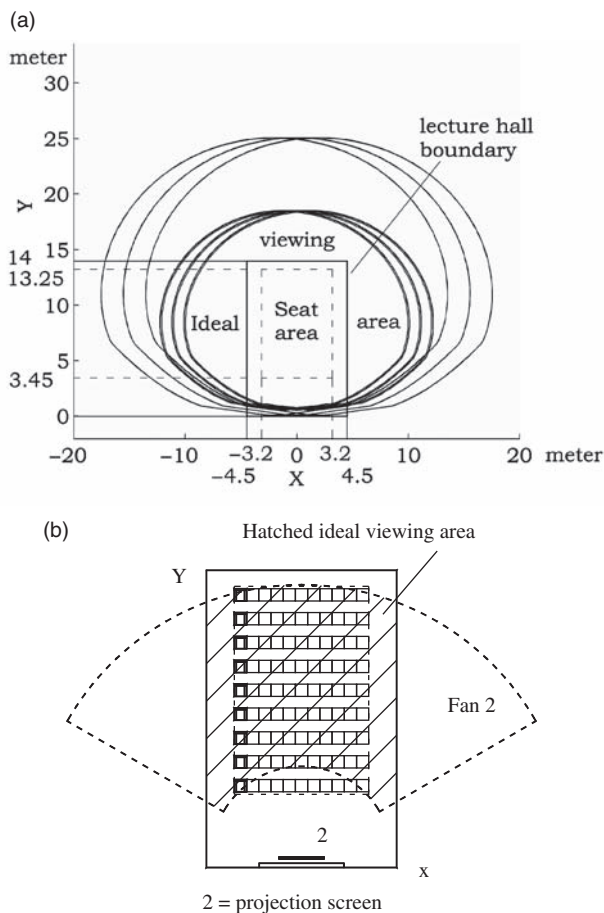
### Test Case 1: Small Hall, Flat Floor, Seating for 99

The first lecture hall is shown in Figure 10, with the original point O (0 m, 0 m, 0 m) preset to the bottom centre of the front wall. The blackboard and projection screen are mounted in the front space. They are viewed by observers with normal 20/20 acuity and a seated eye height of 1.2 m. The table enclosed in Figure 10 also lists the geometries and lighting parameters of text, which could be any Roman letters (A–Z), presented on these two visual displays.

Based upon the values shown in Figure 10, Figure 11(a) depicts the overlapped 2D horizontal ideal viewing area of the blackboard and projection screen. This predicted ideal



**Fig. 10.** Small flat-floor lecture hall inside of which text is presented on a blackboard and a projection screen: (a) plan view and (b) section profile.



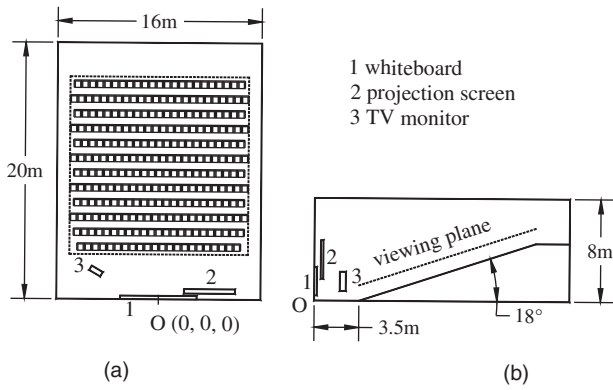
**Fig. 11.** Overlapped horizontal ideal viewing area in test case 1 of: (a) blackboard and projection screen determined using the computer program and (b) projection screen solely defined by the guidelines of Hauf et al. [1] (unit in metres).

viewing area completely encloses the seating area, as shown in Figure 11(a). For comparison, Figure 11(b) illustrates the horizontal fan-shaped area (hatched) of the projection screen, defined using the guidelines that Hauf et al. [1] proposed by assuming viewing angle  $\phi = 60^\circ$ , viewing distance two to six times display width. This empirical method predicts most seats in the audience area with legible view of text, except for the first row, as shown in Figure 11(b). To evaluate the efficiency of each method, the ratio  $\eta$  of usable area to total audience area was calculated. For the computer program  $\eta = 1$ , while  $\eta = 0.9$  for the existing guidelines of Hauf et al. [1].

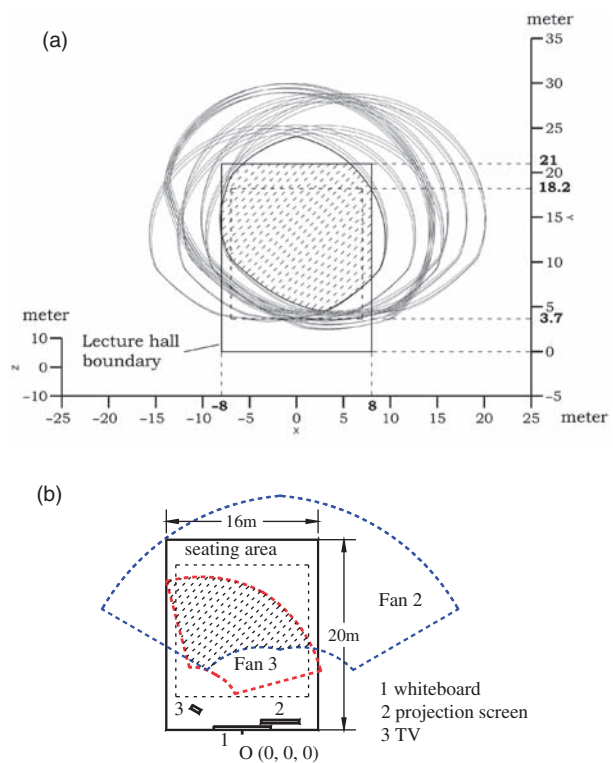
*Test Case 2: Large Hall, Sloped Floor, Seating for 280*

The second lecture hall is shown in Figure 12(a) and (b). The original point O (0 m, 0 m, 0 m) is also preset to the bottom centre of the front wall. The whiteboard, projection screen and video monitor (on a table) are mounted in the front of the hall, which has a sloped floor. They are viewed by observers with 20/20 acuity and a seated eye height is 1.2 m. The geometries and lighting parameters of text (any letters A–Z) presented on the three visual displays are listed in Figure 12(c).

The computer program plots the oblique 2D ideal viewing area (shaded) along the sloped viewing plane, as shown in Figure 13(a), of the whiteboard, projection screen and video monitor. For comparison, the overlapped horizontal ideal viewing area (shaded) of the projection screen and video monitor (whiteboard is not included) defined using the existing guidelines is also shown in



**Fig. 12.** Large sloped-floor lecture hall inside of which text is presented on three visual displays and viewed by observers located along the viewing plane parallel to the sloped floor: (a) plan view, (b) section profile and (c) parameters used.



**Fig. 13.** Ideal viewing area in test case 2: (a) overlapped oblique ideal viewing area (shaded) of whiteboard, projection screen, and video monitor, found by the computer program and (b) overlapped horizontal area (shaded) of projection screen and video monitor defined by the guidelines of Hauf et al. [1].

Figure 13(b), by assuming viewing angle  $\phi = 60^\circ$ ,  $d = 2 - 6w$  for the projection screen and  $\phi = 45^\circ$ ,  $d = 4 - 14w$  for the video monitor, based on Hauf et al. [1]. The calculated efficiency ratio  $\eta = 0.81$  for the computer program predictions, while  $\eta = 0.46$  for the existing guidelines of Hauf et al.

### Conclusions

This paper described a computer-program-aided design method to estimate at which locations in lecture halls text presented to the audience will be legible. The program code is available [12], and online <http://www.umich.edu/~driving/publications/publications.html>. Input to the program includes viewer visual acuity, location and dimensions of each display, text characteristics (height, height-to-stroke width ratio), lighting conditions (background luminance and luminance contrast) and the viewing plane of the audience. Architects are encouraged to explore its use.

This computer program was validated for its accurate prediction in an experiment conducted in a real lecture hall. Further validation from audience in real lecture halls is also needed and will be carried out in the near future. Two supplementary test cases demonstrated the effective applications of this program in modern flat- or sloped-floor lecture halls, where text could simultaneously appear on projection screens, video monitors and blackboards, in different locations, with different sizes, orientations and light levels. It was also found from these two test cases that predictions using the computer program agree with those with existing guidelines and seem to be more efficient (efficacy  $\eta = 1$  vs. 0.9 at case 1,  $\eta = 0.81$  vs. 0.46 at case 2), yet further tests in lecture hall design practice are demanded.

This computer program solves some apparent deficiencies of the existing design guidelines, which do not consider the size of characters, their contrast and luminance, visual acuity of observers and conventional displays such as chalkboards in their predictions. Thus, this program could serve as a useful tool to supplement the existing guidelines for defining ideal viewing areas in lecture halls. In a quantitative manner, the underlying legibility equations enable this program to fulfill some complicated tasks, such as defining an oblique 2D ideal viewing area of text presented on multiple types of displays viewed by observers with different acuity levels under uneven lighting conditions, or assessing the legibility level from the farthest or most off-axis seats. Apparently, these tasks go beyond the existing guidelines. However, note

that in the current version of the computer program, as the first effort of the authors, the text viewed is assumed achromatic illuminated by uniform, glare-free, fluorescent lighting. Further research is needed to include chromatic text, graphics and word legibility, as well as non-uniform lighting.

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