Readability in Classrooms

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Synopsis

Architects and property developers are in charge when lecture halls and classrooms are being (re)build or renovated. In general, the multidisciplinary project team consists of mechanical engineers, installation engineers and acoustic specialists. Striking is the habit of keeping to teaching environments based on single projectors without considering education technologies, such as modern AV-IT equipment, multiple presentation modes and videoconference. Education has been moving into the digital world for years, but consequences for interior design seem thus far ignored.

Once the building plans are finished and the contracts stipulated, it is hard, often impossible, to change details in these building plans. Usually, it is by then that pedagogy details and related education technology are asked for. Should it not be logical that written and presented information in classrooms are easy to produce by the lecturer and easy to read and follow by students? Readability of written and presented characters in lecture halls and classrooms is dependent on sightlines, reading distance, character heights, viewing angles, displays, screens and lighting. For such reason, our advice would be to expand the beforementioned multidisciplinary team with educationalist, AV-IT and ergonomic experts from start on.

This paper aims at readability in classrooms and describes guidelines from out of ergonomic, didactic and audio-visual perspectives. Its objective is to be an addition to the current guidelines in building plans that are used for constructing or renovating classrooms and lecture halls. The following guidelines are propositions, described and explained, to be discussed in the project team:

1. Presentation screen's underside preferably about 140 cm above floor level
2. Vertical viewing angle at the first row preferably about 25 degrees
3. Horizontal viewing angle at the first row preferably about 35 degrees
4. Written and presented character height preferably about 20 arc minutes
5. Written characters preferably presented white on a black background
6. Projector's illumination preferably about 1000 lumen per m^2 of projection screen
7. Projector preferably back projection, prevent hot spot or reflection in case of front projection
8. Brightness of LED display preferably 2000 nits or more
9. Pixel density of electronic displays preferably larger than 30 PPI

Introduction

A combination of factors determines the readability in lecture halls and classrooms. Figure 1 shows some important dimensions, such as screen's underside level, vertical viewing angle, reading distance, height and width of the presentation screen or display. In this paper several dimensions, including character height and (il)lumination, and interdependencies are described. Every section ends with a proposition based on literature or empirical test.

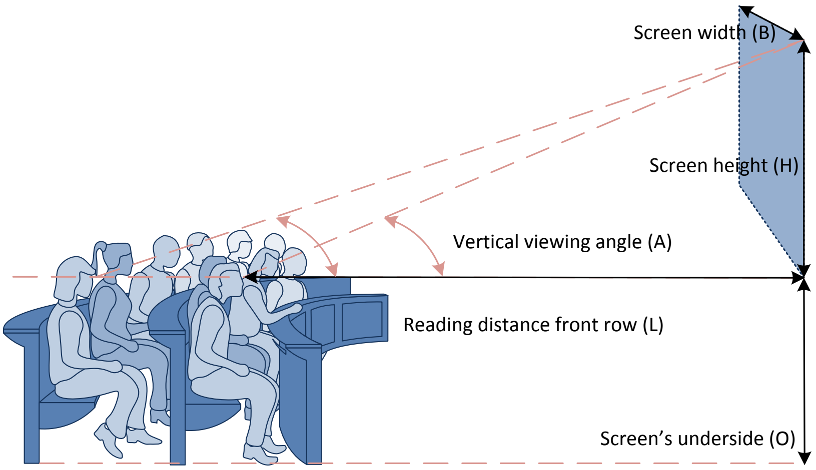


Figure 1: Positioning a presentation screen in the lecture hall; important dimensions are screen's underside (O), vertical viewing angle (A), reading distance from front row (L), height of presentation screen (H) and width of presentation screen (B).

1 Presentation screen's underside preferably 140 cm above floor level

Sightlines in flat level classrooms are determined by its users. The DINED antropometric database [1] of Delft University of Technology (TU Delft) keeps human dimensions for ergonomic purposes of people in the Netherlands, see http://dined.io.tudelft.nl/en,dined2004,302. People databases with human dimensions for different ergonomic purposes (standing, sitting, working) are available world wide.

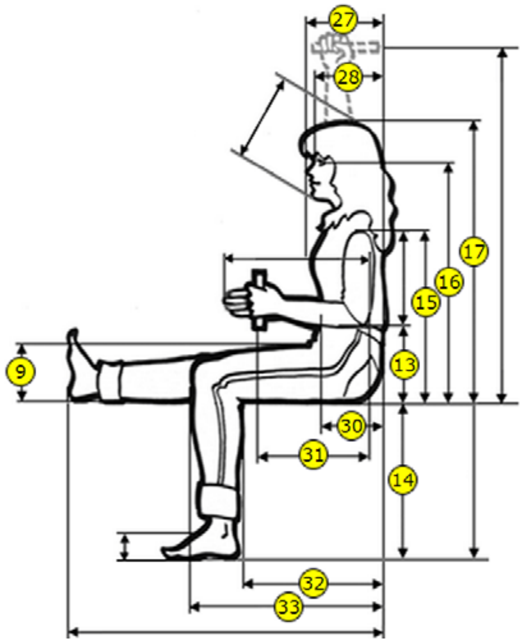


Figure 2: Human measurements of a sitting person. Source: http://dined.io.tudelft.nl/en,dined2004,302.

Figure 2 shows the dimensions of a sitting person to determine the presentation screen's underside height for flat level classrooms. With thanks to Dr. Ir. J.F.M. (Johan) Molenbroek for the availability, use and validation of the applied data.

We focus at dimensions with the numbers 14, 16 and 17. Number 14 is the height of the hollow of the knee (popliteal height), number 16 is eye level and number 17 is crown height of a sitting person. Target group is the population of young people between 20 and 30 years of age, in other words our averaged student. The chosen measurements from the DINED 2004 database are valid for 90 percent of this population. Averaged measurements with corresponding standard deviations are taken for both male (m) and female students (f). Dimensions are in centimetres (cm).

- 14 is interpreted as the seat height with values m = 49.7 ± 3.1 cm and f = 44.1 ± 2.5 cm.
- 16 is the eye height while seated with values m = 84.2 ± 3.9 cm and f = 77.9 ± 3.2 cm.
- 17 is the crown height while seated with values m = 95.7 ± 3.9 cm and f = 88.8 ± 3.2 cm.

Mean values can be combined to determine the averaged sight line (combination of numbers 14 and 16) or the averaged crown height (numbers 14 and 17): $\overline{X}_3 = \overline{X}_1 + \overline{X}_2$. When mean values are summed the corresponding standard deviations sd_1 and sd_2 have to be squared and added with twice the correlation factor for the related length. The square root delivers the corrected standard deviation sd_3 for the combined lengths: $sd_3 = \sqrt{sd_1^2 + sd_2^2 \pm 2 * r * sd_1 * sd_2}$ with a correlation factor r = 0.65. The r-value is to be found at the DINED website and used for combining measures of length.

As a result, the eye level height for our Dutch male students is 133.9 ± 6.3 cm. This result is a normally distributed variable as is shown in Figure 3, which means that 133.9 ± 6.3 cm counts for 90 % of the population. This eye level height is situated between values of the 5th and the 95th percentile.

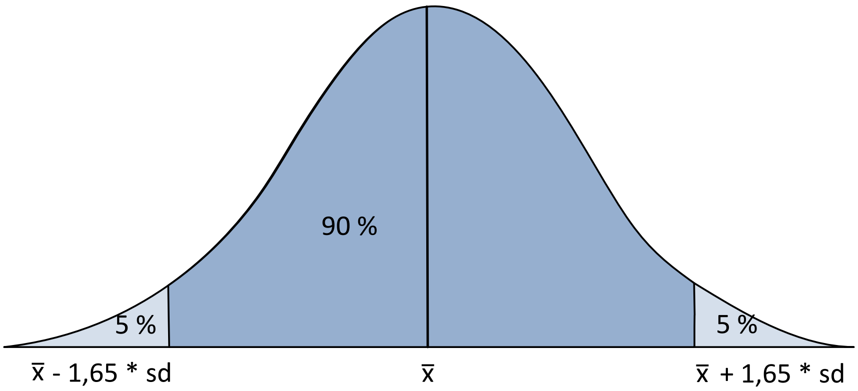


Figure 3: Normal distribution with P_5 and P_{95} at 1,65 x standard deviation.

The distance from the averaged $\overline{X}$ down to the 5th percentile (P_5) or up to the 95th percentile (P_{95}) is 1.65 times the standard deviation sd, which means that percentile values for Dutch male students are P_5 = 133.9 – 1.65 * 6.3 = 123.5 cm and P_{95} = 133.9 + 1.65 * 6.3 = 144.3 cm.
The crown height for Dutch male students is 145.4 ± 6.3 cm, meaning P_5 = 145.4 – 1.65 * 6.3 = 135.0 cm and P_{95} = 145.4 + 1.65 * 6.3 = 155.8 cm.

Values for Dutch female students are 122.0 ± 5.2 cm. Its corresponding percentile values will be P_5 = 122.0 – 1.65 * 5.2 = 113.4 cm and P_{95} = 122.0 + 1.65 * 5.2 = 130.6 cm. Finally, the crown height for Dutch female students will be 132.9 ± 5.6 cm, meaning P_5 = 132.9 – 1.65 * 5.6 = 123.7 cm and P_{95} = 132.9 + 1.65 * 5.6 = 142.1 cm.

Proposition for the presentation screen's underside or LED display's underside

In flat level classrooms students sit next to each other as well as behind each other. Dependent on the position of the projection screen most of the students have to move sideways to follow the presented information on a screen. Mounting the screen at a proper height, derived from the above figures, can prevent such situations. Its height for Dutch students may vary between a minimum height of about 130 cm to a maximum of approximately 155 cm. An underside height (O) of 140 cm will do in most cases.

NB: Sight lines will be better if shorter students sit in front of the classroom and longer students take place at the back rows.

2 Vertical viewing angle at the first row preferably about 25 degrees

Human eyes can rotate about 25 degrees upwards and 35 degrees downwards without moving the neck joint. However, when reading texts one has to focus on a single text line. Hence, the head moves according to a vertical pattern when reading texts from a presentation screen.

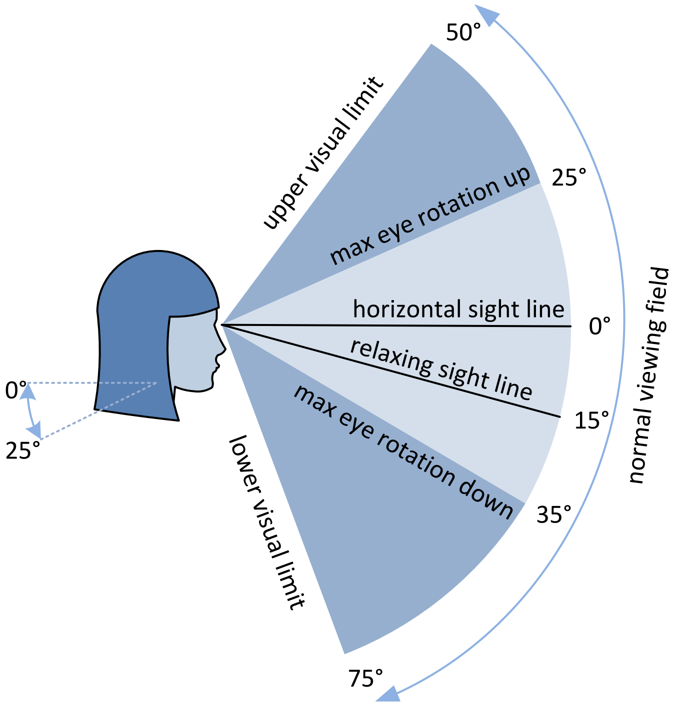


Figure 4: Vertical viewing field of the eye. Information is taken from "The Measure of Man and Woman: Human Factors in Design" (tilley, 2002).

The vertical angle A, as presented in Figure 1, is at its largest for students sitting at the front row of the classroom. Their neck joint tilts the largest angle to follow texts on the projection screen. A neck joint can easily be moved upwards up to 25 degrees as Figure 1 shows. Tilting the neck joint above 30 degrees is possible but very fatiguing. Therefor the viewing angle should not exceed 25 degrees in order to prevent overload. Figure 4 shows a simplified overview of the vertical viewing field. An ergonomic complete overview can be found in "The Measure of Man and Woman: Human Factors in Design, ISBN 0471099554" [2].

The reading distance from projection screen to the seat at the first row (L) is dependent on the applied projection screen height and can be calculated with: viewing angle A = arc tan (H/L) with 25 degrees for angle A at the front row.

When the screen height H in Figure 1 is known, width B of the projection screen can be calculated. Most of the presentation screens have an aspect ratio of 16:9 (when video is leading) or 16:10 (when PowerPoint is leading). The width for non-scaled video images follows from B = 16/9 * H.

Proposition of 25° for the vertical viewing angle at the front row

In order to unburden the neck joint of students at the front row of the classroom it is advised to follow natural movements for reading texts at the presentation screen. With a vertical angle (A) of 25 degrees the maximal dimensions of height (H) and width (B) can be calculated.

3 Horizontal viewing angle at the first row preferably about 35 degrees

Figure 5 shows the horizontal viewing field. In "The Measure of Man and Woman: Human Factors in Design, ISBN 0471099554" [2] an ergonomic more complete overview is presented. Sight is at best at the central axis of the eyes. Only within plus and minus 10 degrees of that central axis the reading takes place. Thus, text recognition happens in the centre of the eye, see http://www.oogartsen.nl/. Horizontal eye rotation is from plus to minus 15 degrees, hence the maximum natural viewing angle is 10 plus 15 is 25 degrees sideways. Figure 5 shows such viewing area for text recognition that varies from 25 degrees to the left up to 25 degrees to the right.

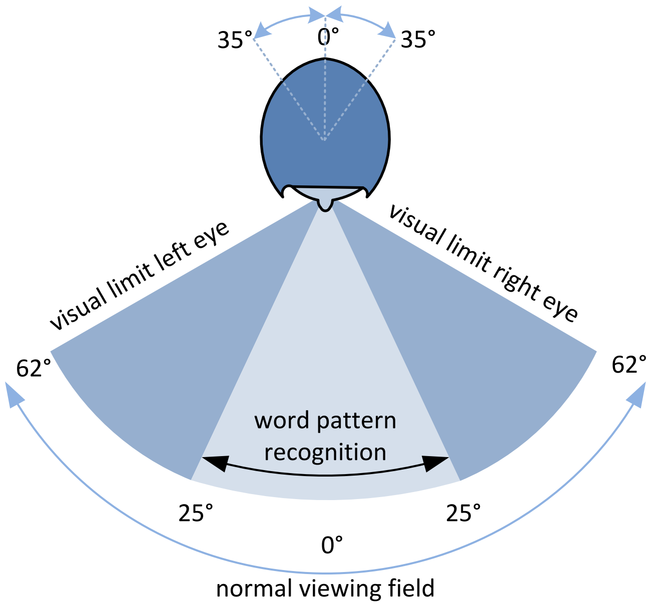


Figure 5: Horizontal viewing field of the eye. Information taken from "The Measure of Man and Woman: Human Factors in Design" (tilley, 2002).

When students sit at the front row, but at far sides, their neck has to rotate overproportionally in order to read the presented text from the presentation screen, see Figure 6a.

Research of C.J. Snijders c.s. about neck stress shows that rotation up to 35 degrees is easy and does not cost any physical exertion, however, angles over 35 degrees cause severe neck stress.
When the neck turns more than 35 degrees the pressure on joints and muscles grows rapidly, see [3]. As a consequence the body is turned, which in the end may lead to physical complaints.

Guidelines should follow natural sight lines. Sometimes this means that a centrally positioned screen is not enough for proper readability. Figure 6a shows an example of such a situation.

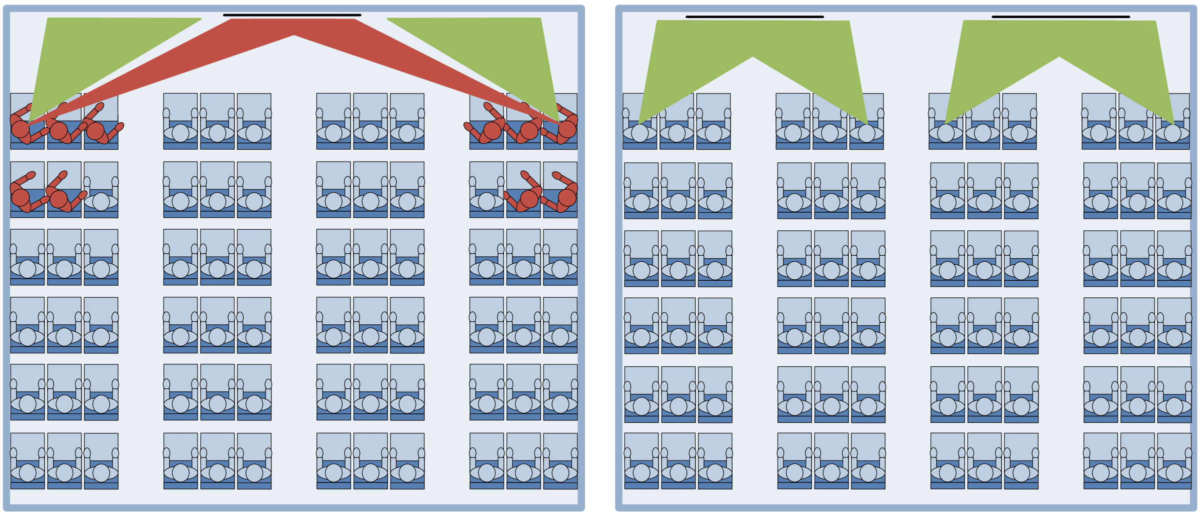


Figure 6: Horizontal viewing angles with a) one centrally positioned projection screen and b) two projection screens.

The green surfaces represent viewing areas that fall within the angle of 35 degrees neck rotation ± 25 degrees eye rotation. Red surfaces show the situation from the seats at the utmost right and left front rows that exceeds those figures. It is obvious that the red seats are bad places to be taken. The bad viewing angles may be nullified by installation of two screens as is indicated in Figure 6b. However, two screens do not always fit conducted education practices.

Proposition of 35° for the horizontal viewing angle at the front row
In order to prevent physical complaints in the classroom it is advised to respect the natural neck rotation and consider a maximum viewing angle of about 35 ± 25 degrees. Dependent on the classroom's situation sometimes it is better to install multiple presentation screens.

4 Written and presented character height preferably 20 arc minutes

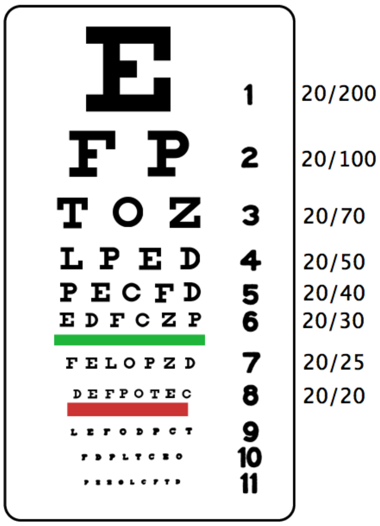


Figure 7: Visual acuity chart by H. Snellen, see [4]. Source; http://commons.wikimedia.org/wiki/File: Snellen06.png.

The guideline of ophthalmologists and opticians is followed in order to determine the readability of written and presented texts. The by them applied Snellen eye chart, as presented in Figure 7, holds characters of certain heights that represent a corresponding vision. For example, the 20/20 vision line represents the ability to see perfectly, it equals 100 percent [4]. Such visual charts were developed by the Dutch ophthalmologist Herman Snellen (1834-1908).

A vision of 100 percent is the same as having a visual acuity (visus) of 1, which corresponds with 1 arc minute. That 1 arc minute is being taken as the minimum perceiving ability of the eye. One arc minute represents the 1/360th part of a circle (1 degree) divided by 60 minutes, resulting in 0.0167 degrees.

The character height for presented and written texts with a perfect readability is advised to be 20 arc minutes according to the Human Factor Research & Engineering Group of the Federal Aviation Administration (FAA) [5]. Subtitles at television seem to follow the same rule with about 20 arc minutes.

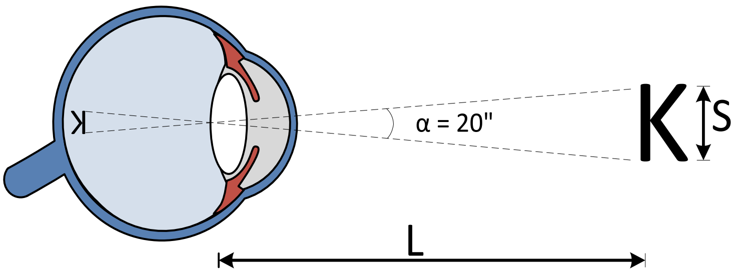


Figure 8: Angle α = 60 minutes * arc tan (S/L).

Figure 8 shows how the character height (K) is calculated in comparison to its distance (L). With 20 arc minutes (angle α) as guideline and a reading distance (L in centimetres) the character stroke height (S in centimetres) is easily calculated with the formula:

α = 60 minutes * arc tan (tan^{-1}) * S/L.

Example: with a reading distance of L = 12 metres the stroke height of characters must be: 20 arc minutes = 60 * arc tan * H / (1200) → H = tan (20/60) * 1200 ≈ 7 cm.

Proposition is 20 arc minutes for written and presented texts

Dependent on the classroom’s dimensions the character height is to be adjusted. The FAA advises a character height of 20 arc minutes at the back row which in practice means stroke heights of 6 to 11 centimetres in classrooms with depths varying from 10 to 20 metres. An often used rule of thumb is a ratio of 1:200 for character height versus reading distance, it results in about 17 arc minutes. Observations in several lecture halls at our university showed written and presented character heights from 7 to 10 centimetres which is similar to 17 to 23 arc minutes dependent on the hall [6].

5 Written characters preferably presented in white on a black background

Written characters differ in height, width and stroke thickness. The width of written characters follows an ideal ratio between 0.6 and 1 compared to its height, the more square a written character is put on the board, the better readable it is.

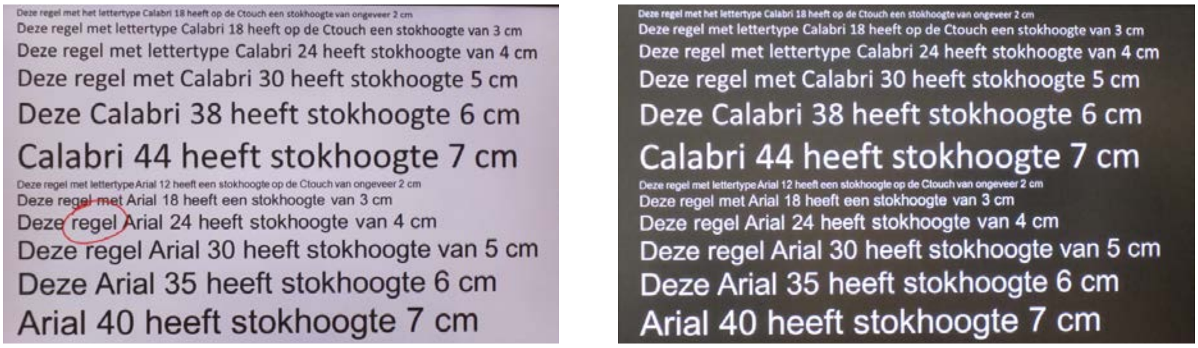


Figure 9: White characters on black backgrounds are still readable under lesser light circumstances.
Source: http://www.hf.faa.gov/Webtraining/VisualDisplays.

Dependent on the reading distance a minimum stroke thickness is advised. The minimum stroke thickness depends on the character height. The FAA advises a thickness of about 1:6 to 1:8 compared to its height [7]. Of course contrast plays an important role. White characters on a pitch black background radiate over the dark surface while black characters on a white background grow smaller at larger distances, because the white background seems to overrun the black characters. Figure 9 shows an impression, but it is hard to be demonstrated on paper. In practice however one immediately experiences it. Conventional chalk remains legible while characters on dry eraser (white) boards decrease in readability with growing distances.

Large writing surfaces on electronic displays, such as interactive whiteboards and SMARTboards, display a much calmer image when white characters are presented on a black background. The high display luminance of a white background causes irritation at the eye resulting in fatigue and head ache. At the same time the readability of white characters on a dark background is much better with low lighting conditions. Whiteboards need higher ambient light conditions for a proper readability, which at their turn has negative effect on the projector's illuminance.

Proposition for readability of written characters

Despite the fact that computer images are displayed more often with black characters on a white background, it is advised to use white characters on a dark background when writing and presenting on an interactive whiteboard or SMARTboard. On the one hand white characters show an excellent readable result; on the other hand it delivers a comfortable picture.

When white boards are used and the reading distance exceeds a reading distance of 8 metres it is advised to use thick markers of up to 1 cm for improved readability.

6 Projector's illumination preferably 1000 lumen per m2 projection screen

Lighting situations in classrooms have huge influence on the readability when projectors are used to display texts. Modern electronic displays hardly know such negative influences.
Light intensity is expressed in 'luminance' and 'illuminance'. Luminance is the light density coming from an emitting light source. It corresponds to the total of emitting light regardless of its direction. It is expressed in lumen (lm). Illuminance is the amount of light shining on (or reflecting from) a certain surface and is expressed in Lumen per m^2, or Lux (lx). When for example the light of a light bulb is reflected by mirrors and aimed onto a certain surface then the amount of Lumen of the light bulb remains the same while the amount of Lux at that surface increases.

To get a feel for light intensities in different lighting circumstances a few guiding values are given in Lumen per m^2 (lx): direct sunlight ≈ 100.000 lx, daylight ≈ 10.000 lx, cloudy ≈ 1.000 lx, dark cloudy day ≈ 100 lx, twilight ≈ 10 lx, offices ≈ 500 – 1.600 lx and education spaces ≈ 750 – 1.600 lx [2].

The luminance of projectors is expressed in ANSI-lumen. The American National Standards Institute (ANSI) proposed a standardised test method ANSI IT7.215 to measure the luminance of different projectors in 1992 [8]. Still, what is the correct luminance for a certain education space?

A small scale experiment was conducted to obtain empirical values for luminance, readability and sight lines. There was (in)direct sunlight in the classroom including strong light sources. Two projectors were used for the experiment: 1) lamp projector ASK Proxima C445 with 4000 ANSI lumen and 2) LED projector CASIO XJ-M250 with 3000 ANSI lumen. A projection screen of 160 by 240 cm was used at which multiple character heights, several test screen shots and different software applications were projected. The obtained results were intuitively compared to situations in other lecture halls and classrooms of our campus.

The experiment showed that sufficient readability with reasonable colours were feasible with an illuminance of about 1000 lumen per m^2 screen despite the disturbing light sources. Illuminance can be calculated by dividing the amount of the projector's ANSI-lumen by the surface area of the projection screen. Accordingly, hereunder a few guiding values are presented for classrooms without blinds or shades:

- Screen dimensions 170 * 272 cm (± 130") ≈ 4500 ANSI lumen
- Screen dimensions 160 * 256 cm (± 120") ≈ 4000 ANSI lumen
- Screen dimensions 150 * 240 cm (± 110") ≈ 3500 ANSI lumen
- Screen dimensions 140 * 224 cm (± 100") ≈ 3000 ANSI lumen

Proposition is illumination of 1000 ANSI lumen per m^2 for a proper readability
An illuminance of about 1000 lumen per square meter of projection screen is advised to get good readability results with projectors in education spaces that are influenced by surrounding light sources. In situations with strong light sources such as indirect sunlight or direct sunlight through blinds it is advised to apply LED displays. The readability of electronic displays is hardly influenced by such surrounding light sources because of the neat contrast and brightness possibilities.

7 Projection preferably back view projection, prevent hot spot or reflection in case of front projection

Sometimes a disturbing reflection occurs when a projector is used in classrooms. The intensity of such a hotspot depends on the applied projection materials. Sometimes whiteboard materials are chosen for both writing and projecting. It seems that such combination offers best of both worlds, however, in practice it is always a compromise for a suboptimal solution.

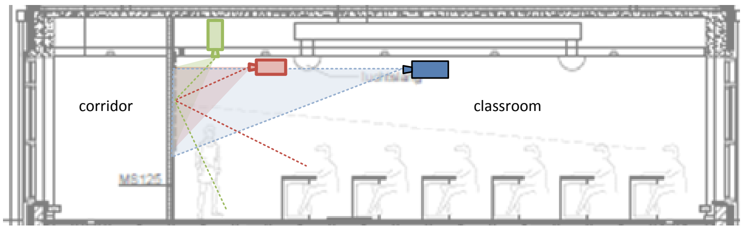
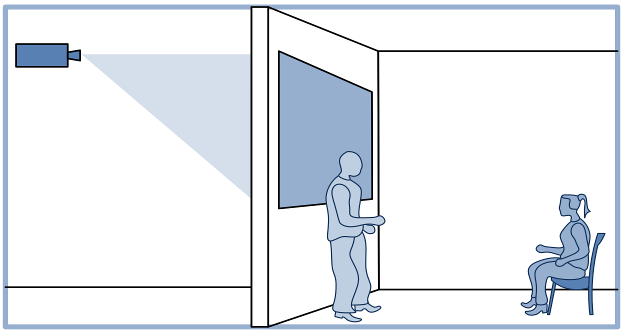


Figure 10: prevent hot spots and reflections with short throw projectors.

Such irritating reflections can be avoided with carefully measuring the position of projector and projection screen. Sometimes it is better to use a short throw projector, but of course a proper projector must be available at the market. An example with different situations is shown in Figure 10. Good installations avoid the lecturer to be able to stand in the light beam.



When back view projection is possible, for example when there is space behind the projection screen, then this is most advisable. With back view projection the lecturer is never in the light beam, hence projection is not interrupted. Moreover, the annoying sound of the cooling fan has disappeared to the space behind the projection screen.

Figure 11: Back projection prevents that the lecturer interrupts the light beam.

Proposition to prevent hot spots and lamp reflection

To avoid irritating reflections and hot spots one can best choose back view projection. Sometimes a short throw projector can avoid reflections and hot spots by bending the reflection downwards.

Electronic displays sometimes have very reflecting surfaces, however when this equipment is turned on people normally are not troubled by it.

8 Brightness of LED display preferably 2000 nits or more

Electronic screens display a relatively constant quality of images despite environmental lighting conditions. The light intensity of electronic displays is called brightness and is expressed in nits or candela per square meter (cd/m^2).

Compared to a projector which beams light onto a screen that reflects (illuminance) it is the screen itself that radiates light (luminance). A brightness of 1 cd/m^2 equals 1 lux in the direction perpendicular on the screen, as is shown in figure 12.

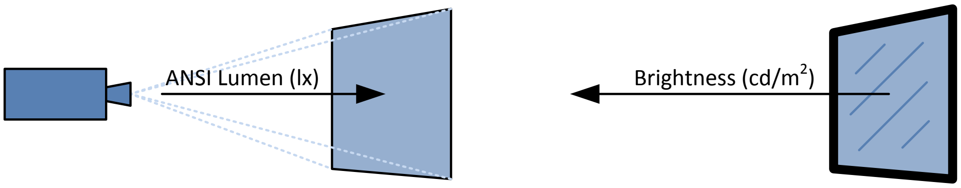


Figure 12: Projection screen with receiving light in lx and LED display with radiating light in cd/m^2.

Most of modern LED displays have a brightness between 1000 up to 14000 nits and are hardly influenced by environmental light conditions. It are the somewhat older plasma and LCD screens that are a bit light weak, especially the larger screens. These have an average brightness of about 300 to 1000 nits. For indication purposes: laptops have an average of 150 to 300 nits. LED lighting for outdoor purposes need a brightness of about 5000 nits for good readability in sunny circumstances, for indoor purposes 3000 nits is more than sufficient for spaces with large windows and much daylight.

NB: Electronic displays have the possibility to regulate the contrast which helps to improve readability of texts.

Proposition to use LED displays with a brightness larger than 2000 nits
When the demanded screen dimensions are available on the market than it is advised to use LED displays. These have such good adjusting possibilities that readability is nearly independent of surrounding light conditions. A second advantage is that they have a lifespan between 20,000 to 50,000 operation hours, while lamp hours of projectors vary between 1,500 to 2,500 operation hours. The upcoming LED and laser projectors do have high operation hours, unfortunately not all resolutions have enough ANSI lumens. As a consequence many lecture halls still be equipped with lamp projectors.

9 Pixel density of electronic displays preferably larger than 30 PPI

The pixel density of electronic displays is important for readability next to its brightness and contrast. Pixel density is the number of pixels per unit of length and expressed in PPI (pixels per inch); the higher the PPI the higher the resolution of a screen. High resolutions on small displays deliver very sharp images and very good legible texts. Apparatus with such high PPI are for example smartphones and tablet computers.

When images on electronic screens have to be smooth and clear and very legible then pixel dimensions should be smaller than 1 arc minute for the eye of the reader. Thus, a pixel free image is dependent on the reading distance.

The size of a pixel with viewing angle α of 1 arc minute and reading distance L of for instance 3 metres is to be calculated with α = 60 minutes * arc tan * (pixel size P) / (reading distance L) = 1 arc minute. Pixel size P = tan (1/60) * reading distance L = tan (0.0167) * 300 cm = 0.000291 * 300 cm = 0.087 cm or 0.0344 inch. Pixel density is the inverse of pixel size and equals 1 / 0.0344 = 29 PPI.

Calculating the pixel density is easy by dividing the diagonal pixels of an electronic display with its screen diagonal size. The number of diagonal pixels is the square root of the squared horizontal and vertical resolutions. For example is the pixel density of a 55 inch (140 cm) 1080p LED display:
Pixel density is $\sqrt{1920^2+1080^2}$ / 55 inch = $\sqrt{4852800}$ / 55 in = 2203 / 55 in = 40 PPI.

The ideal reading distance for such a 55 inch display with Full HD resolution (1920 * 1080) starts at: L > 1 / 40 (pixel size in inch) / tan (0.0167) * 2.54 (pixel size in cm) ≈ 218 cm. As an example some reading distances with corresponding pixel densities for a viewing angle of 1 arc minute are given in the table hereunder:

Reading distance in cm	Pixel density in PPI
100	> 87
200	> 43
300	> 29
400	> 22
500	> 17

Be aware that character height on a higher resolution screen is displayed with smaller dimensions than when displayed on a screen with a lower resolution. For instance the size of a 100 pixels character on a 1920*1080 display of 55 inch with pixel density of 40 PPI has a stroke height of 6.35 cm. That same character of 100 pixels displayed on a 1366*768 display with pixel density of 1567 / 55 = 28.5 PPI has a stroke height of 8.91 cm. The example is taken from the Extron Videowall Systems Design Guide [9].

Finally, the font size and pixel size presented on electronic displays are not the same. These have a ratio of about 1 to 1.35. For example has a 12-points font a height of about 16 pixels, a 18-points font a height of 24 pixels and a 30-point font a height of 40 pixels [9].

Proposition of pixel density larger than 30 PPI

The pixel density of electronic displays determines the resolution and readability. The observer wants to experiment a fluent image hence the pixel size should be smaller than 1 arc minute. If for example the reading distance is 3 metres then the pixel density should be at least 30 PPI.

NB: In order to display sharp characters on the projection screen it is wise to show original video signals and not scaled ones. Scaling characters become blurred or malformed due to its conversion.

Epilogue about readability in classrooms and lecture halls

In practice the interior of lecture halls and classrooms aim at maximum seat capacity. Corresponding dimensions of furniture are the guiding parameters when designing educational spaces. Too often, viewing angles and sight lines are considered in general and not for every seat in particular. This results in a readability taken for granted.

It should be compulsory that written and presented information in classrooms and lecture halls is easy to produce by the lecturer and easy to read and follow by students. It may be of no difference for readability that written or presented texts are projected on dry eraser boards, on projection screens or on electronic displays. A well chosen design taking into account sightlines, reading distance, character heights, viewing angles, displays, screens and lighting, results in proper readability of written and presented characters.

This paper describes guidelines from out of ergonomic, didactic and audio-visual perspectives for an improved readability in lecture halls and classrooms. It ought to be conducive to the building plans used to construct new education spaces or when renovating lecture halls and classrooms.

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