An improved metric for luminance contrast using colour-modified clinical eye charts.

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Summary. ***Background:*** Luminance contrast is the relationship between the luminance reflectance of an object and its immediate background. At the present time there is no international standard for luminance contrast and each country has its own specific way, or no way, for measuring it. Visual acuity is the visual ability to resolve fine detail. By designing a large number of eye charts with contrasting font and background colours, the author (Sapolinski) was able to develop a scientifically-based procedure that produced a quantifiable relationship between the visual acuity measure of a particular eye chart with the luminance contrast between respective font and background colours. ***Methods:*** The author designed and produced 48 unique full-sized ETDRS eye charts that are the "gold standard" for clinical visual acuity tests. Subjects were positioned 6m from the eye charts that were illuminated at 500 lux. The eye charts included a large variety of greyscale and colour combinations that were a mixture of high, medium and low luminance contrast between font and background colours. The author also designed a logarithmic scale visual acuity scoring system that complemented the logarithmic layout of each ETDRS eye chart [1]. Average visual acuity scores were then plotted against luminance reflectance values for each chart that were measured with a spectrophotometer. ***Results:*** The mean age of the 80 subjects (25 female, 55 male) was 27.2 years (range: 6-74 years). The mean visual acuity score for the 48 eye charts was 54.97, out of a maximum 100, for the 14 vision impaired subjects and 68.69 for the 66 normal vision subjects. For the three ISO-recognised luminance contrast equations the plotted root-mean-square correlation values between the luminance reflectance values of the font and background colours of each eye chart and their visual acuity scores was 0.8167 (vision impaired) and 0.7755 (normal vision) for the equation used in the UK standard [2]; 0.7672 and 0.7659 respectively for the equation used in the US standard [3] and 0.8270 and 0.8227 respectively for the Bowman equation used in the Australian standard [4]. Modifications, based on experimental visual acuity results, were made to this equation used in the Australian standard and the resulting Bowman-Sapolinski equation had root-mean-squared correlation values of 0.9254 (vision impaired) and 0.9122 (normal vision). ***Conclusion:*** Overall, for the wide spectrum of colour combinations, the Australian Bowman equation for luminance contrast was most representative of how the human eye differentiates between adjacent matt surfaces, for its correlation values were closest to the perfect 1.000. These correlation values were further improved when data from the low contrast, dark font on dark background eye charts were ignored; 0.9238 (vision impaired) and 0.9209 (normal vision). Meanwhile the correlation values for the UK standard actually decreased to 0.6869 and 0.6380 respectively, with data from the 7 dark on dark charts removed. Through the construction of a single equation with a parameter that could be optomised using visual acuity results, the Bowman-Sapolinski equation negates the dark on dark shortcomings of the Bowman equation. Subsequently, the Bowman-Sapolinski equation has been adopted as the new equation for luminance contrast in the Standards Australia: Design for Access and Mobility (1428.1-2009) [5] and the authors recommend that the Bowman-Sapolinski equation should also be adopted as the inaugural international standard for luminance contrast.

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Introduction

During the last two decades, a concept has been developed in building design called universal design [6]. This entails that all buildings are designed in a way that takes into consideration all people no matter what their physical abilities. Governments worldwide introduced legislation that ensured that all designers took into consideration people with disabilities and gave them full and equal opportunities to participate in the life of their community. In America, an act was passed in 1991, The Americans with Disabilities Act Accessibility Guidelines (ADAAG) [7]. Specifications such as minimum luminance contrast and positioning of tactile ground surface indicators were required to be explicitly detailed. In 2001, Standards Australia introduced AS1428, Design for Access and Mobility [4]. This standard was much akin to ICC/ANSI A117.1-1998 Standard on Accessible and Usable Buildings and Facilities [8] which resulted from the ADAAG act. In these standards, features such as stairways, handrails, paths of travel and signs were required to meet minimum luminance contrast levels according to different luminance contrast equations outlined in each respective standard.

Luminance Contrast - National Standards

Prior to this study, three national standards for luminance contrast were recognised by the International Standards Organisation [9]: the US (used in North America); the UK (used throughout Europe) and the Australian (used in Australasia). These three national standards use luminance contrast equations derived from various equations used in the lighting industry [10] that are used to describe different spatial patterns and have different mathematical behaviors. To date, not one of these equations has been accepted by the community as universally preferable for little objective scientific research has been conducted that relates the concept of luminance contrast with basic visual function.

The three ISO-recognised luminance contrast equations and their mathematical intricacies are compared below:

1. The US ADAAG equation:

$$C = \frac{L_2 - L_1}{L_2} \times 100$$

where:
• L_2 is the L^* (from CIE L*a*b*) value of lighter surface
• L_1 is the L^* (from CIE L*a*b*) value of darker surface.

This equation is recommended by the Americans with Disabilities Act Accessibility Guidelines (ADAAG) [7] in ADAAG A4.29. It is incorporated in the latest revision of the Accessible and Useable Buildings and Facilities Document ICC/ANSI A117.1-2008 [3]. It prescribes a minimum luminance contrast of 50% between adjacent surfaces, which is more attainable for building product manufacturers than the 70% minimum level, prescribed in the earlier 2003 revision [11]. For compliance, adjacent building elements must possess light reflectance values within the non-shaded region of Figure 1.

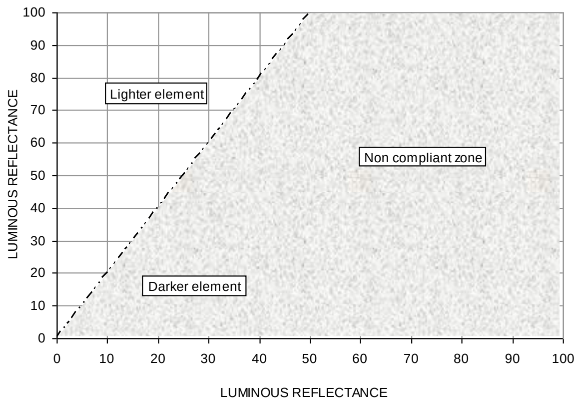


Figure 1. Limit of light reflectance values of adjacent surfaces that can comply with ICC/ANSI A117.1-2008.

2. The UK equation:

$$C = Y_2 - Y_1$$

where:
• Y_2 is the Y value from the *Yxy* chromaticity scale of the lighter surface
• Y_1 is the Y value from the *Yxy* chromaticity scale of the darker surface.

This equation is adopted in the Light Reflectance Value of a Surface - Method of Test Document BS 8493:2008 [2]. Derived from the Project Rainbow research study [12], the luminance contrast is simply the difference between the Light Reflectance Value (LRV) of two flat opaque surfaces, defined by the Commission International d'Eclairage (CIE) 1964 [13] (10 degree observer) *Y* value of the reflected light when illuminated with the CIE D65 standard illuminant. In contrast to the ADAAG equation, it uses luminance reflectance values (*Y*) rather than light reflectance values (L^*) and mathematically it is a difference between adjacent surfaces, rather than a ratio.

The UK equation is somewhat confusing and misleading in its choice of terminology. The standard BS 8493:2008 [2] is entitled, "Light Reflectance Values ...", which is an anomaly as it uses CIE prescribed *Y* values. The CIE 1931 XYZ color space defined the *Y* coordinate as the luminance reflectance of a colour [13]. Meanwhile, the light reflectance value of a colour is a measure of the L^* component of the CIE 1976 (L*a*b*) [13] colour space. Hence, BS 8493:2008 should more correctly be entitled "Luminance Reflectance Values ...". For compliance, the UK standard prescribes a minimum luminance contrast of 30% between adjacent surfaces, which is indicated by the non-shaded regions in Figure 2.

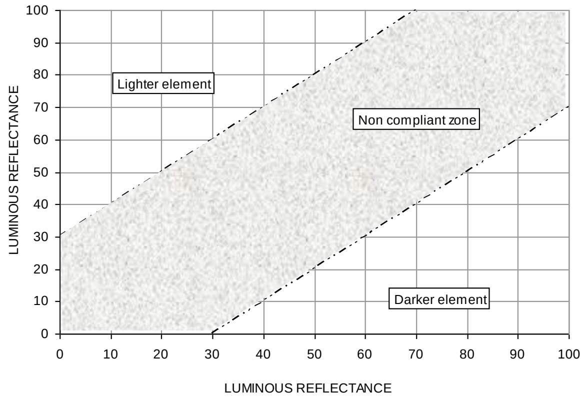


Figure 2: Maximum and minimum limits of luminance reflectance values of adjacent surfaces that can comply with BS 8493:2008.

3. The Australian Bowman equation:

$$C = \frac{Y_2 - Y_1}{\frac{1}{2}(Y_1 + Y_2)} \times 100$$

where:
• Y_2 is the Y value from the *Yxy* chromaticity scale of the lighter surface
• Y_1 is the Y value from the *Yxy* chromaticity scale of the darker surface.

This equation is adopted in the Australian Design for Access and Mobility Document AS 1428.1-2001 [4]. Like the UK equation, it prescribes a minimum contrast of 30%.

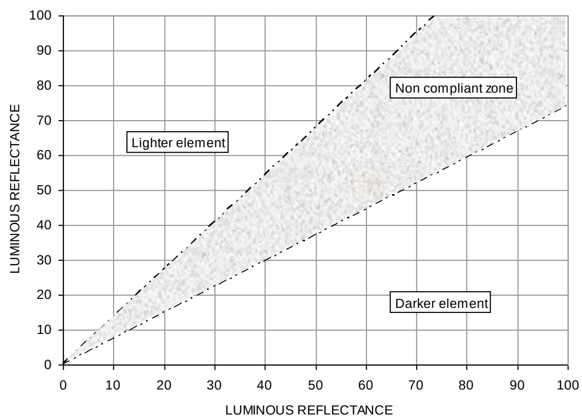


Figure 3: Maximum and minimum limits of luminance reflectance values of adjacent surfaces that can comply with AS 1428.1-2001.

Similarly, the luminance reflectance value (*Y)* that the UK standard has recently adopted has been used in the Australian equation for luminance contrast since 2001. The luminance reflectance value (*Y*) takes into account the light source (illuminant), the observer as well as the surface. In contrast, light reflectance (*L**) only measures the physical nature of a surface. Therefore, luminance reflectance (Y) should be the most appropriate quantity for use in luminance contrast formulae for it is a measure of what the human eye actually perceives.

Finally, the Australian equation for luminance contrast is mathematically different from the UK equation for it is intrinsically a ratio, where the denominator is the average of the luminance value of the two surfaces. It results in a non-compliance zone that is less accepting of two light surfaces than two dark surfaces. Consequently, two dark surfaces such as black and navy, readily pass the Australian standard but rightfully fail the UK and US standards. This is a shortcoming of the Bowman equation.

Experimental Aim

The experimental aim of this study was to develop a scientific procedure that quantifies how the human eye perceives differences in adjacent matt colours. Once developed, this procedure was to be used to recommend the national standard which best represents how the human eye differentiates between these adjacent matt surfaces. Finally, the author (Sapolinski) was intent on developing an improved metric for luminance contrast that compensates for the current shortcomings of each national standard.

Materials and Methods

As a clinical study that can be replicated by any member of the scientific community, the methodology of this project directly followed the ETDRS protocol of the National Eye Institute, USA, for visual acuity tests as outlined in the resolution adopted by the International Council of Ophthalmology [1]. Full-sized ETDRS eye charts were designed that are the "gold standard" for clinical visual acuity tests. This study was approved by the institutional review board.

Choosing Colour Combinations

For the original 40 eye charts, 19 colour combinations were chosen with a mix of high (6), medium (7) and low (6) luminance contrast between font and background colours. An extra chart was chosen for each contrast level that was the reverse or negative of one of the charts. For instance, the high contrast group had both yellow optotypes (font) on a black background and black optotypes on a yellow background. The combination of colours were chosen to rep rep represent sporting teams, major companies and common road signs (Figure 4).

Figure 4: The colour combinations of some eye charts were chosen to represent common road signs from around the world.

In conjunction with this total of 22 coloured eye charts, 12 charts were greyscale with similar luminance contrast to their coloured partners. The remaining 6 eye charts were conventional black optotypes on a white background that were used as the control. These control charts were equally distributed amongst the 40 charts to ensure that consistency of results were maintained and factors such as eye fatigue could be monitored and rest periods provided if a subject's visual acuity results dropped significantly.

A further 8 eye charts were produced after initial results demonstrated major discrepancies between visual acuity results for one particular low contrast chart, Chart 33, and the current national equations for luminance contrast. The black on navy eye chart (Figure 5) passed the minimum luminance contrast 30% for the Australian Bowman equation, however subjects found it virtually impossible to physically differentiate between the two dark colours.

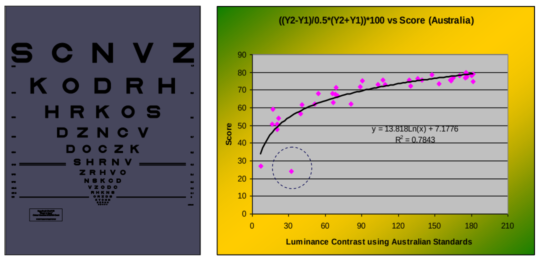


Figure 5: Chart 33 with its black optotypes on a navy background was the outlier, circled above. Extra charts in this dark on dark region were produced to refine the luminance contrast equation.

As this was the only low contrast chart in this dark on dark region, the author decided to print off six more dark on dark colour and greyscale combinations to further explore how the human eye perceives differences in matt surfaces, especially in this dark on dark region. The other two eye charts were produced for a secondary experiment, to find the best colour combinations for road signage.

Designing "Gold Standard" Clinical Eye Charts

Historically, visual acuity was measured with the Snellen Eye chart developed in 1862 [1]. Snellen used a pragmatic sequence of letter sizes with varying sized steps between each row. He varied the letter spacing and the number of letters per line according to the available space. The Snellen design, persisted for clinical use until 1976. It was superseded by the Bailey and Lovie proportional layout, with the following essential features: letter spacing is equal to the letter or optotype width; the line spacing is equal to the height of the lower line, combined with a logarithmic progression. In a personal communication with one of the Australian developers of the Bailey-Lovie chart [14], Jan Lovie-Kitchin explained that the top row of a full-sized eye chart has an overall height of 87.3mm. Subsequent rows are reduced by a factor of $10^{0.1}$.

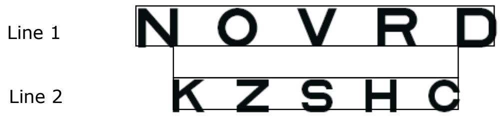


Figure 6: The geometric layout of each eye chart is characterised by even spacing between letters and subsequent rows.

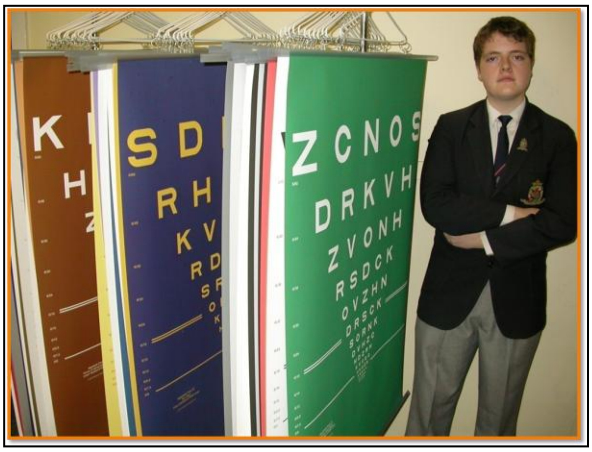


Figure 7: The final 48 full-sized colour-modified clinical ETDRS eye charts, designed and produced by the author.

The charts are referred to as LogMAR charts. Characterised by 5 optotypes or letters in each row, the Bailey and Lovie proportional layout was subsequently adopted for the ETDRS charts of the National Eye Institute in 1982, however they altered the style of font from British to Sloan letters, designed by Louise Sloan in 1959 [15]. The ETDRS charts only use 10 optotypes: N, Z, D, R, V, S, H, O, C, K and these ten letters are randomly arranged, appearing once every two lines. Using a random number generator, each of the author's 48 colour-modified ETDRS "gold standard" clinical eye charts had a unique sequence of optotypes.

Printing Eye Charts

Each of the 48 A0-sized eye charts was professionally printed on the same digital printer at University Publishing Service, Sydney. Print time for each chart was one hour, resulting in an even colour spread without streaking or lines. To ensure colour correctness for the digital printing process, a huge colour swatch was initially designed by the author. For each Pantone colour selected for a particular eye chart, the colour swatch included 10 extra shades that were similar in lightness, chroma and hue. This colour swatch was then printed in A0 with the same paper and printer that the final eye charts were to be printed on. Using the printed A0 colour swatch, the final colours were chosen for each eye chart with full awareness of the final outcome.

Each eye chart was printed on 200gsm matte paper with a tear-free laminated surface on the back. The charts were then suspended from a hanging rack using clear banner rails. The 48 charts were stored in consecutive order on the hanging rack and during experimentation each successive chart was moved to the back after reading.

Measuring Visual Acuity Protocol

Subjects were positioned precisely 6m away from the leading eye chart and the eye chart illumination was 500lux, in accordance with the optimum illuminance of 480lux as outlined in the British Standard BS4274 [16]. With both eyes uncovered, subjects were directed to read down each chart as far as possible or to when 3 or more mistakes were made on the one line. To minimise eye fatigue, subjects were given opportunity to rest their eyes between charts.

To prevent inconsistencies, every eighth chart was a black on white control chart which was identical to the other control charts with the exception of their sequence of optotypes. As well as recording the correctness of each eye chart, the scorer compared the visual acuity results of each control chart with previous controls to ensure consistency of results. Subjects were also started at different eye charts to prevent the problem of the same first charts being poorly attempted as the subject "warms up" to the procedure.

Data Analysis

An original logarithmic visual acuity scoring system was established by the author (Sapolinski). The ETDRS protocol of the National Eye Institute [1] specifies a letter count scoring system. For instance, if a subject could read a chart to the 2nd optotype on the 9th line, they would obtain a visual acuity score of 42 (8 lines of 5 optotypes + 2 optotypes on the 9th line). This was deemed over-simplistic by the author for the difference between a score of 40 and 41 is much more significant than the difference between 39 and 40 as the initial difference involves an optotype on the next line down which was harder to read.

In contrast, the logarithmic scoring system developed for this study complemented the geometric layout of the eye charts. 1 point was received for each of the five optotypes on the first row, $10^{0.1}$ (1.2589) points were scored for each optotype on the second row, $10^{0.2}$ (1.5849) points for the third row and so on until the final 14th row scored $10^{1.3}$ (19.9526) points for each optotype correctly identified. These scores were tallied on a Microsoft Excel spreadsheet and the final score for each chart was adjusted to a visual acuity score out of 100.

Results

Subject Data

The mean age of the 80 subjects (25 female, 55 male) was 27.2 years (range: 6-74 years). 66 subjects were classified as normal vision while 14 subjects had some form of vision impairment. Of these 14 subjects, 13 had differing degrees of colour deficiency, identified by the Ishihara Colour Vision Test [17], while the remaining vision impaired subject had macular degeneration. Of the 66 normal vision subjects, 21 wore glasses (8 long-sighted, 13 short-sighted) and 45 didn't, however, 7 of these subjects had minor vision problems such as stigmatisms or lazy eyes. Presently, no analysis between these vision sub-categories has been made in this study.

All 80 subjects (66 normal vision, 14 vision impaired), were tested with the original 40 colour-modified clinical eye charts. 47 of these original subjects (36 normal vision, 11 vision impaired) were tested with a further 8 eye charts that were dominantly dark fonts on dark backgrounds. Before testing with these extra charts, each subject was tested on 4 of the original charts to ensure reproducibility of results. Small adjustments to seating position had to be made to a small number of subjects whose results were inconsistent to earlier measurements.

Visual Acuity Data

The mean visual acuity score for the 48 eye charts was 54.97, out of a maximum 100 for the 14 vision impaired subjects and 68.69 for the 66 normal vision subjects. In comparison, the average score for the six conventional black font on white background control charts was 68.10, $\sigma = 2.39$ (vision impaired) and 78.58, $\sigma = 0.99$ (normal vision). The smaller sample space and the greater diversity of the vision impaired group accounted for this greater uncertainty. These standard deviation uncertainty measurements for visual acuity scores are represented by the vertical error bars in Figures 8-13.

Luminosity Measurements

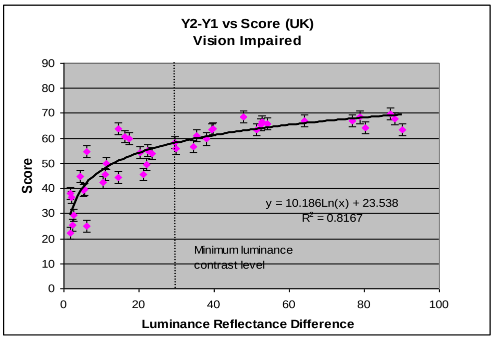
An X-Rite 530 spectrophotometer (on loan from DES) was used to record the light reflectance values (L*) and the luminance reflectance values (Y) of the font and background colours of each eye chart. Five measurements were taken and averaged for each surface. For the six control charts, the black optotypes had a mean luminance reflectance of 5.64, $\sigma = 0.68$, while the white backgrounds averaged at 94.52, $\sigma = 0.48$. The resulting mean of these uncertainty measurements for the spectrophotometer results ($\sigma = 0.58$) has been represented by the width of the data points in Figures 8-13, 19 and 20.

National Standards

A definite correlation was evident between the visual acuity score recorded for each eye chart and the respective luminance contrast for the two surfaces involved. Although some individual results fluctuated, especially for subjects who are sensitive to bright light, the combined results demonstrated a very close correlation between variables. The purpose of the graphs was not to come up with an equation linking visual acuity and luminance contrast, but to find a line (curved or linear) of best fit that had the optimum correlation of points. The shape of each resulting graph was logarithmic as a direct result of the logarithmic scale used in both the visual acuity scoring system and the geometrically proportional eye-charts.

Each ISO-recognised luminance contrast equation was tested with the visual acuity data and the root-mean-square correlation value was determined. For each national standard, the minimum luminance contrast level for compliance was indicated by a vertical line in Figures 8-13, 19 and 20.

For the equation used in the British Standard [2], BS 8493:2008, root-mean-square values of 0.8167 (vision impaired) and 0.7755 (normal vision) were obtained, see Figures 8 and 9.



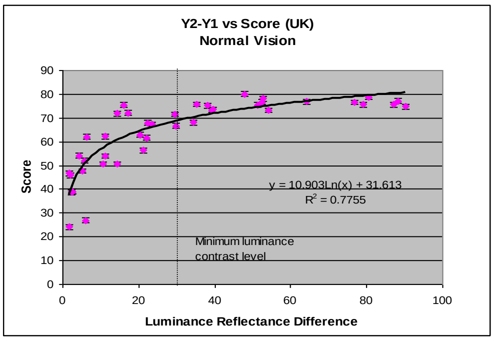
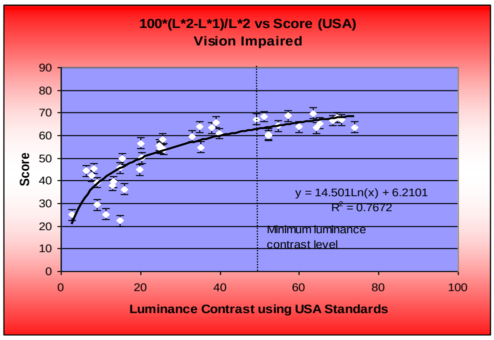


Figure 8 and 9: Correlation between visual acuity scores and luminance contrast values, as measured with British Standard, BS 8493:2008

For the equation in the US Standard [3], A117.1-2008, root-mean-square values of 0.7672 (vision impaired) and 0.7659 (normal vision) were obtained (Figures 10 and 11).



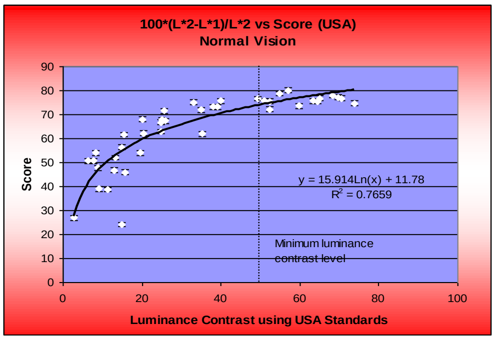
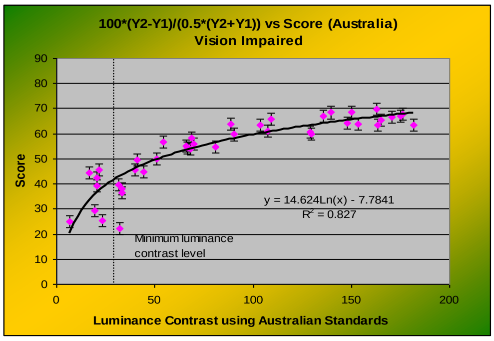


Figure 10 and 11: Correlation between visual acuity scores and luminance contrast values, as measured with US Standard, A117.1-2008.

For the Bowman equation used in the Australian Standard, AS 1428.1-2001 [4], root-mean-square values of 0.8270 (vision impaired) and 0.8227 (normal vision) were obtained, see Figures 12 and 13.



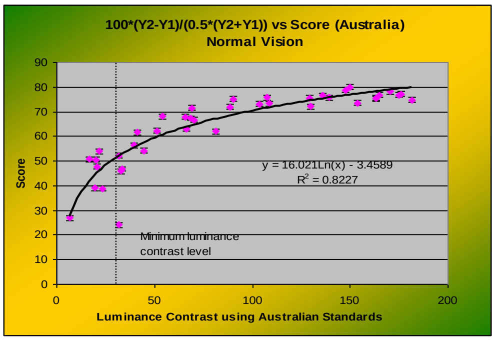


Figure 12 and 13: Correlation between visual acuity scores and luminance contrast values, as measured with Australian Standard, A1428.1-2008.

Discussion

Comparing National Standards

Overall, for the wide spectrum of colour combinations, the Australian Bowman equation for luminance contrast was most representative of how the human eye differentiates between adjacent matt surfaces, for its correlation values (0.8270 and 0.8227) were closest to the perfect 1.000. These correlation values were further improved when data from the dark on dark eye charts were ignored; 0.9238 (vision impaired) and 0.9209 (normal vision). Meanwhile the respective correlation values for the UK standard decreased to 0.6869 and 0.6380 and increased to 0.9047 and 0.8990 for the US standard, with data from the 7 dark on dark charts removed.

Its ability to comply to minimum luminance contrast levels also favourably supports the Australian Bowman equation. Considering only the vision impaired results in Figures 8, 10 and 12, 7 out of the 48 eye charts failed to comply to the Australian minimum luminance contrast level as opposed to 22/48 (UK) and 27/48 (US). Line 11 of the ETDRS eye chart is usually used as the reference point for normal vision. People who can successfully read Line 11 are said to have "20/20 vision" [1]. Using the logarithmic visual acuity scoring system developed for this study, "20/20 vision" corresponds to a score of 49. Meanwhile, scores of 62, 79 and 100 were achieved for successful completion of Lines 12, 13 and 14 respectively. Although 20/20 vision is not perfect vision and most people can read beyond this line [1], it is useful as a reference point for comparing the different national standards for luminance contrast. Therefore, for the purposes of comparison, a visual acuity score above 49 constitutes an eye chart with a satisfactory level of luminance contrast

For Figure 8, nine of the charts with scores greater than 49, failed to meet the minimum UK standards. All of the charts that did meet the standard had scores well above the 20/20 reference point. In summary, the UK's minimum level of 30 is too high, for those nine charts with a satisfactory level of luminance contrast do not meet the minimum standard level. For Figure 10, thirteen charts with scores in excess of 49 failed to meet the US' minimum level of 50, demonstrating that this minimum compliance level is also too high. Finally, for Figure 12, only three of the charts with scores greater than 49, failed to meet the minimum Australian level of 30. However, three charts that did pass should not have, indicating that the Australian minimum compliance level is more accurate, although it may be slightly too low.

This comparison of national standard compliance levels is effectively demonstrated in the varying non-compliant zones for building products in Figures 1-3. Building products have to be basically black and yellow to pass the US minimum standards, while more flexibility is provided for Australian and to a lesser extent, UK building suppliers.

Bowman-Sapolinski Equation - Background

Despite the Australian Bowman equation being the preferred national equation for luminance contrast, it does possess limitations with two adjacent dark surfaces. The UK equation is the preferred equation in this area, however its simplistic nature, causes limitations in other areas, such as two adjacent light surfaces. The UK equation states that the luminance contrast between two light colours, for instance, LRV's of 70 and 90 is equivalent to the luminance contrast between two dark surfaces, such as LRV's of 10 and 30. Experimental data collected in this study, clearly prove that the human eye can differentiate two dark colours better than two light colours as this example demonstrates. Consider three eye charts with low contrast (see Figure 14).

Chart 9	Chart 19	Chart 28
LRV Font = 84.5	LRV Font = 79.5	LRV Font = 4.5
LRV Back = 90.5	LRV Back = 93.5	LRV Back=10.5
Difference = 6	Difference = 14	Difference = 6

Figure 14: LRV values and luminance contrast of three eye charts.

According to the UK equation, Charts 9 and 28 should have similar luminance contrast, however, vision impaired experimental visual acuity scores are 25.02 and 54.85 respectively. Even Chart 19, which should have a much higher luminance contrast, has a visual acuity score of 44.46, which is still well below Chart 28. Examples such as this can be repeated over and over.

Bowman-Sapolinski Equation - A Compromise

Due to the human eye differentiating dark colours better than light colours, the general shape of the compliance graph should be divergent towards light surfaces, as in Figure 3, rather than parallel as in Figure 2. However, as explained earlier for two dark surfaces, Figure 2 is more representative of human vision than Figure 3. In order to satisfy both conditions, the authors constructed a compromise graph, shown in Figure 15.

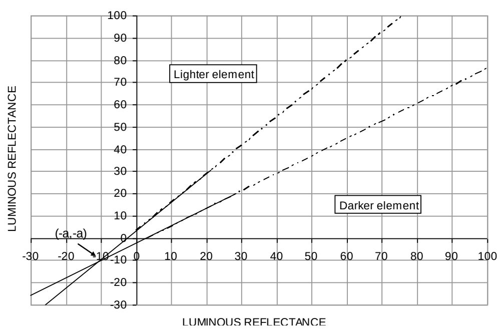


Figure 15: Demonstrating how the vanishing point (-a,-a) originated.

In Figure 15, both the maximum and minimum compliance lines meet at a vanishing point, beyond the origin, at an arbitrary point with coordinates (-a,-a). The equation of this compromise graph is given in Figure 16.

$$\text{Luminance Contrast} = (1 + 2a)\frac{|Y_2 - Y_1|}{(Y_1 + Y_2 + 2a)}$$

Figure 16: Single equation that is derived from the Bowman and UK equation, containing a single parameter, *a*.

As the ordinate a approaches 0, the graph $\rightarrow \frac{|Y_2 - Y_1|}{Y_1 + Y_2}$ tends towards the Bowman equation.

As the ordinate a approaches ∞, the graph $\rightarrow |Y_2 - Y_1|$ tends towards the UK equation.

Visual acuity results were then used to optimise the parameter, resulting in an equation with the highest correlation value between visual acuity scores and luminance reflectance values. The optimum correlation value occurred when the parameter a = 12.5. For this parameter the equation became:

$$\text{Luminance Contrast} = (1 + 25)\frac{|Y_2 - Y_1|}{(Y_1 + Y_2 + 25)}$$

Further modifications had to be performed to give the luminance contrast a range between 0 and 200, which was the range of the Bowman equation. As it stands, the range of this above equation was 0 to 20.8 so it had to multiplied by a factor of 200/20.8 to obtain the desired range. This resulted in a leading term of 250, producing a very neat luminance contrast equation. With approval and verification by the Australian Standards' Access for People with Disabilities Committee [5], this equation has been adopted into the AS 1428 suite of standards as the official equation for luminance contrast. Now known as the Bowman-Sapolinski equation, see Figure 17, it has to be complied with in every new public building in Australia.

$$\text{Luminance Contrast} = \frac{250|Y_2 - Y_1|}{(Y_1 + Y_2 + 25)}$$

Figure 17: The Bowman-Sapolinski equation: new and improved Australian equation for luminance contrast.

The compliance graph is shown below in Figure 18.

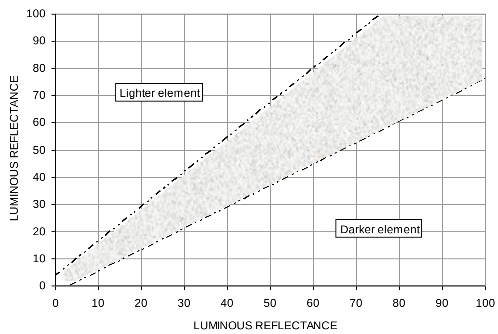
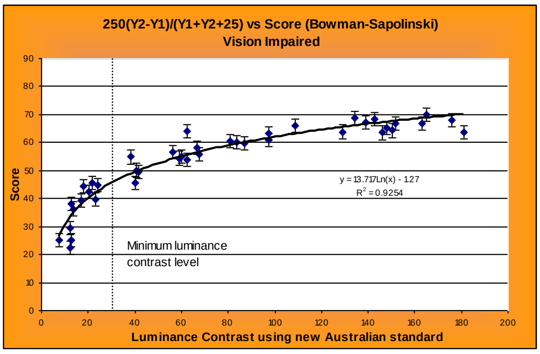


Figure 18: Maximum and minimum limits of Bowman-Sapolinski equation, exhibiting features of both the Bowman and UK equations.

Bowman-Sapolinski Equation - Comparison with other national standards.

The Bowman-Sapolinski luminance contrast equation was tested with the visual acuity data obtained from the 80 subjects and 48 colour-modified clinical eye charts and the root-mean-square correlation values were determined. The correlation values of 0.9254 (vision impaired) and 0.9122 (normal vision), see Figure 19 and 20, were significantly higher than the original Bowman equation values of 0.8270 and 0.8227 and subsequently were much higher than the UK and US national standard equations.



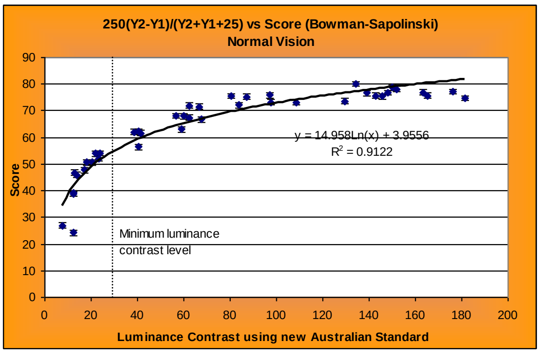


Figure 19 and 20: Correlation between visual acuity scores and luminance contrast values, as measured with Bowman-Sapolinski equation from the new Australian Standard, A1428.1-2009 [5].

The increased ability to comply with minimum luminance contrast levels now favourably supports the Bowman-Sapolinski equation. For the vision impaired data in Figure 19, there were no charts with scores greater than 49 that failed to meet the minimum Australian standards. However, one of the charts that did meet the standard had a score below the 20/20 reference point. Compared to the three ISO-recognised national equations for luminance contrast, the Bowman-Sapolinski equation is therefore much more consistent when dealing with adjacent surfaces with luminance contrast values around the minimum level region. In summary, Australia's minimum level of 30 is quite satisfactory, however, 40 would be the preferred option based on the experimental data displayed in Figure 19. More work needs to be done with subjects who have a higher level of vision loss to quantifiably determine the ideal minimum luminance contrast level for the Bowman-Sapolinski equation.

Conclusion

Overall, for the wide spectrum of colour combinations, the Australian Bowman equation for luminance contrast was most representative of the three ISO-recognised national standards, of how the human eye differentiates between adjacent matt surfaces, for its correlation values were closest to the perfect 1.000. Through the construction of a single equation with a parameter that could be optomised using visual acuity results, the Bowman-Sapolinski equation negates the dark on dark shortcomings of the Bowman equation. Subsequently, the Bowman-Sapolinski equation has been adopted as the new equation for luminance contrast in the Standards Australia: Design for Access and Mobility (1428.1-2009) [5] and the authors recommend that the Bowman-Sapolinski equation should also be adopted as the inaugural international standard for luminance contrast.

Disclosure of Conflict of Interests

The authors state that they have no conflict of interest.

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