The effect of age on white light perception

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Abstract

The way that persons from different age groups experience "white light" is investigated. Human eye lens transmission changes spectrally with age and this may influence the way that humans from different ages experiences light. Such a difference may be important in industrial and medical environments. Two different age groups, one group younger than 40 years of age and another group older than 50 years of age were subjected to the same "white" definition task. A conventional single-booth setup was used where observers were able to adjust the intensity of four coloured LED's. Results of the psychophysical test procedure were used to generate specifications of two light sources, as selected by the two age groups. The two age groups selected different light sources when tasked to achieve a "perception" of white. Results show that the older group prefers a source with a colour rendering index number of 89 and the younger group prefers a source with a colour rendering index number of 74. The sources selected by the two age groups specify correlated colour temperature values of 5150 K for the older age group and 6592 K for the younger group.

Keywords: age, colour rendering, CCT, LED, white perception

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1. Introduction

The designer/engineer working in the field of illumination is responsible to specify/design an optimum solution for a specific application. Modern light sources affords the illumination designer the opportunity and ability to control some basic illuminant parameters such as correlated colour temperature (CCT), colour rendering (R_a), light levels (Lux) and angle of illumination, to name a few. Other parameters are not that readily visible but equally important. This includes light source efficiency. Indeed, Albu et al. [1] investigated luminous and power quality measurements of different office building light sources. Their results show that LED luminaires offer a luminous efficacy advantage over other types of luminaires but also points out that poor power quality management effects LED luminaire performance negatively. They also mention that many electronic equipment power quality problems originate with low power factor as well as harmonics and unbalance in three-phase four-wire systems. Lastly, the illumination designer should pay attention to the way humans interacts with light sources. Humans will overwhelmingly choose to work or sit next to a window with an outside view, when given a choice. [2] Humans thus prefer natural light (or daylight) rather than artificial light. The research field of human-centric lighting is rapidly expanding. Conceptual investigations suggest that the application of human-centric lighting may improve productivity of people in different age groups. [12], [4], [35]. The designer of artificial light sources should thus take human preferences and perceptions into consideration. It may also assist healing in general, and may reduce depression and dementia. This report forms part of a study which investigates human perception regarding colour and light. The study was divided in three parts:

- How two different age groups perceive "white light".
- Colour perception of two age groups, incorporating an alternative method where side-bias is excluded.
- Repeatability of colour matching light tasks using two different age groups.

Only the first investigation is included in this report.

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2. Human factors

2.1 Age related change in colour perception

Senior people (people older than 60) form a substantial part not only of the national population but indeed also the working population. It is estimated that the number of senior citizens in the USA was about 40 million by 2013[7]. Spectral transmission of the human crystalline lens changes with age because the lens optical density changes with age [28]. Less visible light is transmitted over the entire visible spectrum but is more severe at shorter wavelengths. Human lens transmission at shorter wavelengths decreases more than at longer wavelengths and this causes the lens to appear yellower. What are the changes within the crystalline lens which contribute to transmission changes with age? Augusteyn [5] states that the crystalline lens is unique and differs from other bodily tissues especially in the way it changes as a person grows older. The reason for that is that the lens grows continuously through life by adding new cells inside the envelope that surrounds the tissue. Old cells are positioned in and near the organ centre and are not removed, dissolved and destroyed as is usually the case for used cells to be discarded. Mechanisms involved in this process are lens dimensions (both diameter and thickness increases with age) and compaction. The process of compaction consists of internal parameters which changes with age. These include fibre cell dimensions, lens gradiants, water content and lens hardening. Augusteyn mentions the fact that measurement results on some of these parameters are not always consistent and the exact contribution of each of these mechanisms can thus not be clearly defined. Lens hardening and stiffening is a major contributor and is considered to be responsible for increase in presbyopia. Stiffness increase in the complete lens system was measured to increase by 1000 times from an age of 30 to an age of 50. Stiffness on the centerline was measured to increase by 10000 times during the same period. Artigas et al. [3] measured the spectral decrease in transmission of two age groups. One age group consisted of people from 40 to 59 years of age while the second group consisted of people older than 60 years of age. Transmission reduction was measured at five wavelengths and the reduction was calculated as a relative percentage. Reductions measured from 40 % loss at 420 nm (blue) to 18 % at 580 nm (yellow).

2.2 Illuminance levels

The CIBSE Lighting Guide 7: Lighting for Offices and CIBSE Code for Interior Lighting 1994 lists recommendations regarding illuminance levels. According to this code, general office desk work areas should be illuminated at a lighting level of at least 500 lux. Computer station areas should be illuminated at levels ranging from 300 to 500 lux. An open-plan work area is recommended to feature light levels of at least 750 lux. [19]

Moore et al. [20] investigated the validity of specified levels of illumination to determine whether these light levels were realistic. They published results that showed that most office workers (desk and workstation areas) prefer to work in an area where light levels range from 100 to 300 lux. About 25 % of workers prefer the range from 300 to 500 lux and another 20 % prefer to work in an area illuminated at a level of less than 100 lux. These results are unexpected as the light levels are lower than those suggested by Health and Safety recommendations.

A comprehensive industrial, workspace and office illumination study was completed by Van Bommel et al [35]. This study used the EN 12 464-1 standard as guide in the evaluation of illuminance levels. (EN 12 464-1 Light and Lighting- Lighting of work places. Part 1: Indoor work places.) Illumination levels are similar to those published by Moore et al [20] except that more detail is added regarding specific tasks. EN 12 464-1 specifies an illumination level 100 lux for the colour inspection industry. Considering studies by Moore and Van Bommel, a reference and test illumination level is thus specified for the experiments described in this report of between 120 and 160 lux.

An additional aspect (which is not investigated in this report) is the effect of illuminance levels on human behaviour. McCloughlan et al [18] completed a study investigating the impact of illuminance levels on the psychological mood of humans. They found that lower light levels (280 lux) are more likely to induce positive behaviour than high light levels (770 lux). Very high light levels (1500 lux) were responsible for inducing negative behaviour. The study also showed that very big differences in perception can be found between individuals and that differences also exist between sexes. Source correlated colour temperature also plays a part and it was found that negative mood experienced by women tend to decrease under illumination of a warmer source (2950 K). In contrast, men experiencing negative moods needed a cool lamp (4000 K) to enhance their moods. Experiments were completed using lamps with high CRI numbers.

3. Test layout and methodology

3.1 Test booth configuration

A conventional single-booth test setup was used for "white perception" evaluation studies. The use of test booths as a research tool that allows light and vision parameters to be evaluated is well documented. Various designs have been used for test set-ups in single, double and triple format. This study used a single booth configuration similar to that used by Ohno et al. [23] and Rea et al [29]. Test booths are often constructed in cubicle form which may vary in size from 380 mm to 660 mm cubes [21], [10], [14], and [36]. The single-booth design is shown in Figure 1.

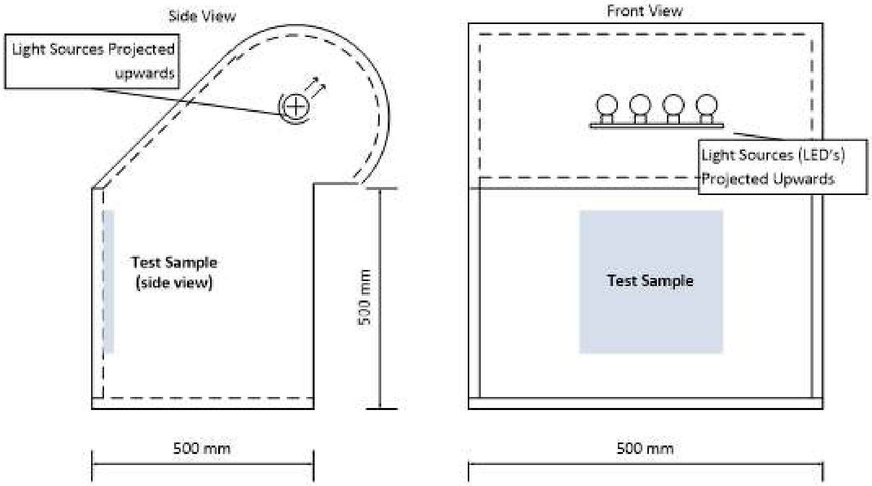

Figure 1. Single test booth layout schematic diagram.

Similar to this study, the observer is positioned in front of the double or single booth and the viewing distance is selected to ensure a particular field of view (FOV). A number of researchers chose booth dimensions and viewing distances such that a FOV of around 40° is achieved [21], [10], [14], and [36]. The light sources are positioned towards the roof to ensure even light distribution on the test sample. The inside surface of the booth is covered with white paint which was measured to feature a reflectivity of 90 % or higher from 420 nm to 800 nm. It is necessary to ensure that reflectivity is spectrally constant and that surface characteristics remains unchanged for all measurements. The reflectivity graph is shown in Figure 2.

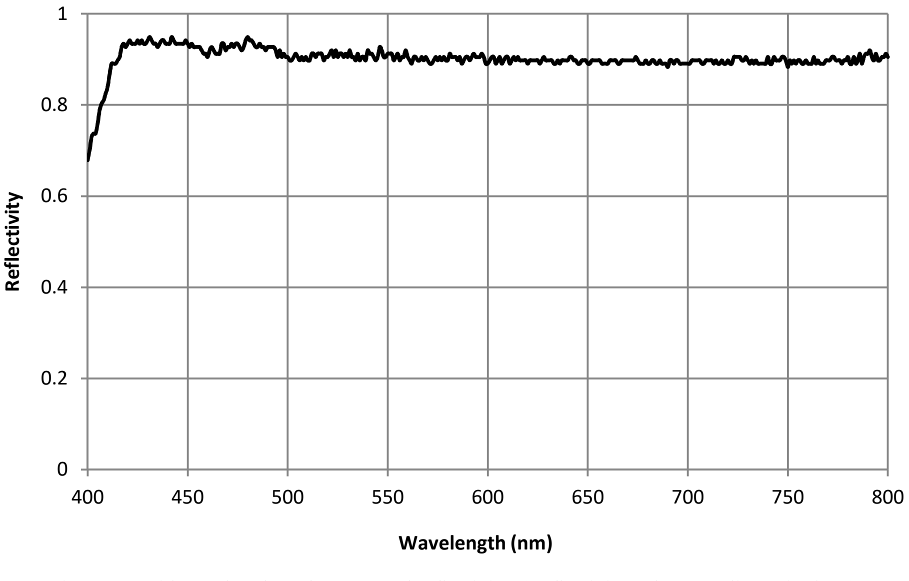

Figure 2. Inside test booth surface spectral reflectivity. (Reflectivity values are dimensionless.)

3.2 Evaluation objects

The CIE developed specific test samples in the form of coloured charts to be used in the evaluation of colour perception. Unfortunately, the original products have been unavailable for a number of years. For this reason the CIE Technical Committee 1-33 recommended that the Macbeth Color Checker (MCC) be used for visual experiments [17]. For the purpose of this test, an X-Rite Classic Color Checker was used. Figure 3 shows a photo of the MCC mounted in the test booth and illuminated by the test source.

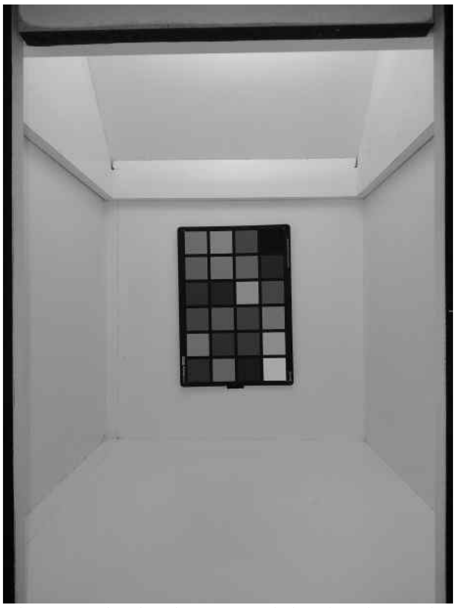

Figure 3. Test booth, as seen by the observer, and showing the Macbeth Color Checker.

3.3 Light source

Many colours can be realized by using only three LED's. (The familiar RGB scenario.) It is also true that an RGB light source will draw a triangle on the CIE chromaticity diagram and this triangle will exclude many other colours. An increase in LED source colours will expand the number of colours that can be "mixed" by the observer. In an effort to smooth the LED spectral power distribution (SPD), Schanda et al [31] constructed luminaires which contained 20 LED sources each. The luminaire clusters consisted of 17 narrow-band LED sources with different wavelengths as well as three white LED sources, which were actually phosphor-covered converting blue LED's. The peak emission wavelengths covered were 414, 424, 448, 465, 466, 504, 527, 533, 590, 592, 596, 624, 632, 636, 638, 658, 667 and 691 nm. A computer-controlled algorithm was used to adjust the brightness of each source in 256 steps. Spacing of LED source wavelengths are not even, with the peak wavelengths of some sources differing by 5 nm or less.

Because humans from different backgrounds are used for psychometric testing, the testing procedure should be simple and not consume too much time. It is obvious that more LED sources will need more adjustment time. In our tests, observers were allowed a 10 minute window to get used to the light environment. This was followed by a 5 minute training session. Observers then took 10 – 20 minutes to complete the test procedure. (No time limit was enforced, observers could use as much time as they required.) The number of LED sources used can thus extend the test procedure to such a long time that it becomes impractical as each LED sources is adjusted separately. (It is our view that the complete test procedure should not extend beyond 30 minutes.)

The question is thus: what number of LED sources will yield satisfactory results with the procedure not taking too long?

Zukauskas and Vaicekauskas [37] describe optimization methods for the optimum LED source combination for the construction of a tetrachromatic source. They suggest four coloured LED's with peak wavelengths in the following sectors: 410 – 490 nm, 490 – 540 nm, 540 – 610 nm and 610 – 680 nm.

Table 1 shows the final selection of wavelengths together with our selection.

Table 1: Selection of LED wavelengths for tetra chromatic light source.

LED source colour	**Zukauskas & Vaicekauskas** (Zukauskas A, 2011)	**Our selection of wavelengths.**
Blue	452 nm	455 nm
Green	523 nm	528 nm
Yellow	589 nm	590 nm
Red	637 nm	657 nm

LED's were selected to cover the photometric spectral region evenly and to have a wide field of transmission for this application (120° inclusive angle minimum).

Another factor to consider is the sensitivity of human eye cones to the three basic colours. Figure 4 shows the human eye cone response for red, green and blue. The cone responses are overlaid with the four LED source wavelengths as used in this study.

When using human observers, the best results can be expected if a LED source wavelength is closest to the peak sensitivity value of a cone. This is achieved in all cases except for the red LED at 657 nm. The orange/yellow LED at 590 nm is thus valuable as it covers the near-peak of red.

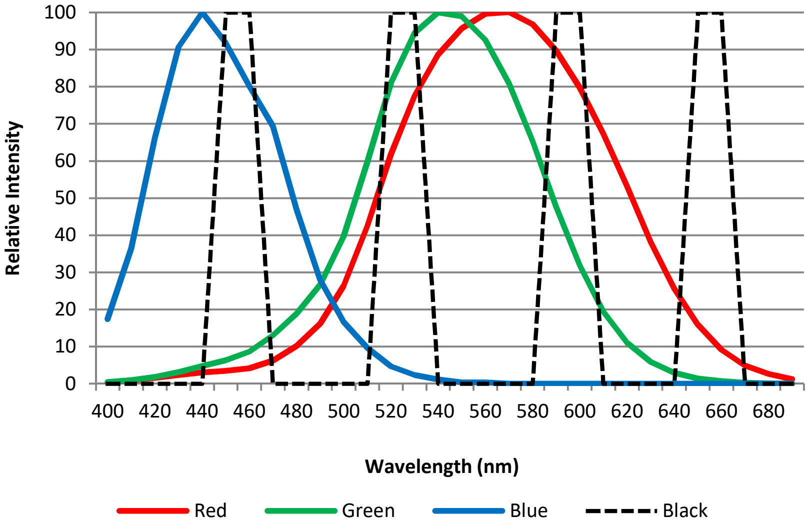

Figure 4: Eye response curves for red, green and blue.The black dotted line shows the wavelength areas covered by the tetrachromatic source in this study. These curves do not show relative cone sensitivity but rather spectral areas where cone colour sensitivity reside. (Colour cone curves were calculated using the procedure as described by DJ Heeger.[13])

To ensure stability of light output, the LEDs were mounted on heat sinks as prescribed by the manufacturer [25]. (Heat sink temperature was measured.) The manufacturer provides data regarding the stability of light output over time. The data shows that a change in LED light output can be expected from 20 000 hours of usage and beyond [26]. LEDs used in this evaluation were switched on for about 20 to 30 minutes at a time (for each psychophysical evaluation, which included a stabilization time of 10 minutes.) Total on-time (all psychophysical evaluations included) was calculated to be 25 hours. It is not expected that light output/wavelength shift will make a measurable difference within the time period of evaluation. LED light output stability also depends on the current used relative to the maximum specified drive current for the LED. Continuous high currents affect the time that an LED can deliver stable light output negatively. During this study, peak currents never exceeded 50% of the specified maximum current. Because observer groups are tested concurrently, any possible degradation in LED performance will affect both groups in the same way and no group will thus be at an advantage/disadvantage. LED intensity and wavelength characteristics were measured before and after the test.

3.4 Observers

For this study, people with significant visual impairment, color vision impairment and persons younger than 16 years of age were excluded. Color vision impairment was established using an Ishihara screening test and general visual impairment statistics as published by Chader [7] were used.

Israel states, however, that the sample sizes of similar studies should also be considered to provide guidance regarding number of observers [11]. Some similar psychophysical studies which can be compared are those of Schefrin and Werner (sample=30) [32], Elliot et al (sample = 30) [9], Narendran and Deng (sample = 20) [21], Sandor and Schanda (sample=10) [30], Spaulding et al (sample=25) [33], Thompson et al (sample=10) [34], Wei et al (sample=48) [36], Fotios and Cheal (sample=21) [10] and Houser et al (sample=40) [14]. The number of observers who participated in this study is 33. Two groups of observers were used. The first group consisted of people 40 years old and younger. (14 people, mean age 28,8, and standard deviation 6,8) The second group consisted of people 50 years and older. (19 people, mean age 57,8 and standard deviation 4,8)

Observers were divided into two age groups. It is desirable to use observers spanning the complete human living range of age. This is logistically difficult and may be one of the reasons why many researchers in the field predominantly use younger adults as observers. Some of these are Wei et al [36], Houser et al [14] and Rea et al [29]. When older observers are included a number of researchers used a younger group with a mean age of 20-25 years and an older group with a mean age of 55-75 years of age. Some of these researchers are Dangol et al [8], Islam et al [16], Elliot et al [9] and Schefrin and Werner [32].

Only persons who achieved 100% in the Ishihara screening test were used as observers. The number of persons subjected to the Ishihara test was thus more than 33.

The observers used are employed in a high-technology company and most are experienced in the fields of electro-optics, radiometry and basic photometry. They had little or no knowledge about the study field of colour spaces, colour rendering and colour perception. (When shown a 1931 CIE chromaticity diagram, most observers recognized the figure but could not explain it. All observers were unfamiliar with the name “Munsell”)

3.5 Method

All observers were subjected to an Ishihara coloured plate screening test in order to ensure basic colour differentiation ability.

Observers were then informed about the procedure and applicable safety aspects. All participants signed a consent form. The research was approved by the Faculty Committee for Research Ethics and Integrity of the Faculty of Engineering, Built Environment and Information Technology of the University of Pretoria.

The tetrachromatic source was allowed to stabilize for 10 minutes prior to commencement. The observer looked at the Macbeth Color Checker (MCC), which was illuminated with the composite LED test source. The MCC consists of 24 colored blocks. (As shown in Figure 3)

The test procedure is as follows:

(a) Source LED’s are switched on and set at minimum currents of 20mA each.

(b) The room is darkened and the observer is allowed 10 minutes to adjust to the visual environment. The illuminance level in the dark room is between 1 and 1,2 lux.

(c) The test commences with the observer looking into the test chamber.
The X-Rite Macbeth Color Checker (MCC) is mounted vertically against the test chamber wall.
The observer considers only the white block on the MCC.

(d) The observer adjusts the currents through the four coloured LED sources inside the test booth until the white block is perceived to be “white”. The observer thus adjusts the four LED sources (red, green, blue, yellow-orange) until the reflection from the MCC white block is considered to be “white” by the specific observer. The observer may re-adjust LED source currents as many times as required. No time limit is enforced.

(e) The facilitator notes the test source inputs and measures the following:
   i. Light level (lux) as measured at the MCC,
   ii. Forward current through LED tetrachromatic test source.

(f) The researcher mounts the tetrachromatic LED source in an integrating sphere as shown in Figure 5. The test method used for the measurement of photometric as well as electrical characteristics is based on the “Approved Method: Electrical and Photometric Measurements of Solid-State Lighting Products” by the

Illuminating Engineering Society (IES) (Illuminating Engineering Society 2008). The IES method (paragraph 9.1, page 4) prescribes the use of a single integrating sphere and an internal baffle is used to screen direct illumination from the entrance of the radiometer. The method used in this study uses a dual integrating sphere where the source is positioned inside the primary sphere and the entrance of the radiometer is aimed at the secondary sphere. The primary and secondary spheres are constructed as a unit, as shown in Figure 5.

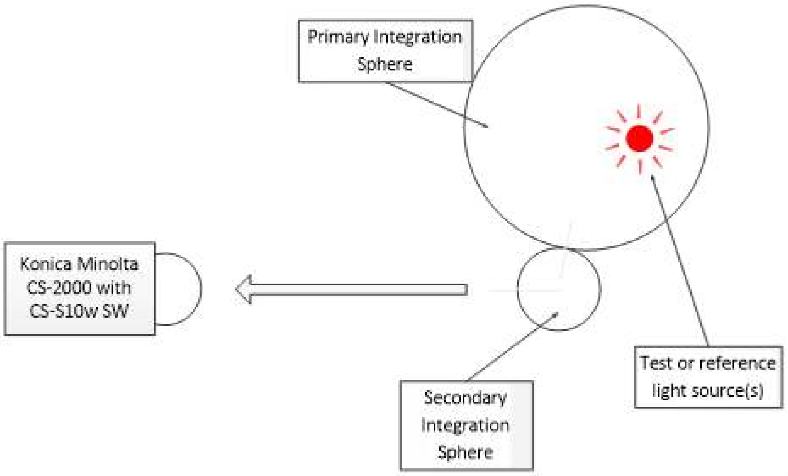

Figure 5. Test setup used to measure photometric data of the source selected by the observer.

(e) The following parameters are measured and recorded.
  i. Correlated Colour Temperature (CCT),
  ii. General Colour Rendering Index (CRI) value (R_a),
  iii. CRI values (R_1 to R_{15}),
  iv. Values x and y,
  v. Spectral Power Distribution (SPD), and
  vi. Duv values.

3.6 Measurement equipment

All photometric measurements were completed using a Konica Minolta CS-2000 photo radiometer with custom CS-S10W software. A calibration certificate was valid at the time of testing.

4. Results

The specifications of an illumination source selected by two age groups to achieve a “perception of white” are presented. Observers considered reflection from the white block on the MCC and adjusted the composite tetrachromatic light source to achieve a “perception of white

4.1 Photometric data

Detailed information regarding the spectral composition of the two different sources selected by two age groups can be extracted by considering some photometric parameters. The CIE specified test colour samples which were Munsell colour samples. These values are the approximate Munsell values for calculating CRI although only the first eight values are used for calculating the general colour rendering index R_a . This section expands on results achieved.

The Spectral Power Distribution (SPD) curves as selected, for a source, by the under 40 group to achieve a “perception” of white is shown in Figure 6.

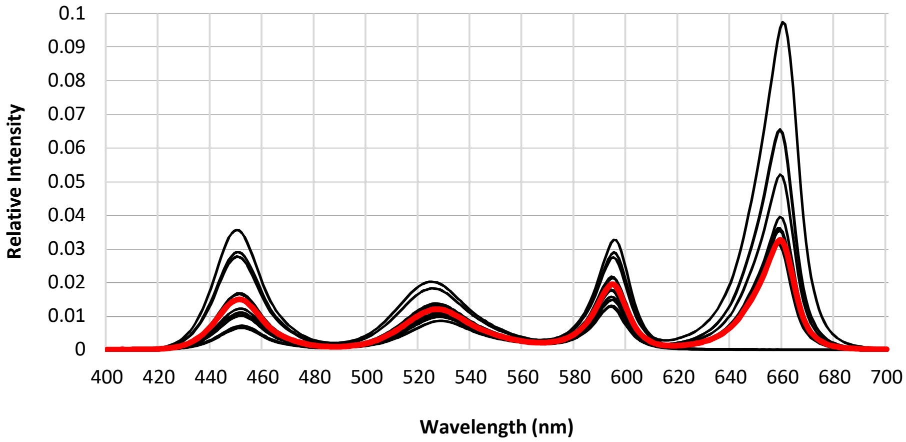

Figure 6. SPD graph for sources as selected by the under 40 age group for a source defined to achieve "white perception". The red line shows the average value.

The Spectral Power Distribution curves of the over 50 group showing observer variation, is presented in Figure 7.

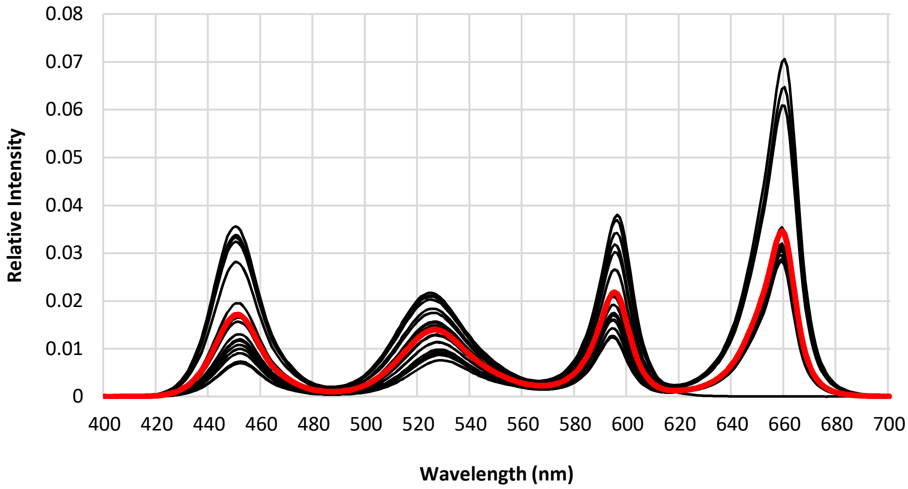

Figure 7. SPD graph for sources as selected by the over 50 age group for a source defined to achieve "white perception". The red line shows the average value

The 1931 CIE chromaticity diagram is shown in Figure 8. The diagram shows x and y coordinates of sources selected by the two age groups.

Nonparametric test were completed using the Independent-Sample Mann-Whitney U test.

The following parameters were statistically evaluated:

- The general colour rendering index number R_a between the two age groups.
- The x coordinates of sources as selected by two age groups.
- The y coordinates of sources as selected by two age groups.

The following hypotheses were tested:

- H01: The distribution of General Colour Rendering Index value R_a is the same across categories of age.
- H02: The distribution of the 1931 CIE chromaticity diagram x coordinate is the same across categories of age.

- H03: The distribution of the 1931 CIE chromaticity diagram y coordinate is the same across categories of age.

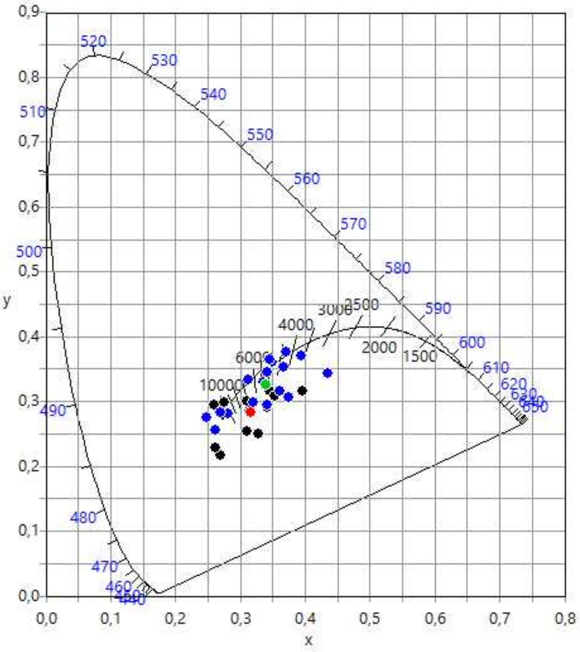

Figure 8: CIE 1931 chromaticity diagram. The black dots show the distribution for the under 40 age group with the red dot showing the average value. The blue dots show the distribution for the over 50 age group with the green dot showing the average value.

Table 2 presents a summary of statistical results.

Table 2. Summary of statistical data.

Null hypothesis	**Mann-Whitney U-value**	**Exact significance (2-sided test, p-value)**	**Decision**
H_{01}	230.000	0.000	Reject the null-hypothesis.
H_{02}	172.000	0.163	Retain the null-hypothesis.
H_{03}	212.000	0.0030	Reject the null-hypothesis

When considering the general colour rendering index R_a, the p-value is calculated to be 0.000 which is smaller than 0.050. The difference in R_a value between the two age groups is thus considered to be significant.

The 1931 CIE chromaticity diagram x and y values shows that the difference in x coordinate values is not significant (p-value>0.050) but the difference in y coordinate values is significant (p-value<0.050). The effect of this can be shown in Figure 9.

Figure 9 shows the average x and y coordinate values of sources as selected by the two age groups, using a sectional 1931 CIE chromaticity diagram. The two spots representing average values shows a larger difference in y values than x values. The average x and y values are encircled with 7-step MacAdam ellipses.

The average SPD's of the two sources selected by the two groups, to achieve a "perception" of white is presented in Figure 10.

4.3 Photos

This section presents colour photos in an effort to practically illustrate the difference in white perception regarding age. (Bearing in mind that colour reproduction processes may not yield a true-colour experience to the reader) Figure 13 shows the inside of the test booth which is populated with various objects generally regarded as "white". (Paper, polystyrene, carton, porcelain and foam.) The objects are illuminated by light sources selected by two age groups to yield a "perception of white".

Figure 14 shows results achieved when using the Macbeth Colour Checker (MCC) and illuminated by two different sources as selected by two different age groups.

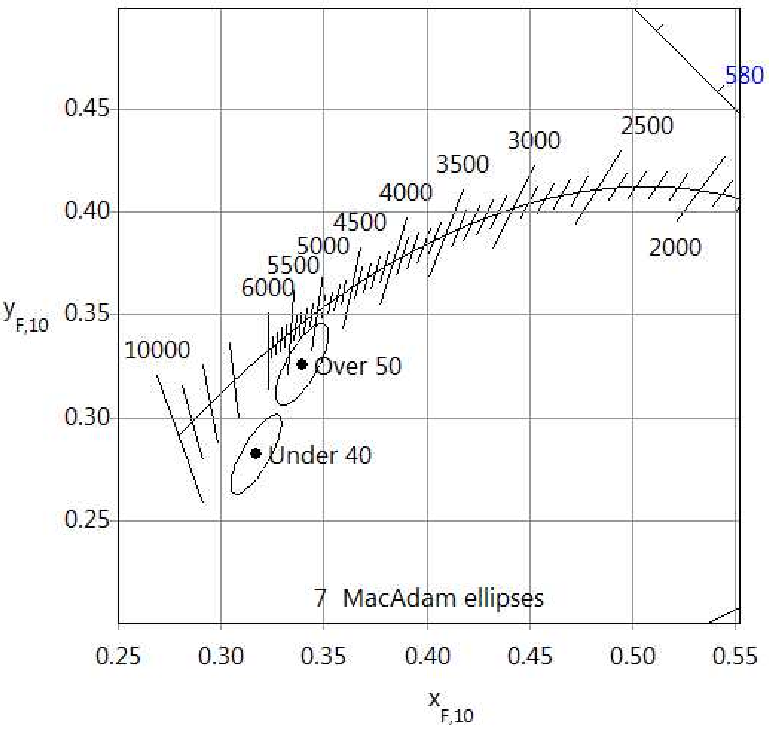

Figure 9. A sectional part of the CIE 1931 chromaticity diagram showing x and y coordinates of sources as selected by two age groups to achieve "white perception". Seven-step MacAdam ellipses are drawn around the x-y points. (CIE 1931 chromaticity diagrams was drawn using free OSRAM ColorCalculator software [24]. [33])

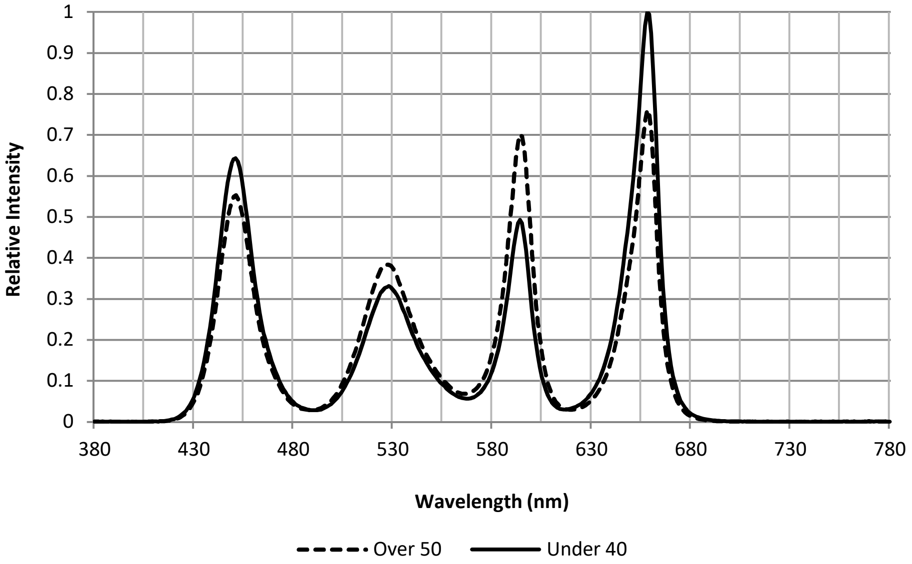

Figure 10. SPD graph for sources as selected by two age groups to achieve "white perception".

Figure 11 shows the white perception test SPD measured with two age groups of observers and multiplied with the photopic V(λ) graph using average observer values.

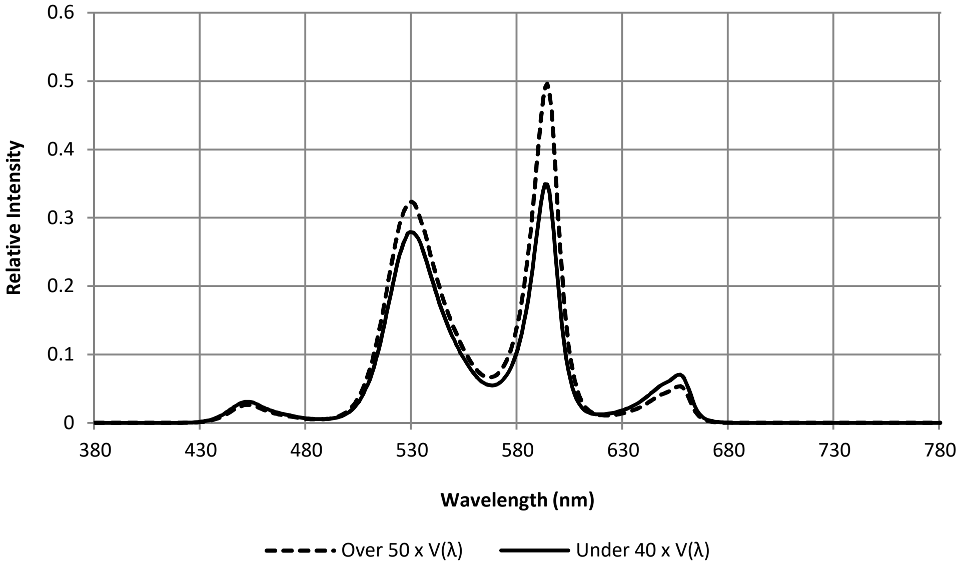

Figure 11. White perception SPD test result multiplied with photopic V(λ) curve. Graphs are calculated using average values.

Figure 12 shows the SPD graph of Figure 10 multiplied by typical human lens deterioration values as lens transmission reduces with age.

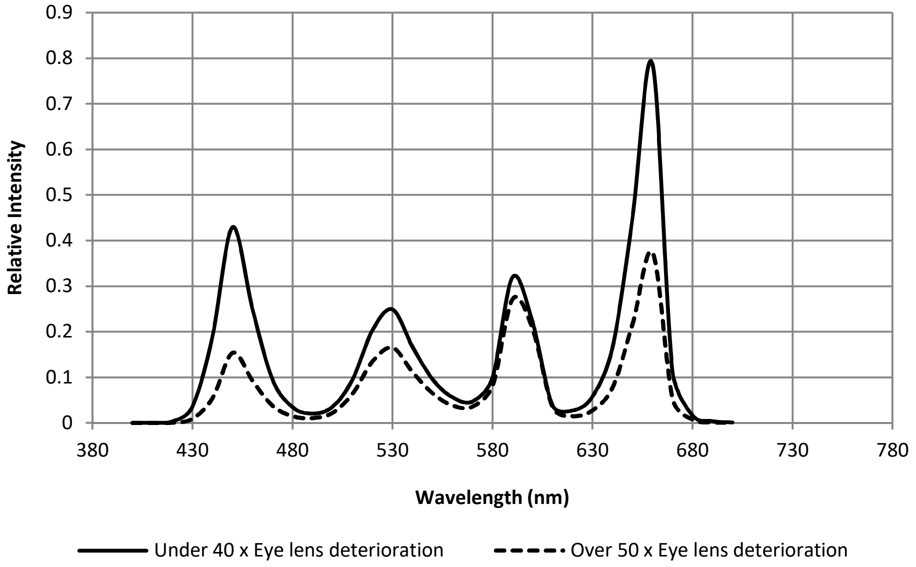

Figure 12: Spectral power distributions as presented in Figure 10 weighted by typical age-dependent human lens transmission for the perception of white.

Table 3. Parameters of illumination sources as selected by two different age groups to achieve a "perception" of white. Some parameters were calculated from measured x and y coordinates values.

Parameter	Older than 50.	Younger than 40.	Statistical significance
R_a (General color rendering index.)	89	74	Table 2
CCT (Correlated Color Temperature)	5150 K	6592 K	Calculated from x and y values.
X coordinate	0.3393	0.317	Table 2
Y coordinate	0.3258	0.2822	Table 2
Duv	-0.0112	-0.0255	Calculated from x and y values.

Figure 13. Test booth on the left is illuminated by a source selected by the under-40 group as yielding “white” light. It shows a higher component of blue. The test booth on the right is illuminated by a source selected by the over-50 group as yielding “white” light. It shows a smaller component of blue and a larger component of yellow.

Figure 14. MCC on the left is illuminated by a source selected by the under-40 group as yielding “white” light. It shows vivid blue and purple coloured blocks while red, yellow and orange seems to be less saturated.. The MCC on the right is illuminated by a source selected by the over-50 group as yielding “white” light. It shows saturated orange, red and yellow while blue and purple appears to be less saturated.

4.4 Complementary statistical analysis

Figure 15 shows the student t probability mass function of sampled CRI R_i values for the two age groups when evaluating the perception of white. These values are drawn for each group of observers. The solid line shows the results for the under-40 group, with a variation from 58 to 89. The dotted line shows the results for the over-50 group, but with a variation from 74 to 92. Each R_i value is plotted on the graph. When a specific R_i value is chosen repeatedly, the value on the y-axis increases. One can thus see that the under-40 group selected a source where most of the R_i values were at the peak, around 73. The over-50 group selected a source where most of the Ri values were at the peak, around 83. These are not R_a values, as only the first eight R_i values are used to calculate R_a. It is nevertheless interesting to note that the two R_a values were measured to be 74 and 89. From the graph shapes, one can also see that the variation of selected choice in the under-40 group is wider than in the over-50 group. As the peak graph grows wider, variance increases. This graph is known as the probability mass function (PMF). The t-distribution was used to deduce the level of confidence in any given range that would contain the true mean. (The probability density function (PDF) is related but uses continuous instead of discrete values), The graph thus show the point values on the R_i scale where a specific group of observers is likely to select a source with values in that area. When considering the "over-50"graph, it can be established that the probability of the over-50 group to select a R_i value of 87 is 0.37 (or 37%).

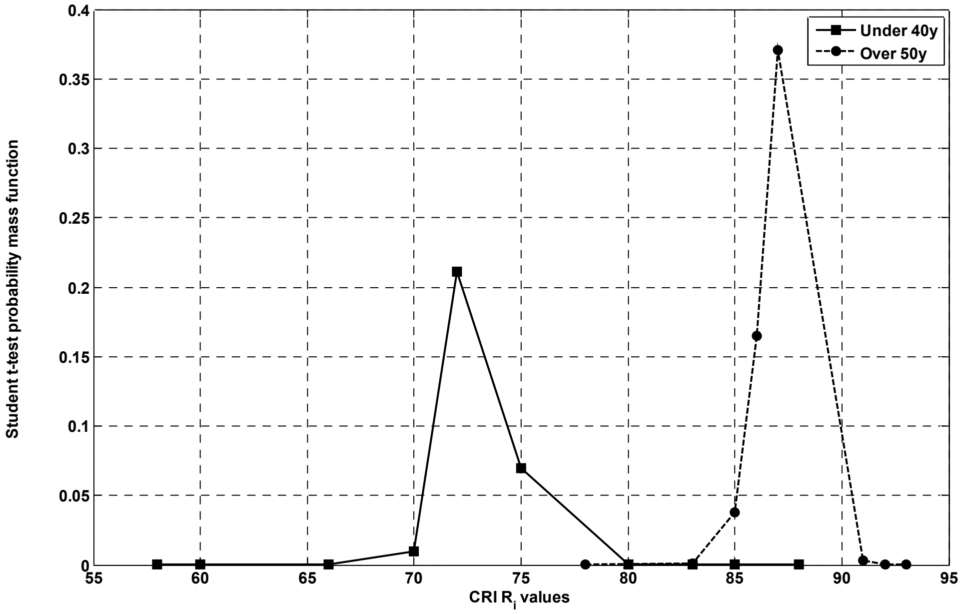

Figure 15. The student t probability mass function of sampled CRI R_i values for the two age groups when evaluating white perception

5. Discussion

5.1 General discussion

Two age groups were tasked to select a light source that produces the "best white perceived light" when a standard MCC colour checker white patch was used for light reflection. It seems that the two age groups differed in the design of a light source to produce "white perceived reflection". Transmission through the crystalline lens of the human eye decreases spectrally with age. The lens becomes more yellow, which means that transmission of shorter wavelengths (blue) is decreased. It is thus to be expected that the older group of observers will select a higher component of blue to compensate for lens transmission loss in the blue region. This physiological measurement is not reflected in the evaluation of "white perception" of the two age groups. It is thus possible that older observers are able to compensate for lens transmission loss when evaluating colours and the loss of blue through the lens is therefore not really a problem. Moving through the spectrum, the older group selected a higher intensity (+13.6 %) at 528 nm (green), a higher intensity (+27.6 %) at 590 nm (yellow) and a much lower intensity (23.5 %) at 657 nm (red) than the younger group. The reasons for these differences cannot readily be explained. One possibility is that older observers may be more accustomed to sources that contain a high component of yellow. Older observers grew up using incandescent sources, while younger observers may be regular users of tablets, computer screens, LED TV screens and cell phones, which feature a high component of blue. Indeed, the younger observers selected a source with a higher (+13.2 %) component of blue. The older observer may thus "perceive" reflected light to be "white" when a high component of yellow/red is included, but in practice only a higher yellow component is selected and not an increased red one as well.

5.2 CRI R_a and CCT values

The younger group selected a source with CRI average colour rendering (R_a) of 74 (CCT = 6592 K), while the R_a value for the older group is 89 (CCT = 5150 K). The difference in R_a number of 15 is significant. Houser et al [15] states that differences in CRI R_a values of less than 5 points are mostly not noticeable. A very important value is that of R_9, which is measured at -7 for the younger group and 39 for the older group. A manufacturer of light sources states that a light source with an acceptable CRI features an R_a value of at least 80 and an R_9 value of higher than 0. [6]Using such a measure as a guide means that the source specified by the older group to achieve "white perception" is close to standard commercial sources.

5.3 MacAdam ellipses and Duv values

Figure 9 shows seven-step MacAdam ellipses drawn around the gamut points. As the outlines of the ellipses do not overlap (or even touch), it can be deduced that the average observer's vision will perceive the two sources to be chromatically different. According to Ohno [22], it is important to consider Duv values, as these are important light source colour quality parameters. The source selected by the older group features a Duv value of -0.0112 and the source selected by the younger group features a Duv value of -0.0255. Both values are below the Planckian locus. Padfield [27] states that Duv values with a value larger than 0.006 are not preferential as "white light". The ideal value for "white light" should be less than 0.001. Both sources selected by the two observer groups can thus be classified as being "white".

6. Conclusion

"White" perception of persons younger than 40 is different than that of persons older than 50 years of age. When specifying a light source for "white" light production, the younger group prefers a source with a larger component of blue (455 nm) and red (657 nm). The older group prefers a source with larger components of yellow (590 nm) and green (555 nm). The younger group prefers a source with a CRI R_a number of 74 and the older group prefers an R_a number of 89. CCT values also show that the older group prefers a warmer variation of white (5150 K) than the younger group (6592 K).

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