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TECHNICAL REPORT

Lighting for Older People and People with Visual Impairment in Buildings

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Descriptor: Colour contrast. Luminance contrast
Contrast. sensitivity
Visual acuity
Defects of colour vision

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3. Richtlinien für die Anwendung von Prinzipien und Vorgängen in der Entwicklung internationaler und nationaler Normen auf dem Gebiet der Lichttechnik zu erstellen.
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This Technical Report has been prepared by CIE Technical Committee 3-44 of Division 3 "Interior Environment and Lighting Design" and has been approved by the Board of Administration as well as by Division 3 of the Commission Internationale de l'Eclairage. The document reports on current knowledge and experience within the specific field of light and lighting described, and is intended to be used by the CIE membership and other interested parties. It should be noted, however, that the status of this document is advisory and not mandatory.

Ce rapport technique a été élaboré par le Comité Technique CIE 3-44 de la Division 3 "Environnement intérieur et étude de l'éclairage" et a été approuvé par le Bureau et Division 3 de la Commission Internationale de l'Eclairage. Le document expose les connaissances et l'expérience actuelles dans le domaine particulier de la lumière et de l'éclairage décrit ici. Il est destiné à être utilisé par les membres de la CIE et par tous les intéressés. Il faut cependant noter que ce document est indicatif et non obligatoire.

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LIGHTING FOR OLDER PEOPLE AND PEOPLE WITH LOW VISION

Summary

This report summarizes lighting recommendations on lighting and visual environment in interior spaces such as offices, public spaces, and residences for healthy older people (defined as people aged 50 years and older) with normal vision, and people with low vision, and implements guidelines described in CIE 196:2011 into practical solutions.

The report provides (1) illuminance recommendations, derived from simulations with existing visual models for older people, (2) state of art of studies on how light helps people with low vision see objects by reviewing recent literature, and (3) design guidelines for lighting practitioners how to design appropriate visual environments for people with low vision.

ECLAIRAGE POUR PERSONNES ÂGÉES ET DES PERSONNES À VISION RÉDUITE DANS BATIMENTS

Résumé

Ce rapport résume les recommandations d'éclairage pour l'éclairage et l'environnement visuel dans les espaces intérieurs tels que bureaux, espaces publics et domicile, pour les personnes âgées en bonne santé ayant une vision normale. Les personnes âgées en bonne santé sont définies comme personnes de 50 ans et plus. Ce rapport vaut également pour les personnes ayant une vision réduite. Il met également en œuvre des lignes directrices décrites dans CIE 196:2011 en proposant des solutions pratiques.

Ce rapport fournit (1) des recommandations d'éclairage, qui sont issues de simulations avec des modèles visuels existants pour les personnes âgées. Il fournit (2) l'état de l'art actuel, rapporté dans la littérature, des études réalisées sur la façon dont la lumière aide les personnes ayant une vision réduite, sur la façon dont ils voient les objets. Il fournit (3) des guides de conception pour les praticiens de l'éclairage afin de concevoir un environnement visuel approprié pour les personnes à vision réduite.

BELEUCHTUNG FÜR ÄLTERE PERSONEN UND MENSCHEN MIT SEHSCHWÄCHE IN GEBÄUDEN

Zusammenfassung

Dieser Bericht fasst Beleuchtungsempfehlungen in Bezug auf Beleuchtung und die visuelle Umgebung in Innenräumen zusammen. Anwendungsgebiete sind Räume wie Büros, öffentliche Räume und Wohnräume für gesunde, ältere Personen (hier definiert als Personen ab dem 50. Lebensjahr) mit normalem Sehvermögen, sowie für Personen mit schwachem Sehvermögen. Darüber hinaus gibt der Bericht Vorschläge, wie die in CIE 196:2011 beschriebenen Richtlinien praktisch anwendbar sind.

Der Bericht umfasst (1) Beleuchtungsstärkeempfehlungen, basierend auf Simulationen mit bestehenden visuellen Modellen für ältere Personen, (2) den aktuellen Forschungsstand anhand der neuesten Literatur zum Effekt von Licht auf die Objektwahrnehmung durch Personen mit Sehschwäche, sowie (3) Leitfäden für Lichtanwender zur Gestaltung einer auf die Bedürfnisse von Personen mit Sehschwäche angepassten visuellen Umgebung.

1 Introduction

Recently, energy conservation has become a global concern. Lighting is often the first thing to be turned off when electrical energy has to be conserved. For instance, after the Great East Japan Earthquake hit Tohoku Japan on March 11 in 2011, not only the quake-hit area but also the capital area, which used a large amount of electric energy, were demanded to reduce energy use. Turning off lighting and removing lamps are the most convenient measure for local municipalities and public transportation to demonstrate electric energy savings. Even without such an emergency situation, recent international, national and regional energy conservation codes have strictly regulated the maximum acceptable energy usage within a given unit of floor area and/or time. It may be easy to say that unnecessary lighting should be turned off or dimmed.

While lamps emitting too much light for people with normal vision are removed or dimmed, illuminance levels required for older people and people with low vision have been neglected. These people often encounter difficulties in seeing obstacles and edges of steps in public and commercial buildings under lighting conditions dimmer than a few years ago.

Current lighting requirements were established based on results of experiments that employed young subjects. In addition, a recent growing interest in global warming and a sustainable society has resulted in reduced illuminance requirements for the same visual tasks in global regulations and codes. Thus, it is important to summarize recommendations for lighting and visual components so that people with visual disadvantages will not have difficulties and problems when performing visual tasks in interior applications.

1.1 Growing ageing society

As Figure 1 depicts, ageing population has dramatically increased in many countries. E.g. in Japan one quarter of the population is already 65 years and over, and this ageing population will reach 40 % in 2050. Japan is the worst case, but Korea and other countries will catch up with Japan in the near future.

After typically the age of 45 years, people need significant additional amounts of light to be able to perform the same visual tasks comfortably (Sagawa et al., 2003).

The 2010 World Population Data Sheet by the Population Reference Bureau reported that there were nine working-age people for every older person in the world. There are fewer than five working-age people for every older person in many European and Asian countries. The ratio is lowest in Japan, Italy, and Germany—at three to one.

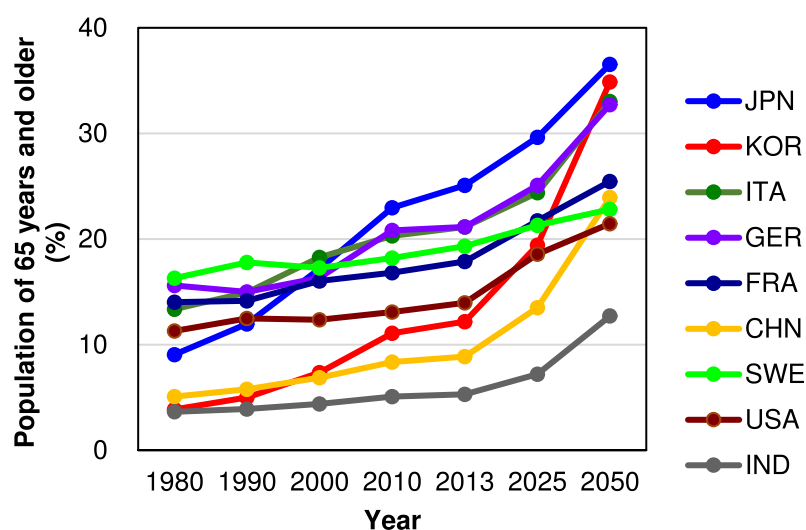


Figure 1 – Ageing population of 65 years and over by country (UN (2013.6) World Population Prospects: 2012 Revision)

1.2 Prevalence of low vision

Based on the definition of low vision as presenting vision (i.e. visual acuity with the best possible correction) (Resnikoff et al., 2004), WHO reported that 272 million people were estimated to have low vision and 43 million people to be blind (315 million visually impaired in total) in the world in 2004 (WHO, 2004a). The estimated number of people visually impaired was reduced to 285 million, 39 million blind and 246 million having low vision, in 2010 (WHO, 2010). Such reductions reflect international investments and collaborations in improving eye health services. However, there are still many people with visual impairments who need medical support and improvement in lighting environment. Table 1 shows prevalence of blind and low vision by WHO region.

Table 1 – Prevalence of selected conditions by WHO region in 2010 using presenting vision (millions) (WHO, 2010)

	World	Africa	North America and South America	Eastern Mediterranean	Europe	South-East Asia (India excluded)	Western Pacific (China excluded)	India	China
Low vision*	246,0	20,4	23,4	18,6	25,5	23,9	12,4	54,5	67,3
Blind**	39,4	5,9	3,2	4,9	2,7	4,0	2,7	8,1	8,2
* Low vision (presenting visual acuity < 6/18 and ≥ 3/60) due to glaucoma, cataracts, macular degeneration or refractive errors. ** Blindness (presenting visual acuity < 3/60) due to glaucoma, cataracts, macular degeneration or refractive errors.									

Table 2 shows a global estimate of the number of people visually impaired by age, suggesting that 63 % of people with low vision and 82 % of all blind are 50 years and older. This implies that the number of low vision people may increase as people live longer.

Table 2 – Global estimate of the number of people visually impaired by age (millions) (WHO, 2010)

	Population	Low vision	Blind
0–14 years	1 848,5	17,5 (0,9)	1,4 (0,1)
15–49 years	3 548,2	74,5 (2,1)	5,8 (0,2)
50 years and older	1 340,8	154,0 (11,5)	32,2 (2,4)
All ages	6 737,5	246,0 (3,7)	39,4 (0,6)
NOTE Corresponding prevalence (%) is shown in parenthesis for each category and each age group.			

1.3 Relevant CIE publications

CIE 123-1997 “Low vision: Lighting needs for the partially sighted” (CIE, 1997) reviewed studies on low vision and summarized the features of the major diseases causing low vision. These diseases include macular degeneration, retinal pigmentosa, cataract, and glaucoma. This report also reviewed studies that addressed the effects of light on visual functions such as visual acuity, contrast sensitivity, visual field and colour vision. It introduces visual aids, such as neutral and selective absorbing glasses, light amplification systems, high power additions, magnifiers, telescopes, closed circuit television systems, etc. and provides lighting recommendations for people with low vision.

CIE 196:2011 “CIE Guide to Increasing Accessibility in Light and Lighting” (CIE, 2011), was written for lighting designers and engineers, as well as scientists of light, colour, and vision to assist them in taking account of the needs of older persons and persons with disabilities. The

guide was developed in accordance with ISO/IEC Guide 71:2001 “Guidelines for standard developers to address the needs of older persons and persons with disabilities” (ISO/IEC, 2001) and its technical guidelines IES/TR 22411:2008 “Ergonomics data and guidelines for the application of ISO/IEC Guide 71 to products and services to address the needs of older persons and persons with disabilities” (IES, 2008) in order to implement accessible design in the field of light and lighting. Some content has been shared with those two documents. This guide provides fundamental knowledge and data on vision of older people and people with disabilities, as well as design considerations based on these data, in order to facilitate consideration of the needs of older people and people with disabilities.

1.4 Goal and outline of the present report

The goal of this report is to summarize lighting recommendations on lighting and visual environment in interior spaces such as offices, public spaces, and residences for older people and people with low vision.

Other guidelines such as ANSI/IES RP-28-07 (ANSI/IES, 2007) already provide comprehensive area-specific lighting solutions for various lighting applications like in stairs, corridors, bedrooms, bathrooms and entrance transitions. Such lighting design guides may not be suitable for international recommendations since life styles in worldwide countries differ from each other. Thus, the focus in this report was laid on fundamental aspects (for instance illuminance and glare) common in various applications and countries. This report provides general guidance for practical lighting design, leaving application-specific guidelines to be developed by regional bodies that are better able to take into account local culture, habits, and preferences. Lighting recommendations for healthy older people with normal, ageing vision are also provided, based on simulations that use existing models for age-related changes in vision.

CIE 123-1997 (CIE, 1997) provided a comprehensive review and lighting guidelines for people with low vision as of 1997. In the present report the state-of-art studies on the effects of light on low vision are updated by focusing on publications in the years from 1997 to the present, and design guides for lighting practitioners and environmental designers are provided to design an appropriate visual environment for people with low vision. Guidelines described in CIE 196:2011 (CIE, 2011) have also been implemented into practical solutions.

In this report, older people are defined as people with more than 50 years of age. This means that the report is also relevant for the rapidly growing ageing workforce, taking into account those parts of the population that are still working but start experiencing a significant reduction in visual acuity due to their age (Sagawa et al., 2003). See also www.age-platform.eu.

2 Research update of low vision and visual changes with age

In order to provide guidance on lighting for older people and people with low vision, it is important to understand the mechanisms of ageing vision and low vision. Literature reviews on visual changes and impairments with age have already been undertaken (Weale, 1963; CIE, 1997; Boyce, 2003; ANSI/IES, 2007; CIE, 2011; Owsley, 2011). This clause summarizes these reviews.

2.1 Ageing eyes

Most components in the human visual system deteriorate with age (Figure 2). Older people often experience noticeable changes in visual performance and task object appearance. These changes originate due to (1) reduced accommodation, (2) increased intraocular light scatter, (3) reduced spatial contrast sensitivity, (4) reduced retinal illuminance, and (5) slower dark adaptation.

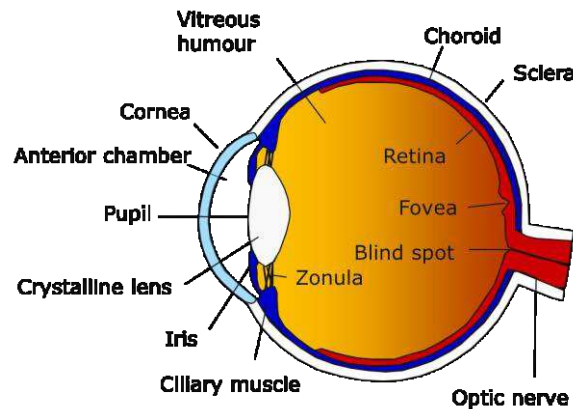


Figure 2 – Section of the human eye

2.1.1 Reduced accommodation

After approximately 45 years of age, people often experience reduced capabilities in accommodation. The refractive power of a human eye is determined by the curvature of the cornea and the thickness of the crystalline lens. The curvature of the cornea is fixed while the thickness of the crystalline lens is variable so as to change the focal length of the crystalline lens. When looking at objects at various distances, a young observer adjusts the thickness (or focal length) of the crystalline lens so that the objects' images can be formed on the focal point of the lens (i.e. the fovea on the retina).

However, the lens becomes more rigid and flatter with age, and therefore it becomes more difficult to focus on short-distance objects. This is regarded as presbyopia or farsightedness due to age. Such refractive errors often impair contrast sensitivity.

Lighting cannot help older people fix such optical errors or ease presbyopia. Wearing glasses or contact lenses helps older people remove or at least reduce such refractive errors. To further discuss lighting for older people and people with visual impairments in the following subclauses, it is assumed that older people wear glasses or contact lenses in order to optically remove the above-described refractive errors.

2.1.2 Increased intraocular light scatter

Intraocular light scatter is caused mainly by the cellular structures of cornea, crystalline lens and fundus (including the retina, blind spot, and the fovea) for young adults (Figure 3). However, the light scattering in the crystalline lens dramatically increases with age. Proteins in the crystalline lens gradually denature and degrade, and therefore the lens becomes clouded over time (Vos, 1984). Since the size of the protein particles is too large to cause wavelength-dependent Rayleigh scattering, the intraocular light scatter is independent of wavelength (Steen et al., 1993). Due to the light scatter, older people often experience reduced retinal contrast and subsequently disability glare.

It is important to carefully design lighting so as to minimize such intraocular light scatter in interior spaces where older people perform detailed visual tasks.

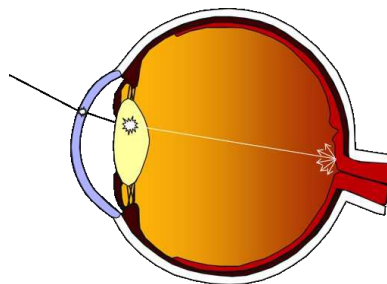


Figure 3 – Origins of intraocular light scatter

2.1.3 Reduced spatial contrast sensitivity

Spatial contrast sensitivity is diminished with age due to increased intraocular light scatter and neural factors. The process of increasing intraocular light scatter with age has already been discussed in 2.1.2. The neural factors include increased noise density (i.e. tiny yellow or white accumulations of extracellular material) in the retina, decreased photoreceptor density, and decreased ganglion cell density during the ageing process (Keunen et al., 1987; Adrian, 1993).

However, loss in spatial contrast sensitivity is largely optical in origin at photopic levels while neural factors become more important for the sensitivity loss under mesopic and scotopic conditions (Owsley, 2011).

Since this report focuses on interior spaces that are usually illuminated at photopic light levels, it may not be necessary to take such contributions of neural declines to reduce spatial contrast sensitivity into account for further discussion on lighting for healthy older people. This implies that it is important to increase task illuminance to obtain finer images as well as to minimize the increment of ambient illuminance in order to minimize increased intraocular light scatter.

2.1.4 Decreased retinal illuminance

Retinal illuminance declines with age due to reduced pupil size (also called pupillary miosis) and increased spectral absorption of the crystalline lens. It is reasonable for lighting practitioners to increase task illuminance to help older people compensate for the age-related losses in retinal illuminance.

Increased spectral absorption with age is caused by an increase in the size of the crystalline lens and an accumulation of a yellow pigment during life (Pokorny et al., 1987; Xu et al., 1997; van de Kraats and van Norren, 2007). Since the yellow pigments absorb more short-wavelength radiation than long-wavelength radiation, the spectral transmittance of the crystalline lens becomes higher at longer wavelengths with age than at shorter wavelengths (Figure 4), effectively causing the older viewer to see the world through a yellow filter.

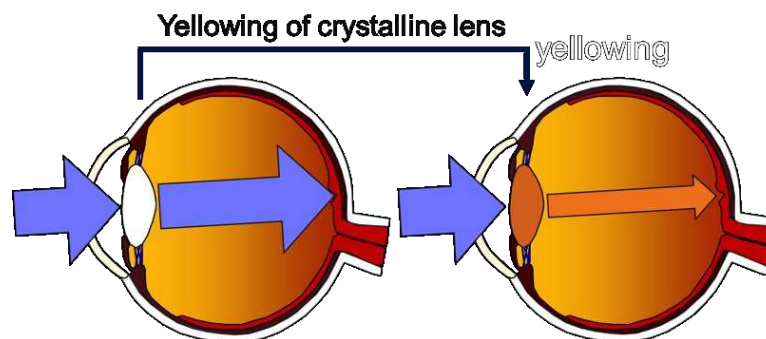


Figure 4 – Reduction of lens transmittance due to lens yellowing

Pupil diameter is determined by adaptation luminance, spectral power distribution, and age (Holladay, 1926; Crawford, 1936; Moon and Spencer, 1944; De Groot and Gebhard, 1952; Stanley and Davies, 1995; Barten, 1999; Blackie and Howland, 1999; Winn et al., 1994), as shown in Figure 5. Pupillary miosis is caused by many ageing factors. These factors include a comparative atrophy of the dilator relative to the sphincter muscle, iridal rigidity, decrease in sympathetic tone, reduction in parasympathetic inhibition, and chronic fatigue. A few studies investigated how many millimetres the pupil is contracted with age (Winn et al., 1994). A recent study combined these findings and developed a unified formula to estimate pupil diameter (Watson and Yellott, 2012).

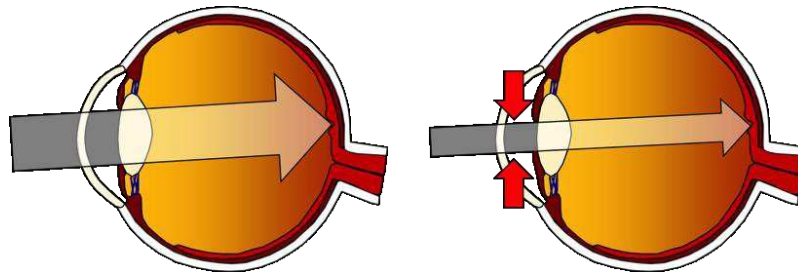


Figure 5 – Effect of a contracted pupil diameter

2.1.5 Slower dark adaptation

Older people have decreased visual sensitivity in the dark. Increased optical density of the aged crystalline lens and pupillary miosis contribute to their scotopic threshold elevation. However, the visual cycle, the biochemical pathway responsible for rhodopsin regeneration is perturbed with age (Owsley, 2011). Therefore, older people experience substantial delays in adapting to darkness (Jackson et al., 1999).

Older people need longer photo-stress recovery time, or time needed for the retinal pigments to recover after they have been bleached by a bright light source (e.g. the time to recover after looking into a glaring light source). During this longer recovery time, the visual system is in a transient state of insensitivity, subjectively perceived as an after-image (Elliott et al., 1991). It is therefore important to conceal high-luminance light sources from older people.

Older people's lower visual sensitivity in the dark and the slower dark adaptation often raise risks while driving and walking on streets at night. It is very important to examine how these age-related visual deteriorations affect night-time traffic safety. However, this report focuses on lit interior spaces, and therefore will not deal with this area.

2.2 Change of colour vision with age

Due to the anatomical and physiological ocular changes with age, the spectral power distribution (SPD) and intensity of light reaching the retina are changed. Therefore, it can be predicted that such changes should result in dramatic changes in human colour vision. However, at suprathreshold levels in normal interior lighting applications, human colour vision maintains remarkably stable across the life span, implying that the visual system may adapt to compensate for the anatomical and physiological changes in spectral sensitivity (Werner et al., 2004; Sinomori, 2003). This sub-clause first outlines human colour vision, second describes senescent declines in cone sensitivity, and finally shows evidence of the renormalization processes recalibrating the visual system for changing retinal stimuli and altered signals from the visual pathways. Colour appearance for people with low vision will be described in 3.6.3.

2.2.1 Outline of how human colour vision works

Human colour vision starts with the absorption of photons by three types of cones which differ in sensitivity range of wavelength. Cones having their peak wavelengths at the shortest, middle and longest wavelength ranges are called S-, M- and L-cones respectively. Human colour perception is based on a transformation of signals from these cones into red-green and yellow-blue chromatic channels, and a black-white achromatic channel according to Boynton and Gordon (1965). Figure 6 illustrates the classic model of human colour vision and ocular optics. The black-white achromatic channel receives signals from the M- and L-cones. The red-green opponent channel produces the difference between the signal of the M-cones and the sum of the signals of the L- and S-cones. The blue-yellow opponent channel produces the difference between the S-cones and the sum of the M- and L-cones. Human colour perception is based on the above described relative outputs from the three types of cones rather than their absolute outputs. This is the key to the renormalization of colour vision from infancy through senescence as described below.

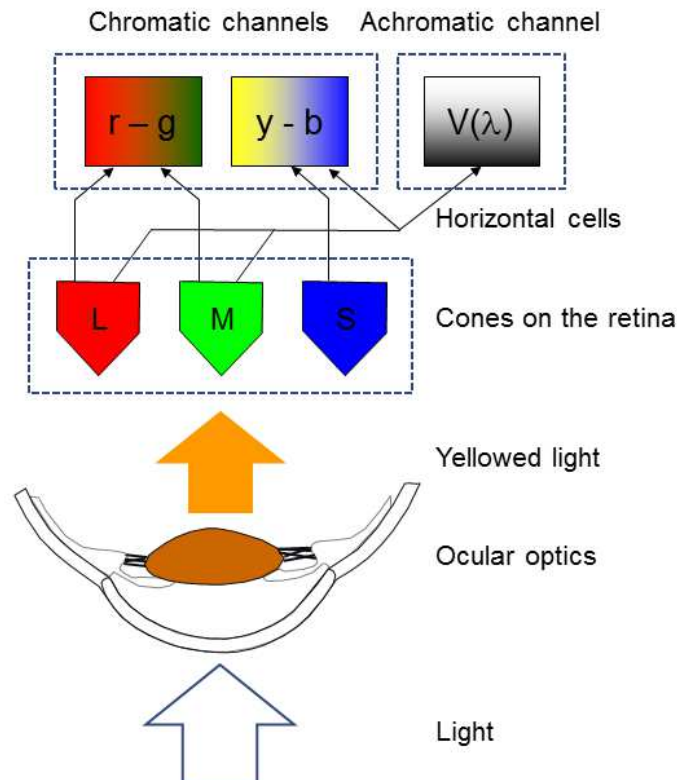
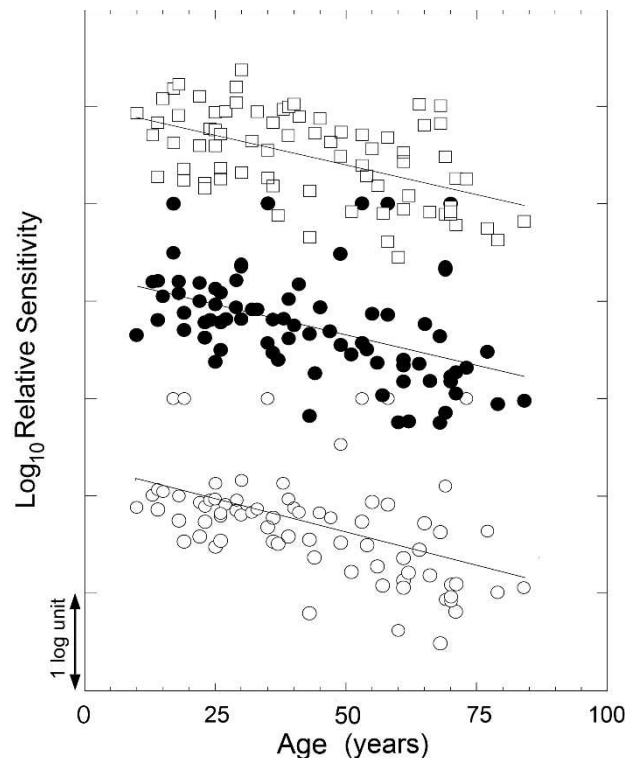


Figure 6 – Classical model of human colour vision and ocular optics

2.2.2 How anatomical and physiological changes with age cause psychophysical changes at threshold

Salient anatomical and physiological senescent changes impacting signals generated by the retina are reductions in the retinal and choroidal blood supply, a decrease in cell density of the retinal pigment epithelium, a reduction in photoreceptor numbers and changes in photoreceptor morphology, and a loss of retinal ganglion cells (Werner et al., 2004). For instance, a study (Curcio et al., 1993) counting cones in 27 whole mounted retinas from donors aged 27 to 90 years reported that changes in cone density had no consistent relationship to age or retinal location, and the total number of foveal cones was relatively stable while rod density decreased by 30 %. At the temporal equator, however, cone density declined by 23 %. Studies, which directly measured responses from cones and rods using electroretinogram, reported that amount of responses from cones and rods are continuously reduced after early adolescence (Birch et al., 2002).

Many psychophysical studies, which attempted to determine absolute sensitivities of three types of cones, showed that S-cone sensitivity decreases with age (Eisner et al., 1987; Johnson, 1988). Several studies found similar losses in the sensitivity of M- and L-cones (Knoblauch et al., 2001; Werner and Steele, 1988). For instance, Werner and Steele (1988) measured spectral sensitivities of S-, M-, and L-cones by testing detection thresholds for 76 observers ranging from 10 to 84 years in age. Figure 7 shows the results of the measurements. The sensitivities at all wavelengths correlated negatively with age. The sensitivity at 560 nm declined at a rate of 0,11 log unit per decade for both M- and L-cones. These data support the view that the sensitivities of all three cone types and/or their pathways after the retina declines from 10 to 84 years of age.



NOTE The logarithm of the relative sensitivity is plotted as a function of age for S-cone (unfilled squares), M-cone (filled circles), or L-cone (unfilled circles). The data are normalized arbitrarily along the sensitivity axis for each of the three cone types.

Figure 7 – Relative sensitivity as a function of age for S-, M- and L-cones (Werner and Steele, 1988)

2.2.3 Colour discrimination

Knoblauch et al. (2001) tested colour discrimination performance for 75 subjects ranging between 20 and 78 years of age by using the Farnsworth-Munsell 100-hue test at five illuminance levels. The results of the experiment revealed a similar tendency of defects in colour discrimination in both young and older subjects at lower illuminance levels. In addition, the ability of colour discrimination appears to decline with age. To understand mechanisms of such an age-related decline in colour discrimination Shinomori et al. (2001) developed stimuli consisting of monochromatic lights with individually determined constant luminance values so that the SPD and intensity of light reaching the retina of each of the subjects can be physically the same. The experimental results suggested small but consistent increases in colour discrimination thresholds in older observers compared to young observers. Shinomori et al. suggested that these age-related losses in colour discrimination are attributed not to reduction in retinal illuminance, but to neural changes because the retinal illuminance of the stimuli was constant across all observers. The results of the above described experiments conducted at threshold levels suggest increasing light levels for the elderly to maintain their visual performance in interior lighting applications.

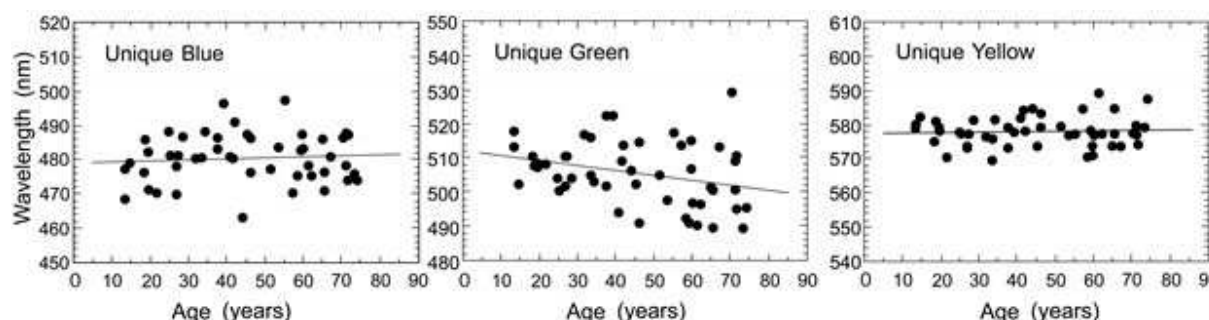
2.2.4 Colour appearance at suprathreshold levels

The former subclauses showed large losses in sensitivity of cone mechanisms and a significant decline in colour discrimination performance. It is also important to understand how colour appearances of objects change with age under suprathreshold conditions where we normally live.

Schefrin and Werner (1990) measured the wavelengths of unique hues (blue, green, and yellow) as a function of age for 50 observers ranging in age from 13 to 74 years. Figure 8 shows the results. Each of the unique blue and unique yellow does not have significant differences in wavelength among different age groups. However, Figure 3 also suggests significant shifts of unique green wavelength to shorter wavelength region. Schefrin and Weber (1993) conducted

a colour naming experiment for 15 young (21,3 years on average) and 15 older (71,9 years on average) subjects. The subjects were asked to scale the percentage of each fundamental hue (red, green, yellow and blue), and then to scale the proportion of overall chromatic and achromatic content. As a result, hue-naming percentages used by subjects did not differ by more than 5 % between young and older subjects for any hues. However, older subjects perceived colours to have more achromatic content (less chromatic content) than young subjects. Okajima et al. (2002) reported similar results using a larger set of colour chips. The subjects were asked to choose one of 11 common colour names for each stimulus. Essentially no difference between young and older subjects was found. However, reductions in perceived colour saturation appeared in older subjects. Similar tendency can be found from an experiment conducted by Sagawa and Takahashi (2003) as described later.

From the above described studies on colour appearance by using techniques for identifying unique hues and colour naming, colour appearances of objects seem to be maintained relatively constant over the life span.



NOTE 0,95° diameter foveal stimuli with a luminance of 7,1 cd·m⁻².

Figure 8 – Wavelengths of unique hues as a function of age (Scheffrin and Werner, 1990)

2.2.5 Renormalization of chromatic mechanisms

If mechanisms of human colour vision have been altered by changes in input and adaptation, a shift in the neutral white point should appear. Werner and Scheffrin (1993) measured the white points for 50 normal observers ranging in age from 11 to 78 years. The observers were asked to vary the intensity ratio of their individually determined unique blue and unique yellow in order to define their white points while maintaining a constant retinal illuminance. The results suggested no significant change in the white point as a function of age.

Delahunt et al. (2004) measured the locus of the achromatic point before and after cataract surgery for four cataract patients (63–84 years). The subjects were asked to determine the chromaticity of stimuli that appeared achromatic (white point) before surgery, and at various intervals after surgery for up to 1 year. The locus of the achromatic point for each of the observers showed a large shift in the white point in the yellow direction. However, the white point slowly moved back in the direction of the chromaticity before the surgery. The white point eventually reached a fairly stable chromaticity at about three months after the surgery. This result implies that there should be processes that compensate for the changes in the retinal stimulus caused by lenticular senescence to maintain the white point stable across the life span.

2.2.6 How findings on change in colour vision with age can be applied for interior lighting

The above described studies have demonstrated that the visual system recalibrates itself for changing retinal stimuli and signals on the visual pathways. Therefore, shifts in chromaticity predicted based on changes in ocular density of optical media should not be applied for assessing senescent changes in colour appearance. However, such renormalization processes are not perfect, suggesting some deteriorations in colour vision especially in threshold conditions. Saturations of perceived colours decrease and colour discrimination thresholds increased. This is especially true for threshold conditions at low retinal illuminances and low saturations.

Therefore, it is important to maintain sufficient illuminance on visual tasks. It can be also recommended to use lamps with higher colour rendering in order to maintain perceived colour saturation (Shinomori, 2003).

2.3 Low vision

This present study follows the definitions of visual impairment, low vision and blindness, given in the international statistical classification of diseases, injuries and causes of death, 10th revision (WHO, 1993). The definitions are listed below:

- Visual impairment includes low vision as well as blindness.
- Low vision is defined as visual acuity of less than 6/18, but equal to or better than 3/60, or a corresponding visual field loss to less than 20° in the better eye with best possible correction.
- Blindness is defined as visual acuity of less than 3/60, or a corresponding visual field loss to less than 10° in the better eye with best possible correction.

As described in CIE 196 (CIE, 2011), low vision is referred to as the deteriorated visual function due to diseases and injuries. Such deteriorations in visual function cannot be improved even by using well-corrected glasses. These diseases include macular degeneration, retinal pigmentosa, cataract, and glaucoma. It is important to understand that there are diversities in the type of impairments and wide individual variations in the degree of impairments.

WHO provided a breakdown of the causes of visual impairments, inclusive of blindness: cataracts (33 %), refractive errors (42 %), glaucoma (2 %), age-related macular degeneration (1 %), trachoma (1 %), corneal opacities (1 %), diabetic retinopathy (1 %), childhood (1 %) and undetermined (18 %) (WHO, 2010). The data demonstrate the lack of interventions for easily treated conditions such as uncorrected refractive errors and unoperated cataracts. This is especially true for low-income countries (WHO, 2004b). It should be possible to ease a high number of cataracts and refractive errors if interventions are made available. This breakdown also suggests the importance of understanding that there are various causes of visual impairments to improve lighting for low vision.

CIE 123 (CIE, 1997) addressed the definitions, terminology, and classifications of deteriorated visual functions of low vision. CIE 123 also reviewed relevant articles comprehensively and provided lighting recommendations for people with low vision. It covered the following areas:

- The effect of light on visual functions such as refraction, accommodation, visual acuity, ocular pathology, contrast sensitivity, visual fields and colour vision.
- The effect of increased light levels on performance of people with low vision for practical tasks such as reading, computer tasks, and miscellaneous office tasks.
- The effect on dark adaptation of people with low vision including achromatopia, avitaminosis, cataract, cone degeneration, retinal detachment, diabetic retinopathy, glaucoma, juvenile macular degeneration, age-related macular degeneration, high myopia, optic atrophy, retinitis, and pigmentosa.
- Adverse lighting effects on people with low vision such as disability glare, discomfort glare, photophobia, low or high illuminance/irradiance, actinic kerato-conjunctivitis, cataract, retinal injury, light hazards from ophthalmic instruments, and ocular hazards from natural lighting.
- Basic features of lighting design related to low vision such as geometrical distribution of light in an interior space, uniformity of illuminance, directional and diffused lighting, veiling reflections, flicker, lamp spectra and colour vision efficiency, lamp colour preferences, versatility and self-adjustment of illuminance, cost-savings in lighting installations, choice of lamps and luminaires, lamps, and local lighting.
- Visual aids such as reducing retinal illuminance, chromatically selective filters, increasing retinal illuminance, object magnification, optical magnification, electronic magnification, and visual field expanders.
- Lighting design recommendations for people with low vision as a group. These include recommendations for private homes, residential facilities, schools, working places, public

buildings (e.g. banks, post offices, recreational buildings, museums, art galleries, restaurants, and shops), and outdoor environments for driving and public transport.

As described above, CIE 123 provides a comprehensive review and detailed guidelines for people with low vision. The present report will not challenge CIE 123 to provide a similar review but update the status of studies on the effect of light on visual performance by focusing on papers published from 1997 to present. This update is reported in 3.7.

3 Lighting requirements for visual tasks defined by visual models

What illuminance levels do older people need to obtain the same performance as young people? In 2007, the Illuminating Engineering Society of North America (IESNA) published a recommended practice, "Lighting and the visual environment for senior living", which was approved by the American National Standards Institute (ANSI) (RP-28-07) (ANSI/IES, 2007). For the recommended practice, the IESNA committee on "Lighting for the Elderly and Partially Sighted" reached a consensus of illuminance recommendations for older adults, in which the higher limit in the range of conventional illuminance recommendations is suggested as the minimum illuminance for older people. It seemed reasonable to follow the IES RP-28 committee's consensus. However, since it is important to confirm the rationale of the recommendations, this clause attempts to examine the introducing question through the following approaches.

3.1 Approaches to illuminance requirements for older people and people with low vision

There are several potential approaches to identify illuminance requirements for older people and people with low vision. In this clause literature is investigated concerning the impact of increasing illuminance for older people and people with low vision to improve their visual performances. The following approaches are investigated:

- 1) Application of models representing age-related changes in eyes, e.g. reduction in spectral transmittance of the human crystalline lens and contraction of pupil area;
- 2) application of visual performance models, which include an ageing factor;
- 3) application of contrast sensitivity functions (CSF) of different age groups and people with low vision; and
- 4) comparison of illuminance levels preferred by older people in different experiments.

In the following the above-described approaches are introduced to guide lighting practitioners in selecting an appropriate illuminance for a given task condition (e.g. task size and task contrast) or select an acceptable task condition for a given illuminance. The third approach (CSF) is especially useful for discussion of lighting requirements for people with low vision.

3.2 Age-related changes in spectral transmittance of the human crystalline lens and pupil area

To address how much more illuminance is needed for older people, age-related changes in pupil diameter and crystalline lens transmittance were reviewed and analysed.

3.2.1 Age-related changes in spectral transmittance of the crystalline lens

The optical density of the human crystalline lens changes with age. Pokorny et al. (1987) reviewed literature regarding both the spectral density function and the rate of such changes. They found that the average lens density increases linearly at 400 nm by about 8 % per decade between the ages of 20 and 60, and by about 30 % per decade above 60. They also found that two factors governed the spectral lens density function, which shows a gradual increase during the human life span. One factor has the highest absorption in the UV radiation and shows a rapid increase in the first two decades (0–19 years). This factor is attributed to an increase in lens material. The second factor has peak absorption in the visible spectrum and increases gradually during life. This factor represents an accumulation of a yellowing pigment during life. Based on the above-described literature review, Pokorny et al. developed a model to estimate retinal illuminance reductions with age, based on changes in ocular spectral transmittance. It is known as the two-factor model. They provided a tabulation of the two factors of the average 32-

year-old lens as well as an equation to derive the average spectral lens density functions for observers aged 20–80. Figure 9 depicts the spectral transmittance of human crystalline lenses for different age groups.

By using the two-factor model, Okajima and Iwata (1998) attempted to estimate age-related changes in retinal illuminance with standard illuminants D65 and A. The results showed that the retinal illuminance for a 70-year-old is 75 % of that for a 22-year-old in case of illumination with standard illuminant A (i.e. incandescent) and 72 % in case of illumination with standard illuminant D65. This implies that to obtain a certain illuminance on the retina, older people need approximately 1,3 times the illuminance that young people need.

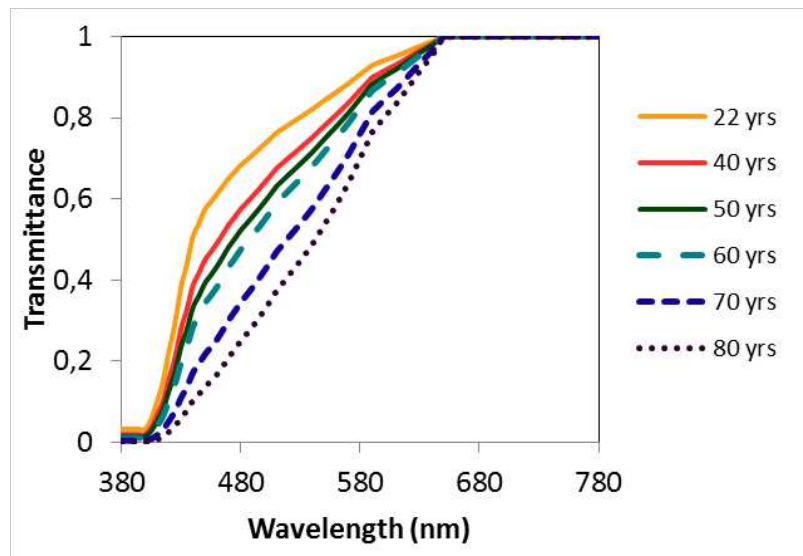


Figure 9 – Spectral transmittance of human crystalline lenses with different age groups

In order to estimate age-related reductions in spectral transmittance, van de Kraats and van Norren (2007) developed a more comprehensive model. The model is composed of five templates that represent optical transmittances of five kinds of human visual media and therefore is regarded as the five-template model. For further analyses of lens transmittance in this report, this model was used.

3.2.2 Age-related pupil reduction

Winn et al. (1994) investigated the effect of age, gender, refractive error and iris colour on light-adapted pupil size in humans. They measured pupil diameters of 91 subjects (aged between 17 and 83) using an objective infrared-based continuous recording technique under five photopic ocular illuminance levels between 2,15 lx and 1 050 lx, and the accommodative status of each subject was precisely controlled at a constant level. The ocular illuminance is the illuminance at the entrance to the eye (on the pupil).

They found that pupil size decreased linearly as a function of age at all illuminance levels. The rate of change of pupil diameter with age decreased from 0,043 mm per year at the lowest illuminance level to 0,015 mm per year at the highest. On the other hand, pupil size was found to be independent of gender, refractive error or iris colour.

By using Winn et al.'s experimental results, Okajima and Iwata (1998) developed a model to estimate changes in pupil size with age. By using the model, it is possible to calculate a pupil size for a certain age subject for a certain illumination condition (e.g. illuminance level and spectral power distribution). Based on the above-described changes in lens transmittance and pupil size, Okajima and Iwata found that a 70-year-old person needs a 2,9 times higher ocular illuminance than a 20-year-old person for the same retinal illuminance for an ocular illuminance of 10 lx. Older people need a 2,6 times higher ocular illuminance at 100 lx and a 2,4 times higher illuminance at 400 lx.

Recently, Watson and Yellott (2012) reviewed seven published models including the Winn et al.'s model and constructed a unified formula that describes the rate of change in pupil diameter as a function of luminance for different visual field sizes, ages and reference ages. The unified formula essentially originated from the formula of Stanley and Davies (1995), which defines pupil diameter based on corneal flux density or adaptation luminance. The unified formula also considers the effect of age on pupil diameter, based on Winn et al.'s data (1994). Figure 10 depicts pupil diameter as a function of adaptation luminance for different age groups calculated by using the unified formula.

In this report, the unified formula provided by Watson and Yellott was used to calculate retinal illuminance for different age groups. This formula does not include the effect of spectral power distribution (SPD) on pupil diameter. It may be possible to take the SPD effect on pupil diameter into account by combining a model proposed by Berman et al. (1990). This model describes the relative contributions of photopic and scotopic luminances to the determination of pupil area. However, such a compensation was not applied in the following analyses in the present report because the model does not include an age factor.

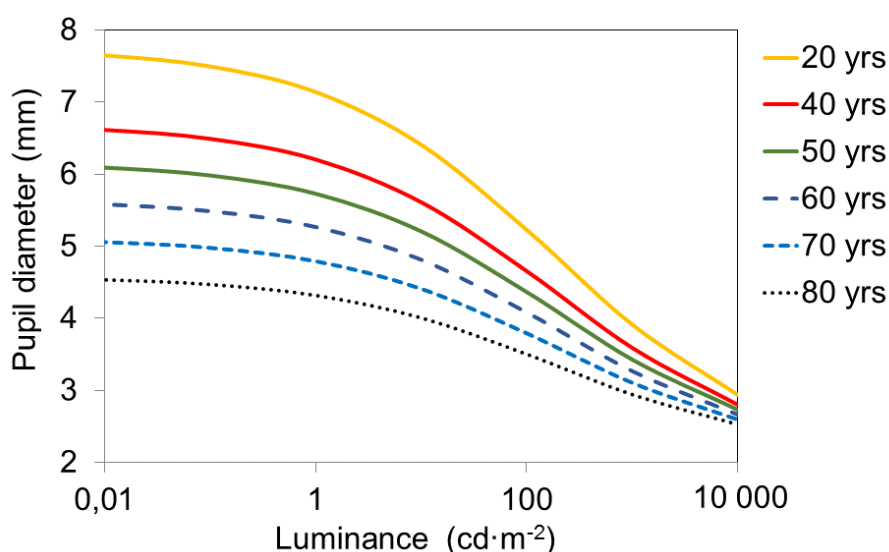


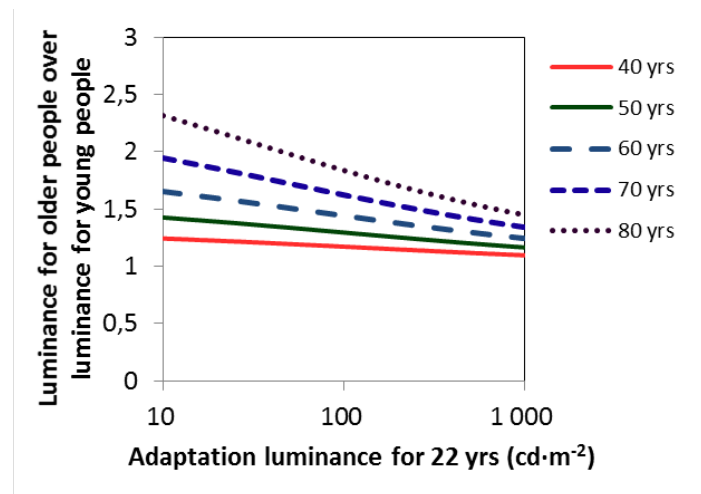
Figure 10 – Pupil diameter as a function of adaptation luminance for different age groups (Watson and Yellott, 2012)

3.2.3 Age-related reduction in retinal illuminance

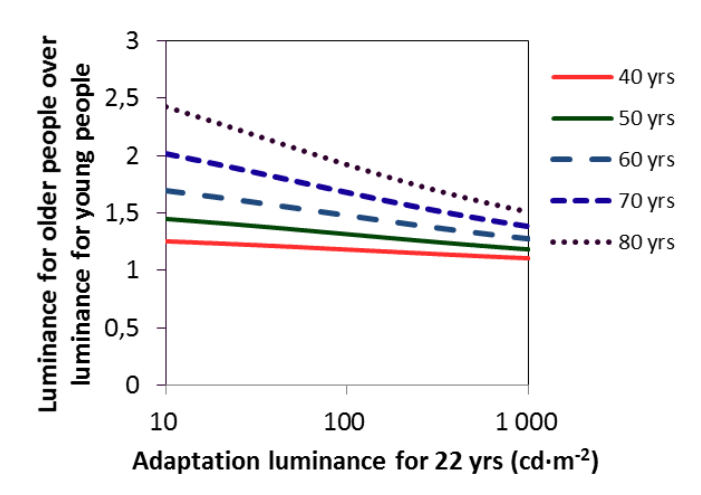
As described above, in order to estimate age-related reductions in retinal illuminance, age-related changes in the spectral transmittance of the crystalline lens and pupil size were calculated by using the five-template model and the unified formula respectively. A Matlab program was developed to calculate how much higher illuminance is needed for older people than for young people, based on a lamp SPD, a target age, and a reference age for different adaptation-field luminances. The ratio of the luminance required for older people to the luminance required for young people was calculated for equivalent retinal illuminance, by that receiving multipliers indicating how much more illuminance is needed for older people (60, 70, and 80 years old) than for young people (22 years old) for a D65 lamp and an illuminant A lamp.

Figure 11 depicts the result of the calculation suggesting that a 1,5 times higher task illuminance is needed for people at an age of 70 years than people at an age of 22 years to equate their retinal illuminances at a luminance of 1 000 $\text{cd}\cdot\text{m}^{-2}$ for both the D65 lamp and the illuminant A lamp. Although this figure is based on adaptation luminance instead of horizontal task illuminance, the luminance multiplier on the vertical axis is equivalent to the illuminance multiplier. A luminance of 1 000 $\text{cd}\cdot\text{m}^{-2}$ is roughly equivalent to a horizontal task illuminance of 400 lx. This implies that, although older people do need higher illuminances on visual task than young people do, twice the illuminance for young people may be more than enough for the older

work force up to around 70 years of age. There was little difference in multiplier between the two-factor model and the five-template model.



(a) Standard illuminant D 65



(b) Standard illuminant A

Figure 11 – Multipliers of luminance needed for older people to that for young people at an age of 22 years calculated by the five-template model for lens spectral transmittance (van de Kraats and van Norren, 2007) and the unified formula for pupil size (Watson and Yellott, 2012)

The results of the calculations also suggested that larger multipliers are needed for a D65 lamp than for an illuminant A lamp. This is because a lamp with more short-wavelength components tends to reduce pupil size. This implies that it may not be appropriate to suggest using a lamp with more short-wavelength radiation for older people. However, it is also noted that the focal depth of retinal image is increased as pupil size decreases. This is because a smaller pupil eases optical aberrations of a retinal image. This calculation does not take the effect of a shorter focal depth on the sharpness of a retinal image into account.

3.3 Visual performance models including ageing factors

There are three types of visual performance models that specify the relationship between adaptation (i.e. background) luminance, target (i.e. font) size, and target contrast in terms of contrast sensitivity (CS), visual acuity (VA) and visual task performance. In fundamental experimental phases to determine CS, subjects identify threshold contrast of targets with different sizes against their backgrounds with different luminances. Visual acuity is determined by asking subjects to identify threshold sizes of targets with different adaptation luminances. Visual task performance is determined by asking subjects to perform visual tasks under various task sizes, contrasts, and background luminances. Dependent variables are often (a) speed to

complete a certain amount of tasks, or (b) amount of tasks completed in a certain period of time. Some of them include ageing factors. This subclause introduces recently developed visual performance models which include ageing factors so that lighting practitioners can determine an appropriate illuminance or target contrast under a given condition.

3.3.1 Visual acuity model

1) Defining visibility

Generally speaking, visibility of a visual stimulus viewed by an observer is determined by the characteristics of the visual stimulus and the observer's visual capability. The characteristics of the visual stimulus are represented by four elements; they are the size (or a visual angle) of the visual target, adaptation (background) luminance, luminance contrast of the visual target to the background, and viewing time. If viewing time is longer than 100 ms, visibility becomes stable regardless of time, and therefore viewing time becomes less important. A flow chart of determining visibility is shown in Figure 12. This chart treats visual response and visual performance, e.g. visible distance or threshold luminance, as visibility. Although human visual capability can be defined by various attributes, visual acuity is one of the most important characteristics among them.

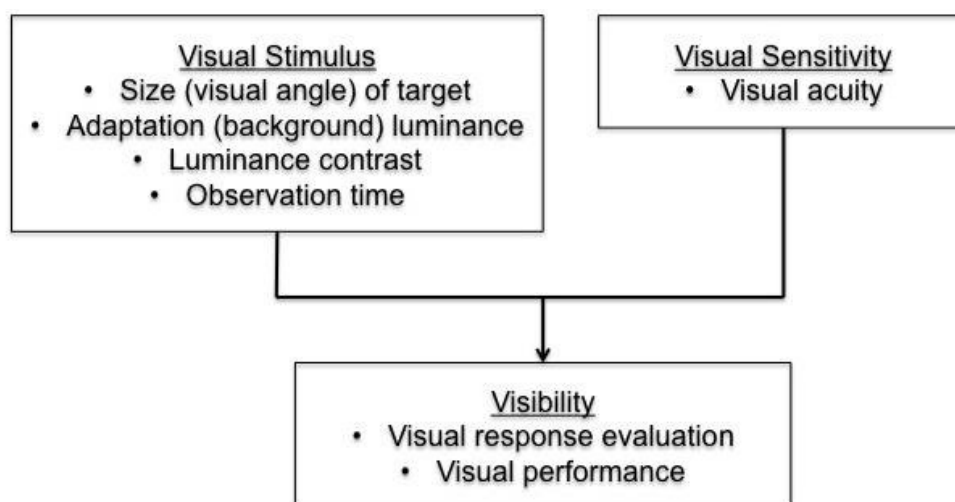


Figure 12 – Flowchart to evaluate visibility

2) Defining visual acuity

Visual acuity represents the ability to resolve fine details. Visual acuity can be defined as the spatial resolution of the visual processing system, and measured by identifying orientations of Landolt rings or identifying letters and numbers on a test chart from a set distance. The test chart characters (e.g. Landolt rings) are represented as black symbols against a white background at high luminance contrasts over 0,9 (in Weber contrast (see Annex A)). A Landolt ring (see Figure 13) is a ring with a gap, thus looking similar to the letter C. The Landolt ring is one of the standard optotypes for visual acuity measurement in most countries. It was standardized, together with measurement procedures, by ISO 8596:2009 (ISO, 2009). The ISO specifies a range of Landolt optotypes and describes a method for measuring distance visual acuity under daylight conditions for the purposes of certification or licensing. The stroke width is 1/5 of the diameter, and the gap width is the same. The gap can be at various positions (usually left, right, bottom, top and the 45° positions in between) and the task of the tested person is to decide on which side the gap is. The size of the Landolt ring and its gap are reduced until the subject makes a specified rate of errors. The minimum perceivable angle of the gap is taken as a measure of the visual acuity. For example a person who can correctly identify a 1,454-mm gap on the Landolt ring from 5 m distance, i.e. a visual angle of one arcminute, has a visual acuity of 1,0. The distance between the observer's eyes and the test chart is set at a sufficient distance to approximate infinity in the way the lens attempts to focus.