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International Commission on Illumination
Commission Internationale de l'Eclairage
Internationale Beleuchtungskommission

TECHNICAL REPORT

Lighting for Older People and People with Visual Impairment in Buildings

CIE 227:2017

UDC:	612.843.35	Descriptor:	Colour contrast. Luminance contrast
	612.843.355		Contrast. sensitivity
	612.843.632		Visual acuity
	612.845.5		Defects of colour vision

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The International Commission on Illumination (CIE) is an organization devoted to international co-operation and exchange of information among its member countries on all matters relating to the art and science of lighting. Its membership consists of the National Committees in about 40 countries.

The objectives of the CIE are:

1. To provide an international forum for the discussion of all matters relating to the science, technology and art in the fields of light and lighting and for the interchange of information in these fields between countries.
2. To develop basic standards and procedures of metrology in the fields of light and lighting.
3. To provide guidance in the application of principles and procedures in the development of international and national standards in the fields of light and lighting.
4. To prepare and publish standards, reports and other publications concerned with all matters relating to the science, technology and art in the fields of light and lighting.
5. To maintain liaison and technical interaction with other international organizations concerned with matters related to the science, technology, standardization and art in the fields of light and lighting.

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2. D'élaborer des normes et des méthodes de base pour la métrologie dans les domaines de la lumière et de l'éclairage.
3. De donner des directives pour l'application des principes et des méthodes d'élaboration de normes internationales et nationales dans les domaines de la lumière et de l'éclairage.
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5. De maintenir une liaison et une collaboration technique avec les autres organisations internationales concernées par des sujets relatifs à la science, la technologie, la normalisation et l'art dans les domaines de la lumière et de l'éclairage.

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Die Internationale Beleuchtungskommission (CIE) ist eine Organisation, die sich der internationalen Zusammenarbeit und dem Austausch von Informationen zwischen ihren Mitgliedsländern bezüglich der Kunst und Wissenschaft der Lichttechnik widmet. Die Mitgliedschaft besteht aus den Nationalen Komitees in rund 40 Ländern.

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1. Ein internationales Forum für Diskussionen aller Fragen auf dem Gebiet der Wissenschaft, Technik und Kunst der Lichttechnik und für den Informationsaustausch auf diesen Gebieten zwischen den einzelnen Ländern zu sein.
2. Grundnormen und Verfahren der Messtechnik auf dem Gebiet der Lichttechnik zu entwickeln.
3. Richtlinien für die Anwendung von Prinzipien und Vorgängen in der Entwicklung internationaler und nationaler Normen auf dem Gebiet der Lichttechnik zu erstellen.
4. Normen, Berichte und andere Publikationen zu erstellen und zu veröffentlichen, die alle Fragen auf dem Gebiet der Wissenschaft, Technik und Kunst der Lichttechnik betreffen.
5. Liaison und technische Zusammenarbeit mit anderen internationalen Organisationen zu unterhalten, die mit Fragen der Wissenschaft, Technik, Normung und Kunst auf dem Gebiet der Lichttechnik zu tun haben.

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Alle vier Jahre findet eine Session statt, in der die Arbeiten der Divisionen berichtet und überprüft werden, sowie neue Pläne für die Zukunft ausgearbeitet werden. Die CIE wird als höchste Autorität für alle Aspekte des Lichtes und der Beleuchtung angesehen. Auf diese Weise unterhält sie eine bedeutende Stellung unter den internationalen Organisationen.

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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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The following members of TC 3-44 “Lighting for older people and people with visual impairment in buildings“ took part in the preparation of this Technical Report. The committee comes under Division 3 “Interior Environment and Lighting Design”.

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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 REDUITE 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'éclairement, 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.

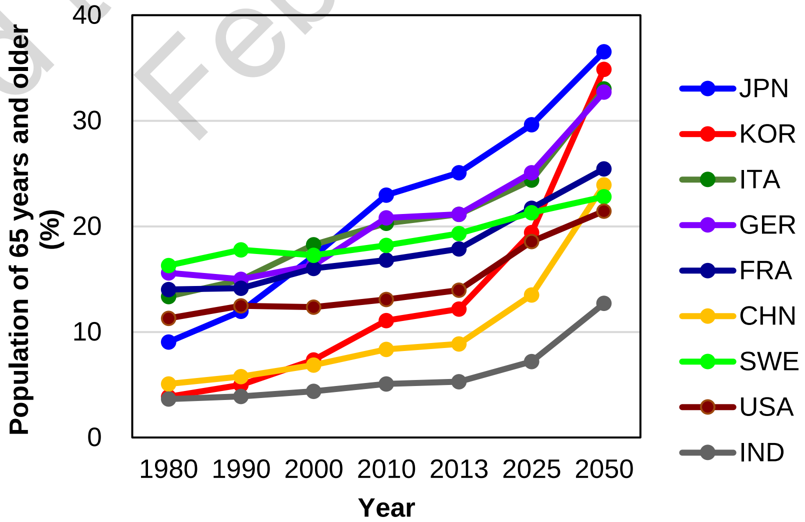


Figure 1 – Ageing population of 65 years and over by country (UN (2013.6) World Population Prospects: 2012 Revision)

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 Mediter-ranean	Europ e	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.

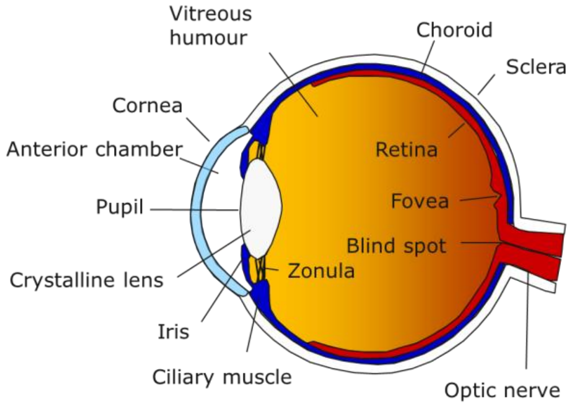


Figure 2 – Section of the human eye

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.

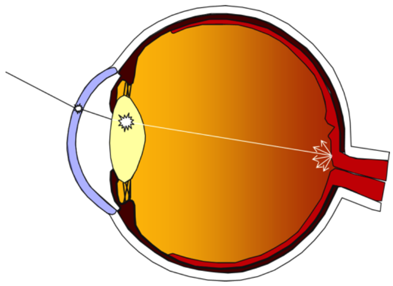


Figure 3 – Origins of intraocular light scatter

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 node 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.

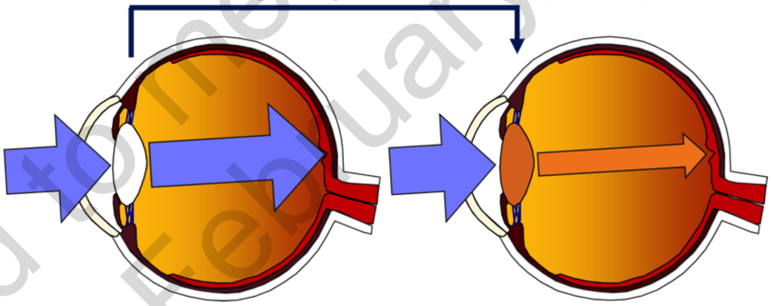


Figure 4 – Reduction of lens transmittance due to lens yellowing

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).

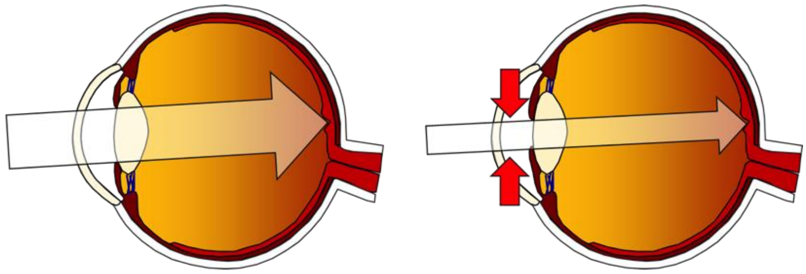


Figure 5 – Effect of a contracted pupil diameter

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.

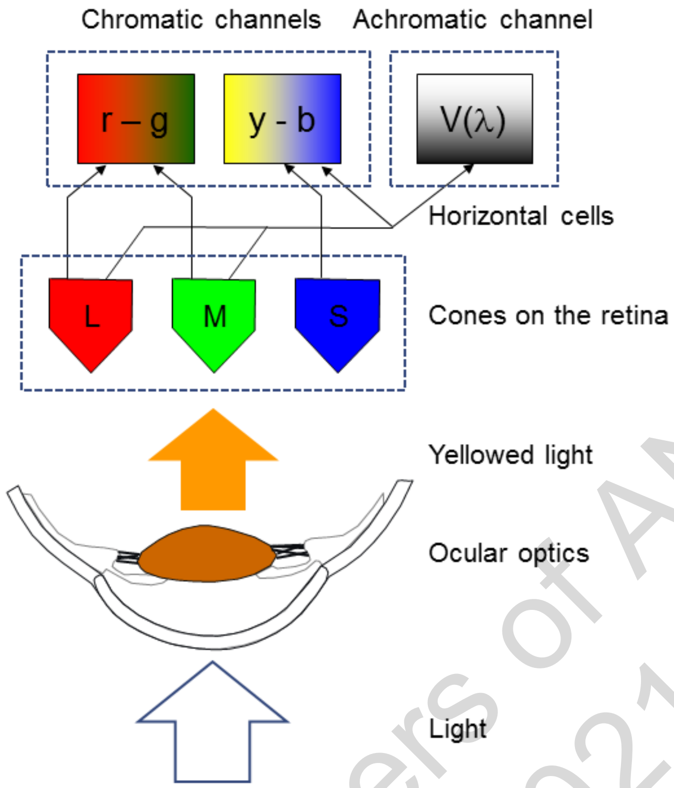
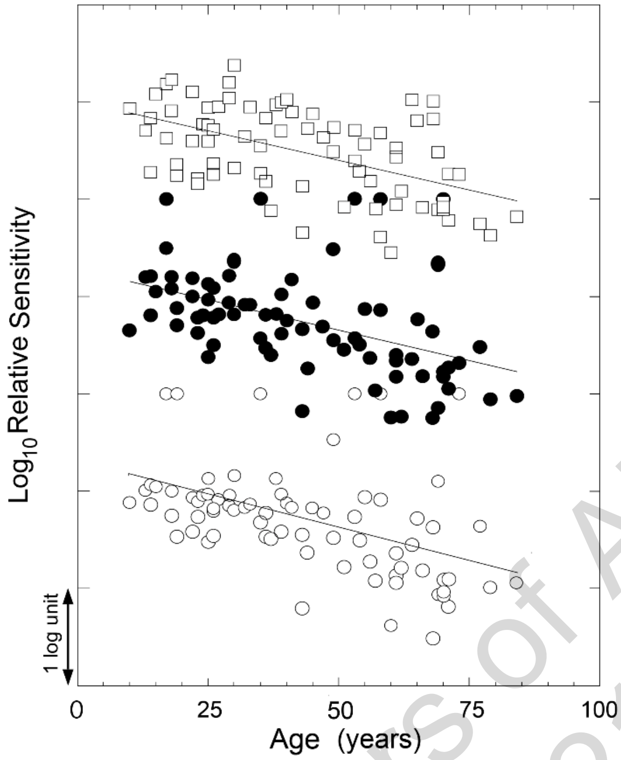


Figure 6 – Classical model of human colour vision and ocular optics

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

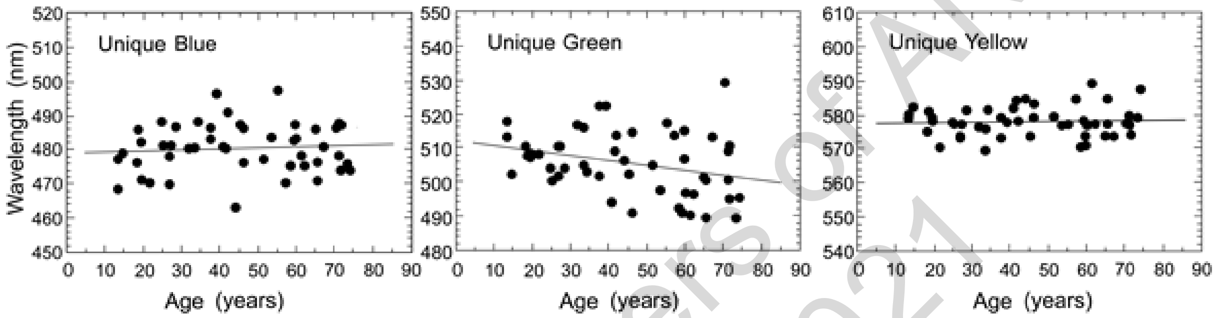
Knoblanch et al. (2001) tested colour discrimination performance for 75 subjects ranging between 20 and 78 years of age by using the Farnsworth-Munsell 100-hue test at five illuminance levels. The results of the experiment revealed a similar tendency of defects in colour discrimination in both young 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 (Schefrin 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 Schefrin (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.

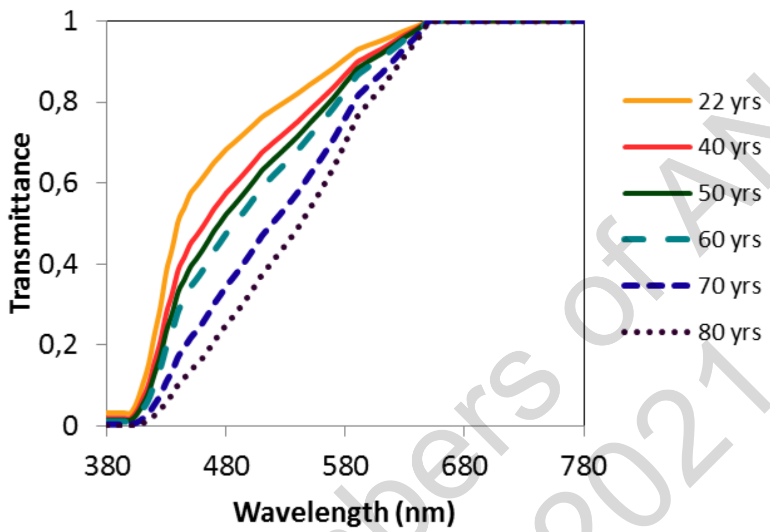


Figure 9 – Spectral transmittance of human crystalline lenses with different age groups

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.

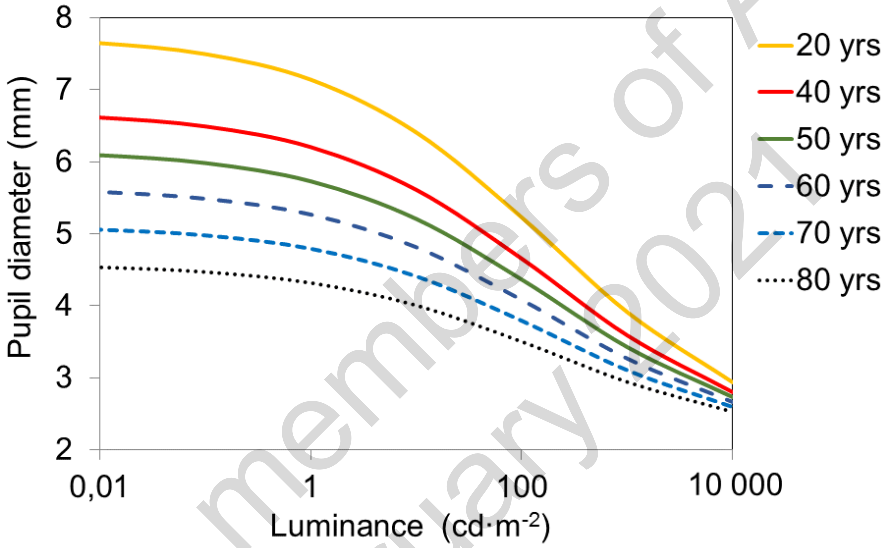
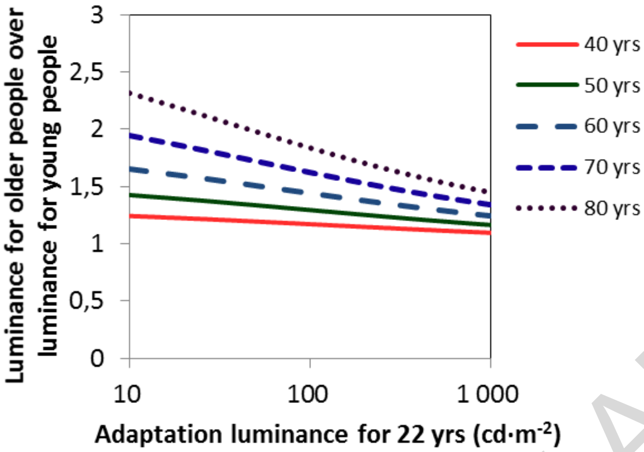


Figure 10 – Pupil diameter as a function of adaptation luminance for different age groups (Watson and Yellott, 2012)

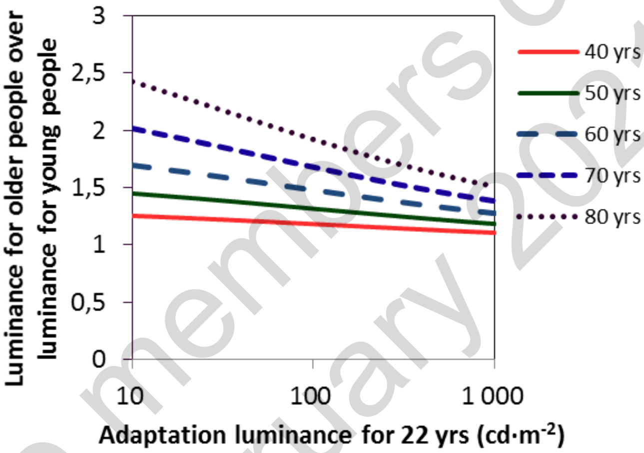
3.2.3 Age-related reduction in retinal illuminance

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 cd·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 cd·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.

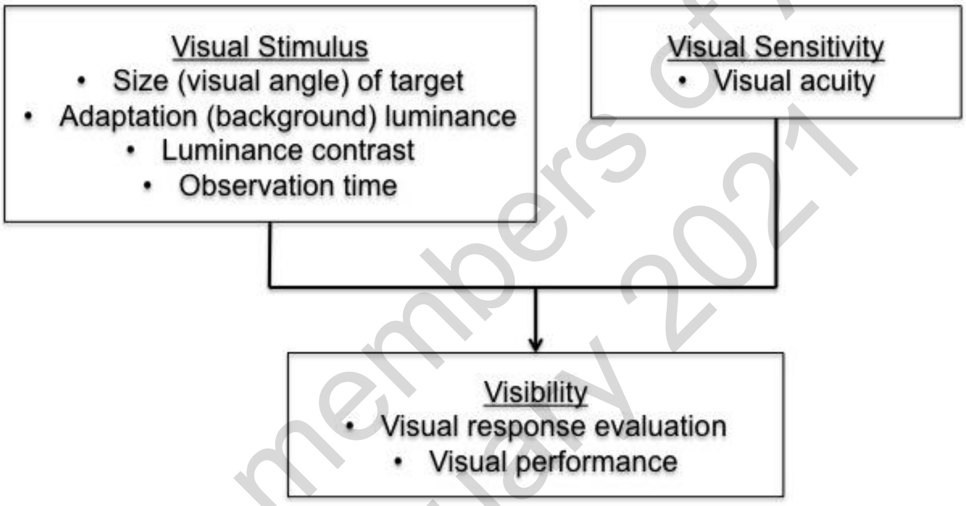


Figure 12 – Flowchart to evaluate visibility

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.

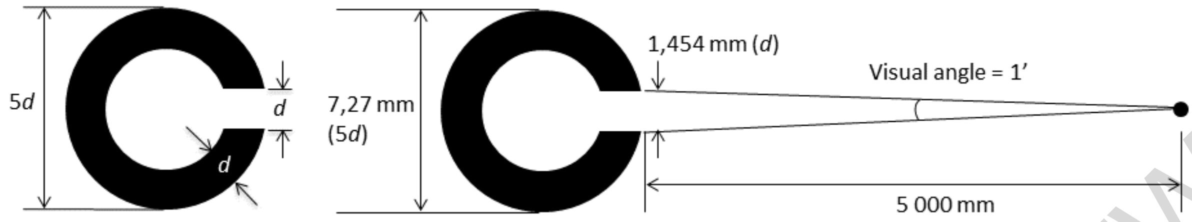


Figure 13 – Landolt ring as the standard optotype for visual acuity test

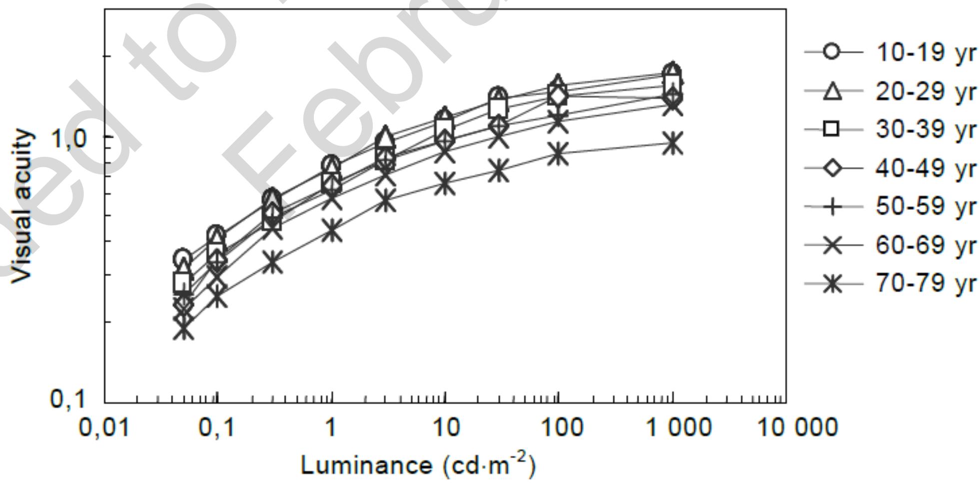
Visual acuity becomes worse as the eye lens becomes more opaque with age, thereby reducing the apparent luminance contrast within image details. Sagawa et al. (2003) showed such an ageing effect on visual acuity as depicted in Figure 14, copied from Figure 13 in CIE196:2011 (CIE, 2011). These data were collected from 111 subjects stratified into 7 different age groups who view targets at a viewing distance of 5 m. The figure shows that visual acuity becomes worse for all age groups as luminance decreases. Table 3 shows visual acuities at two luminance levels of 100 cd·m^{-2} and 200 cd·m^{-2}, and a fixed viewing distance of 5 m for different age groups. The bottom line in the table shows the ratio of the average visual acuity in each of the age groups to that of the 70-year-old group ($VAR_{age/70yr}$, symbol R_V). This table shows data read from Figure 14. For example, the visual acuity of a 25-year-old person at a luminance of 100 cd·m^{-2} and a viewing distance of 5 m can be obtained as 1,554 (as shown in the shaded cell of Table 3). The visual acuity at a luminance of 200 cd·m^{-2} is 1,036 times the visual acuity at 100 cd·m^{-2}. This implies that the effect of luminance on visual acuity may be small.

Based on the data listed in Table 3, regression functions can be developed. It is also possible to estimate visual acuities for people with other ages by using such regression functions. For a luminance of 100 cd·m^{-2} and a viewing distance of 5 m, the visual acuity, V, can be calculated as follows:

$$V = 1{,}9952\ \mathrm{e}^{-0{,}01\,A} \tag{1}$$

where

A is the age of the observer.



NOTE Viewing distance at 5 m. Eyes corrected for best acuity at 5 m. A total of 111 subjects.

Figure 14 – Relationship between visual acuity, luminance and age (copied from CIE 196:2011)

Table 3 – Visual acuity (VA) at 5 m distance based on CIE 196:2011

Background luminance	Age (years)								
	10	20	25	30	40	50	60	70	80
100 cd·m^{-2}	1,806	1,634	1,554	1,479	1,339	1,211	1,096	0,992	0,898
200 cd·m^{-2}	1,871	1,693	1,610	1,532	1,387	1,255	1,135	1,028	0,930
$VAR_{age/70yr}$	1,821	1,647	1,566	1,491	1,350	1,221	1,105	1,000	0,905

Akizuki and Inoue (2004) characterized visual acuity as a function of background luminance for four individual subjects similar in age. As depicted in Figure 15 (left), for each of the subjects, visual acuity generally increases as the background luminance increases until it reaches its plateau. However, the slope of the increase of visual acuity differs depending on individual visual capability rather than age. Each subject usually obtains the maximum visual acuity (MVA, symbol V_m) at a proper viewing distance and high background luminance around 800 cd·m^{-2}. Therefore, they introduced a "visual acuity ratio" against an individual MVA, to examine modulation of visual acuity caused by changes in background luminance. As shown in Figure 15 (right), the relationship between the background luminance and the visual acuity ratio can be specified by a single curve regardless of the individual visual acuity level.

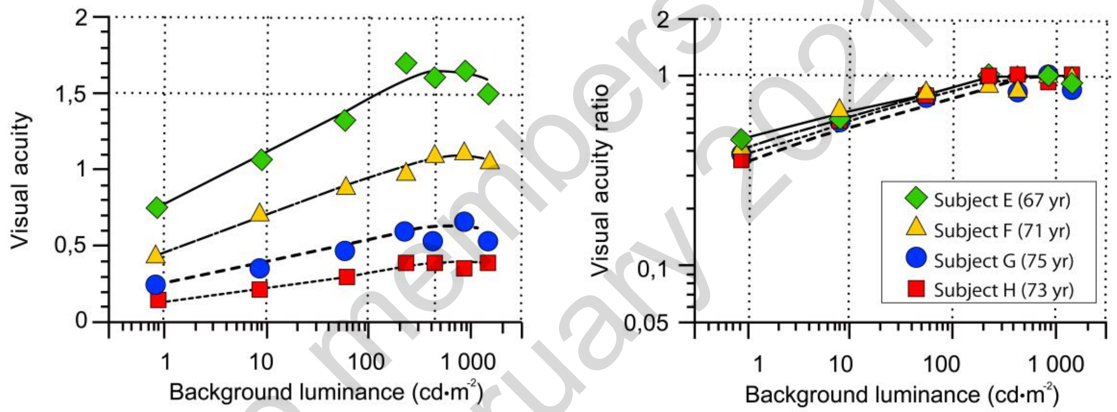
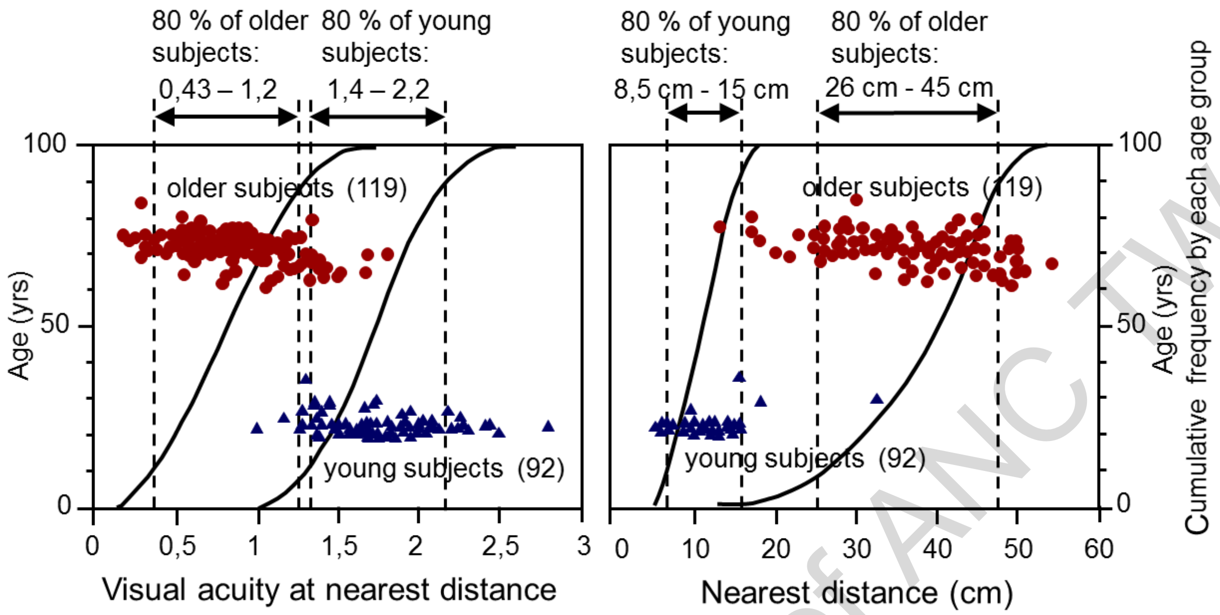


Figure 15 – Individual visual acuities and visual acuity ratios as functions of background luminance

There are significant differences in visual acuity not only among age groups (young/aged) but also among individuals. Akizuki and Inoue (2004) analysed the relationship between age and visual acuity of observers who viewed achromatic Landolt charts with a luminance contrast of 0,93 (in Weber contrast) and a background luminance of 220 cd·m^{-2}, as shown in Figure 16. The data were collected from 211 subjects stratified into 2 different age groups. Visual acuities for 80 % of the young subjects ranged between 1,4 and 2,2. On the other hand, visual acuities for 80 % of the aged subjects ranged between 0,43 and 1,2. The averaged visual acuity of the young subjects was about twice as large as the one of the aged subjects. The "nearest distance" means the minimum focusable distance, which is lengthened with increasing age. The nearest distances of the young subjects with sufficient accommodation capability were short, and ranged between 8,5 cm and 15 cm. On the other hand, the nearest distances of the aged subjects with deteriorated accommodation capability were longer, and ranged between 26 cm and 45 cm. The above-described tendencies imply that visual acuity and nearest distance alter largely according to the subjects' age. More importantly, there are great differences between individuals in each of the same age groups.



	Young (mean ± SD*)	Older (mean ± SD*)
Age	22,9 ± 2,6	71,6 ± 4,0
VA at 5 m distance	1,43 ± 0,42	0,87 ± 0,35
VA at nearest distance	1,80 ± 0,33	0,88 ± 0,34
Nearest distance / cm	11,9 ± 5,2	38,2 ± 8,3
* SD: standard deviation		

Figure 16 – Individual visual acuity and nearest distance of two age groups (Landolt's contrast 0,93 and background luminance 220 cd·m^{-2})

Visual acuity increases as the light level increases. Akizuki et al. (2008) showed changes in visual acuity against background luminance of Landolt charts with a luminance contrast of 0,94 (in Weber contrast) viewed by young and older subjects at a viewing distance of 1,5 m (Figure 17). These data were collected from 60 subjects, stratified into 2 different age groups. The average age of the young group was 25 years and 70 years for the aged group. Figure 17 suggests that visual acuity is improved as background luminance increases. The figure shows large variations among individual results. However, positive correlations were confirmed between visual acuity and background luminance. Equation 2 shows the relationship between luminance and visual acuity for the two age groups. It shows that the visual acuity of the aged group was consistently about half of that of the young group under any background luminance condition. Therefore, Akizuki et al. (2008) proposed an age-related constant, γ, to specify differences in visual acuity with age.

$$V = \gamma(\log_{10} L_b + 1{,}85) \qquad (2)$$

Applicable scope: 0,022 cd·m^{-2} ≤ L_b ≤ 800 cd·m^{-2}

where

V is the visual acuity;

L_b is the background luminance of the Landolt chart with a contrast of 0,94 (in Weber contrast) (in cd·m^{-2});

γ is an age-related constant (see Table 4, e.g. γ = 0,17 for an age of 70 years and γ = 0,34 for an age of 25 years).

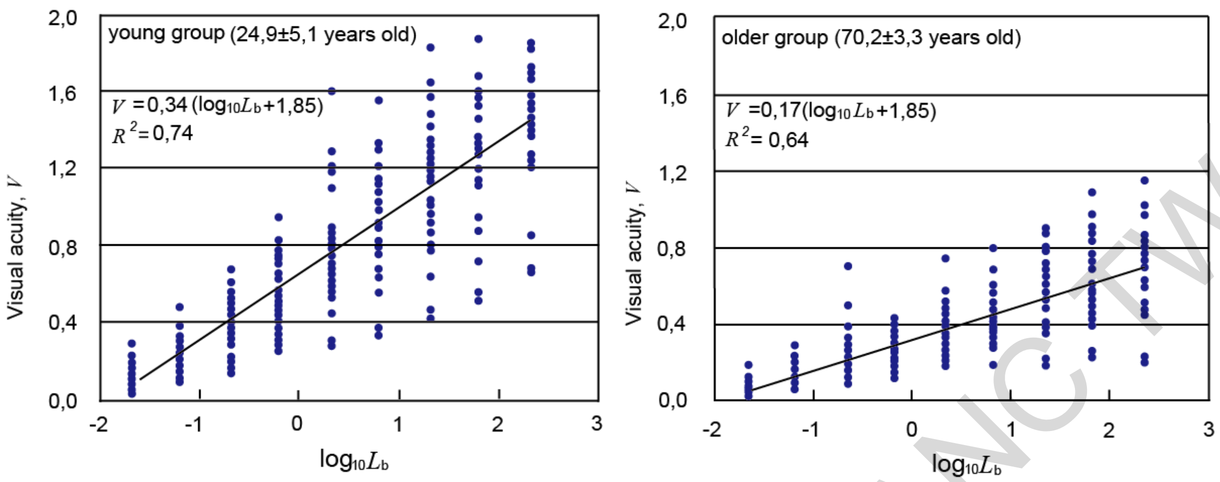


Figure 17 – Relationship between background luminance and visual acuity

3) Visual acuity model to design adequate visual environment

As indicated in Figures 15–17, there are large variations in visual acuity among subjects even if they belong to the same age group. There also appear to be differences in absolute visual acuity among different experiments. Akizuki and Inoue (2004) therefore compared visual acuities among three experiments, but under identical conditions. For instance, visual acuities of a 25-year-old subject viewing a target with a background luminance of 200 cd·m^{-2} at a viewing distance of 5 m were (1) 1,61, (2) 1,43 and (3) 1,41 for (1) CIE 196:2011, (2) Akizuki and Inoue (2004) represented by Figure 16 and (3) Akizuki et al. (2008) represented by Equation 2, respectively.

It is therefore important to consider individual difference in visual acuity in addition to experimental conditions. Thus, this subclause proposes a visual acuity model applicable for designing real visual environments. This visual acuity model is described below.

With Equation 3 age-related constants, γ, can be estimated for any age group. The equation was developed according to $VAR_{age/70yr}$ values in Table 3 and two γ values, 0,34 and 0,17, as shown in Figure 17. Table 4 shows results of calculated constants, γ, for different age groups. The constants, γ, in Table 4 were derived from experimental data only for the two age groups of 25 years and 70 years, while constants, γ, for the other age groups were interpolated or extrapolated by means of Equation 3 (shaded cells in Table 4). This is because the fitting of Equation 3 was much better than a simple linear interpolation.

$$\gamma = 0{,}17 \cdot R_V^{1{,}5445} \qquad (3)$$

where

R_V is the ratio of the average visual acuity for the considered age to that of the 70-year-old group ($VAR_{age/70yr}$) as presented in Table 3.

Table 4 – Age-related constants, γ, calculated with Equation 3

	Age (years)								
	10	20	25	30	40	50	60	70	80
Age-related constant, γ	0,43	0,37	0,34	0,32	0,27	0,23	0,20	0,17	0,15
Maximum visual acuity, V_m	2,044	1,759	1,616	1,521	1,283	1,093	0,951	0,808	0.713

Table 4 also shows the MVA of each age group, calculated by inserting L_b=800 cd·m^{-2} into Equation 2. To deal with individual differences in visual acuity when designing visual environment, it is necessary to use not only the age-related constant, γ, but also MVA.

The reciprocal of visual acuity, V, (see Equation 2) indicates the recognizable threshold of the gap size of the Landolt ring, s_{gap}, measured in arcminutes. The recognizable threshold character size (Japanese character), s_{char}, measured in arcminutes, can be obtained by multiplying s_{gap} by 10 as shown in Equation 4, derived from another study (Inoue and Akizuki, 1998). The effect of contrast (in Weber contrast), C_i, is equivalent to the recognizable threshold defined by Inoue et al. (1990) as shown in Equation 5. The surface illuminance, E, of the visual target is calculated by Equation 6 with the background luminance, L_b, and reflectance of the visual target, ρ. Therefore, the lowest necessary illuminance, E_n, on the surface of the visual target can be expressed by combining Equations 2, 4, 5 and 6 into Equation 7. The above described studies used Japanese characters composed of about eight strokes on average while Latin characters are composed of four strokes at most (in case of “E”). Therefore, when the results of these studies are applied to English characters, care is needed. For instance, the lowest necessary illuminance according to Equation 7 can be lower for English characters. It has not been investigated how much the illuminance can be lowered for English characters to be recognized.

$$s_{\text{char}} = 10 \cdot s_{\text{gap}} = \frac{10}{V} \tag{4}$$

$$C_1 \cdot s_{\text{gap},1} = C_2 \cdot s_{\text{gap},2} \tag{5}$$

$$E = \frac{L_{\text{b}} \cdot \pi}{\rho} \tag{6}$$

$$E_{\text{n}} = \frac{\pi}{\rho} \cdot 10^{\left(\frac{10}{\gamma \cdot s_{\text{char}}} - 1{,}85\right)} \cdot \frac{1{,}0}{C_i} \tag{7}$$

Applicable scope: 0,022 cd·m^{-2} ≤ L_b ≤ 800 cd·m^{-2}

Table 5 shows the results of a case study using Equation 7 and calculating the lowest necessary illuminance on a document surface needed to see and recognize characters of a given size.

Generally documents use white paper and black ink, so the reflectance of paper is high, e.g. 0,87 and the luminance contrast between paper and ink is also high, e.g. 0,93 (in Weber contrast). At a surface illuminance of approximately 1 lx a young subject can just recognize characters on a white paper when the character size is 24′ (i.e. 8,0 point). An aged subject requires a surface illuminance of at least approximately 15 lx to see and recognize the same characters.

A sheet of newspaper uses black ink on recycled paper, so the reflectance of paper may be as low as 0,35 and the contrast of inked letters to the background is about 0,82 (in Weber contrast). Therefore, the illuminance necessary to recognize 24′ characters on the newspaper are higher than that for a sheet of white paper; e.g. approximately 3 lx for the young and approximately 44 lx for the aged.

If the typical character size on newspaper is increased to 36′ from 24′ (as above) the necessary illuminance can be reduced to approximately 1 lx for the young (25 years of age) and approximately 7 lx for the aged (79 years of age). If a typical character size on newspaper is reduced to 16′, the necessary illuminance level for the aged should be much higher, e.g. 734 lx while the young requiring only approximately 11 lx. For very challenging reading tasks, the differences in the necessary illuminance level between age groups become even more extreme although such a case is not listed in Table 5. For example, to read a character size of 15′ (i.e. a font size of 5 points) printed on newspaper (ρ = 0,35) with a luminance contrast as low as 0,4 (in Weber contrast), a 25-year-old person requires at least approximately 29 lx, while a typical 60-year-old person (γ = 0,20, see Table 4) needs at least 736 lx. An average 70-year-old person would require 2 646 lx to accomplish this task. In order to ensure visibility, it is far more effective to increase the size of the visual targets than to increase the illuminance.

Table 5 – Case study calculations of the minimally required task illuminance that is needed to execute a reading task successfully for different ages

Paper type	ρ	s_{char} (′)	s_{char} (point*)	Contrast**	Necessary illuminance E (lx)		E ratio of older/young
White paper	0,87	24	8,0	0,93	young, 25 yr (γ=0,34)	1	15
					older, 70 yr (γ=0,17)	15	
Newspaper	0,35	16	5,3	0,82	young, 25 yr (γ=0,34)	11	67
					older, 70 yr (γ=0,17)	734	
	0,35	24	8,0	0,82	young, 25 yr (γ=0,34)	3	15
					older, 70 yr (γ=0,17)	44	
	0,35	36	12,0	0,82	young, 25 yr (γ=0,34)	1	7
					older, 70 yr (γ=0,17)	7	

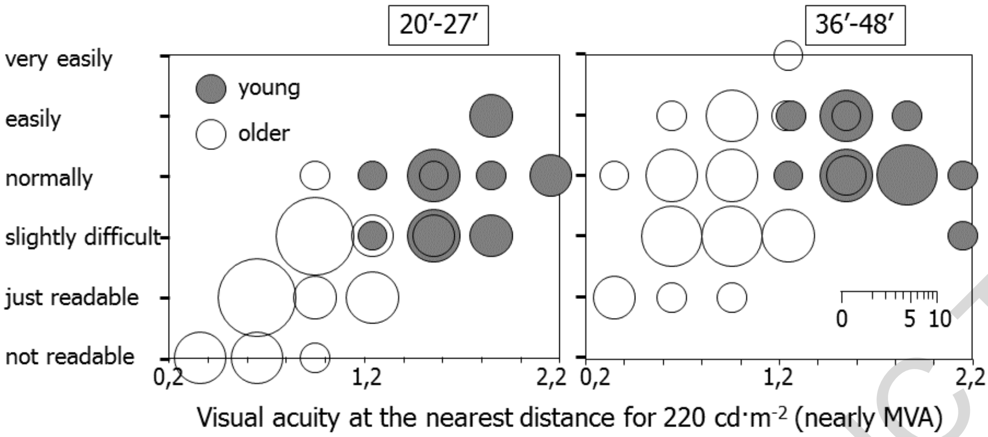
* 1 point = 3′
** Contrasts in this table are given as Weber contrasts.

Moreover, ratios of illuminance necessary for the aged to that for the young are shown in Table 5. In order to be able to read the 24′ characters, the illuminance necessary for the aged should be about 15 times higher than that for the young. For a sheet of newspaper with 36′ characters the ratio is smaller as compared to a sheet of newspaper with 24′ characters. In order to design proper visual environments for the aged, it is important to take not only lighting but also sizes of visual targets into consideration.

4) Visual acuity model for designing comfortable visual environment

It should be noted that the former case study is based on the threshold illuminance, or the lowest illuminance necessary for a character to be barely visible. Where it is necessary to provide a comfortable visual condition that allows observers to read documents easily, the illuminance on the document surfaces should be much higher than the illuminance values given in Table 5. It is therefore important to consider another model for higher-demanding “readability” evaluation.

Inoue and Akizuki (1998) examined proper illuminances for various background luminances on a work surface while taking subjects’ visual acuities into account for the reason described above. The study employed 46 subjects stratified into two age groups (young and older). Under various lighting conditions, these subjects read B5 size documents on which letters (Mincho typeface) with five font sizes (from 15′ to 65′) were printed. The subjects evaluated the readability of the letters. For each of the subjects, visual acuity at the shortest distance at which an object of a given size can be seen clearly, was also measured by using a Landolt test chart at a background luminance of 220 cd·m^{-2} and a luminance contrast of 0,93 (in Weber contrast) to determine the subject’s MVA. Figure 18 shows the relationship between MVA and readability evaluations in the case of a document with surface illuminance of 30 lx, character sizes between 20′ and 27′, and 36′ and 48′ respectively, and a luminance contrast of 0,93 (in Weber contrast). The readability level of “just readable” in Figure 18 closely corresponds to the legibility threshold. In this figure, the size of the circle represents the number of responses. The readability becomes higher as visual acuity increases in both age groups. Moreover, overlaps between the circles of the young group and those of the older group show that readability levels of subjects are similar regardless of age as long as their visual acuities are the same. Therefore, the ageing effect on readability can be expressed by decreases in MVA.



NOTE The scale in the right figure indicates the size of the circle corresponding to the number of responses.

Figure 18 – Relationship between visual acuity and readability for surface illuminance 30 lx, character size 20′–27′ and 36′–48′, and contrast 0,93 (in Weber contrast)

The evaluation method becomes very complex because the relationship among five factors (target size, contrast, adaptation illuminance/luminance, observer's MVA and readability level) must be considered. Therefore, in order to present a simpler and clearer evaluation method, Inoue and Akizuki (1998) proposed the quantity "Relative Acuity" (RA, symbol V_r) that is a product of MVA (symbol V_m) divided by 10 and threshold character size (s_{char}, measured in arcminutes) as defined in Equation 8. The threshold character size is the smallest size which viewers can see.

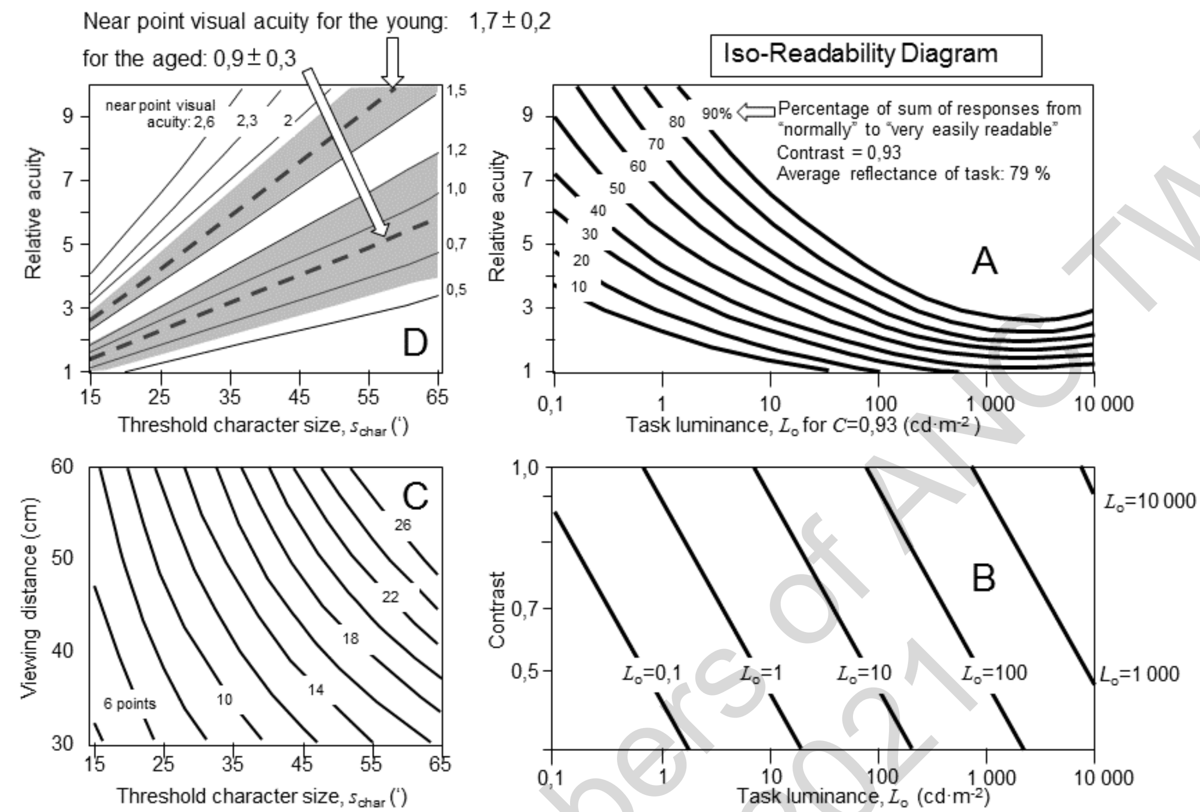
$$V_r = \frac{V_m}{10} \cdot s_{char} \tag{8}$$

Figure 19 shows four diagrams that are used to evaluate readability of letters, relative acuity, sizes of letters, task luminances, and task luminance contrasts. Figure 19-A represents the relationship between target luminance and RA for different readability levels for a fixed task luminance contrast of 0,93 (in Weber contrast). The iso-readability curves in Figure 19-A correspond to the percentages of sums of responses for readability levels between "can read normally" and "can read very easily" to all responses. In other words, Figure 19-A can be used to determine a task luminance, L_0, for a given RA and a given readability level. However, this diagram allows a lighting practitioner to determine task luminance, L_0, only for a default task luminance contrast of 0,93 (in Weber contrast). To convert the default task luminance, L_0, to a task luminance, L, for a different task contrast, Figure 19-B should be used.

Figure 19-B shows the relationship between task luminance contrasts and task luminances for various default task luminances, L_0. As described above, the default task luminance has been selected for a given readability level and a given RA in Figure 19-A. All regression lines in Figure 19-B have a single inclination of −0,23 that was derived from the authors' experiment (Inoue and Akitsuki, 1998). Combining Figure 19-A and Figure 19-B allows a lighting practitioner to determine a required task (i.e. desk) luminance for a given readability level based on the luminance contrast and the relative acuity of the task.

Figure 19-C shows the geometrical relationship between letter size (in points), viewing distance (in centimetres) and threshold character size (in arcminutes). This diagram can be used to convert a threshold character size (in arcminutes) to the letter size (in points) and vice versa. Figure 19-D shows the relationship between the threshold character size (in arcminutes), individual visual acuity (at the shortest distance at which objects can be seen clearly), plotted on the ordinate on the right hand side, and the relative acuity (RA), plotted on the ordinate on the left hand side.

The set of the four diagrams enables lighting practitioners to evaluate the level of readability for n various lighting conditions. Annex B demonstrates how to use these four diagrams.



NOTE L_o is the target surface (i.e. desk) luminance set to the contrast C=0,93 (in Weber contrast).

Figure 19 – Diagram to evaluate readability taking visual acuity into account by introducing relative acuity

3.3.2 RVP model

In order to assess visual performance for supra-threshold tasks in actual environments such as offices, schools and roadways, several visual performance models have been developed (Weston, 1945; Blackwell, 1970; Rea and Ouellette, 1991). These models use common variables, i.e. illuminance on a visual task target for a certain target size and the contrast of the visual target against the background. Some of the existing models include ageing factors, which consider the effect of visual changes with age on visual performance. One of these models is the Relative Visual Performance (RVP) model (Rea and Ouellette, 1991). By using the RVP model, it was estimated how much more illuminance is needed for older people than for young people.

In the RVP model, visual performance is defined in terms of the speed and accuracy with which visual information is processed. To evaluate illuminated visual tasks in terms of visual performance a computational model was developed, which relates measureable salient aspects of the visual environment (i.e. target contrast, target size, and background luminance) to measureable human responses (i.e. visual response time and accuracy). The visual performance is quantified as the ratio of visual performance under a given condition to the maximum visual performance under which RVP equals 1.

The RVP model demonstrates that increasing retinal illuminance will result in an improvement of visual performance. The RVP model takes the effect of age on visual performance into account to adjust the retinal illuminance by employing Weale's model (1961). A decreased pupil size and an increased absorption of light in the eye reduce the retinal illuminance. This reduction is calculated based on Weale's estimates of the thickening of the crystalline lens and reductions in pupil area with age. Both factors reduce transmission and increase scatter, resulting in a retinal illuminance reduction, P, which can be calculated according to

$$P = 1 - 0{,}017(A - 20) \tag{9}$$

where

A is the age, in years, between 20 and 65.

Equation 10 provides an estimate of the age-dependent losses in retinal contrast, ε, between the ages of 20 and 65:

$$\varepsilon = 1 + \left[(0{,}113/45)(A - 20)\right] \tag{10}$$

By using the RVP model, differences in relative visual performance between different age groups for the same visual task can be calculated. For instance, Figure 20 depicts relative visual performance as a function of task illuminance for young and older people under a normal task condition. As the normal task condition in this calculation a background with reflectance of 0,8 (recycled white paper) was employed, a target contrast of 0,75 (newspaper) (in Weber contrast) and a letter area extending to a solid angle of 3,5 μsr (roughly equivalent to 10-point letter size). The figure shows that the 65-year-old needs about five times the illuminance (e.g. 2 500 lx) of that for a 20-year-old (e.g. 500 lx) in order to perform the same visual task.

It should be noted that the RVP of the 65-year-old is 0,968 and 0,985 for the 20-year-old at 500 lx. This implies that this metric is not sensitive to a subject's age when the task condition is better than normal. Figure 20 shows that visual performance within the range of the illuminance recommendations for normal visual tasks is generally on the plateau regardless of age. This implies that it may be difficult to determine a multiplier of how much more illuminance is needed for older people than for young people unless the minimum acceptable RVP is specified. In addition, the RVP model is not applicable to people over 65 years of age.

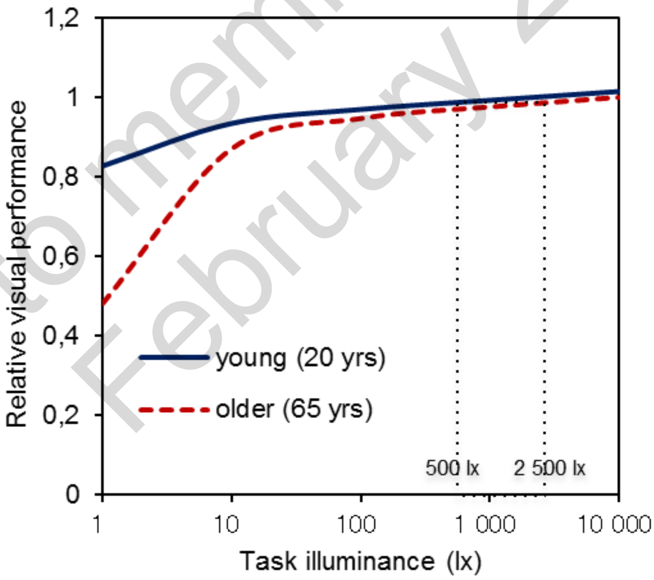


Figure 20 – Relative visual performance as a function of task illuminance for young and older age groups

3.4 Contrast sensitivity

Contrast sensitivity is one of the most important performance measures of the visual system, and describes the visual performance of how fine the details are that a person can identify. Researchers often depict this visual performance by using the contrast sensitivity function (CSF). CSF is defined as a series of reciprocal numbers for threshold modulation contrasts of grating patterns with different spatial frequencies under different background luminance conditions.

3.4.1 Contrast sensitivity of older adults with normal vision

Researchers have studied age-related changes in CSF and suggested that young people have better contrast sensitivities than older people at spatial frequencies above two cycles per degree under photopic light conditions (Crassini et al., 1988). For older people, spatial contrast sensitivity loss under photopic conditions increases with increasing spatial frequency. Major contributors to such spatial contrast sensitivity deficits in older adults are optical factors as opposed to neural factors (Owsley, 2011).

CIE 196 (CIE, 2011) shows three sets of CSF data for different ages, but for a limited number of background luminances (Owsley et al., 1983; Higgins et al., 1988; Ujike and Sagawa, 2002). CIE 196 also introduces a formula for an age-related multiplier, which increases the required contrast for older people, recommended by ISO 9241-303 (ISO, 2011). This formula represents the minimum contrast required for characters designed for electronic displays as a function of the background display luminance, and therefore it is not useful for us to identify appropriate illuminance levels for older people.

Since there had been few studies on the effects of both ageing and illuminance on CSF, another study measured CSF under four illuminance conditions (1 lx, 10 lx, 100 lx, and 1 000 lx) for 15 young subjects and 15 older subjects (Iwata et al., 2001). The results of the experiment showed that contrast sensitivity was worse in older subjects than in young subjects at high spatial frequencies, especially at low illuminance levels. However, at higher illuminances, older people do not need much higher illuminances than young people to perform easy visual tasks with large fonts.

3.4.2 Contrast sensitivity of people with low vision: Effects of mean luminance

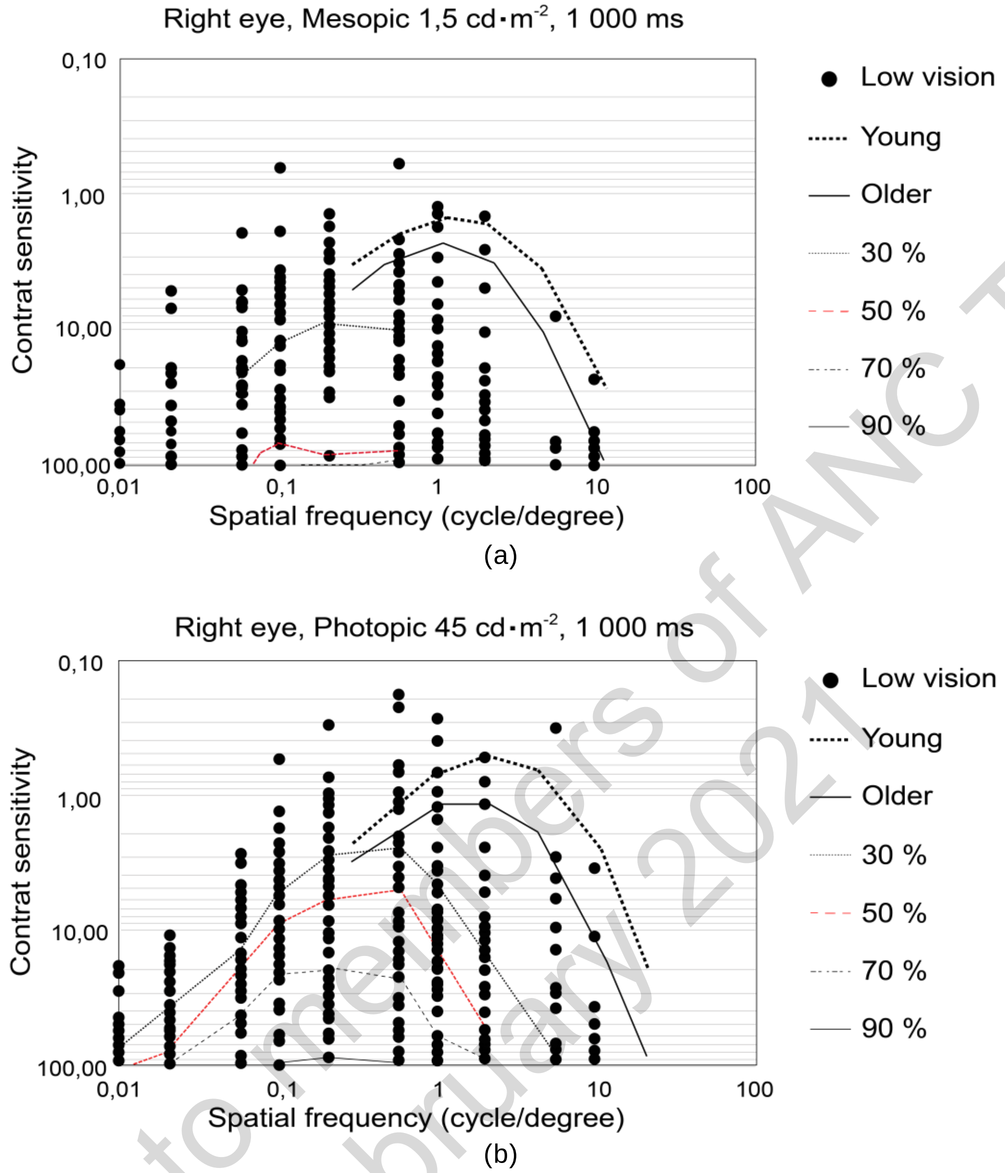
Figure 21 presents results of CSF measurements for 72 people with low vision (Itoh and Sagawa, 2010). Contrast sensitivity was measured by defining the minimum contrast required for a subject to identify the orientation of a 30-degree-diameter grating pattern with a given spatial frequency. The measurements were conducted for the grating patterns with different spatial frequencies in photopic and mesopic conditions with monocular viewing. Each grating pattern was presented to the subject for one second. The abscissa shows the spatial frequency in cycles per degree (cpd). The ordinate represents the contrast sensitivity, which is the reciprocal of the contrast (in Michelson contrast (see Annex A)) threshold, to detect the grating pattern. Both axes are expressed on a logarithmic scale.

The small closed dots denote individual data of the 72 people with low vision. It is readily apparent that the data are widely distributed along with the ordinate, meaning that low vision of various types exists with different sensitivity. Because of this large variation, it is inappropriate to take an averaged value. The median (50 %) and 30-, 70-, and 90-percentile values are presented. To compare the present data with the CSF of people with normal vision, the averaged data of young and older people are also presented in Figure 21.

It is readily apparent that the CSF data of the subjects with low vision show much lower sensitivity than that of young or older people with normal vision. The most remarkable difference in sensitivity between people with low vision and people with normal vision can be seen at the higher frequency region greater than 1 cpd.

In the case of the photopic condition, the peak of the function of low vision shifts to the lower frequency region. It peaks at around 0,5 cpd, whereas the peak of the normal CSF is at 3 cpd or 4 cpd. This is a consideration when designing visual signs, since their fine details might not be recognized, even in the photopic condition, by people with low vision.

Similar results were obtained for mesopic conditions. It is noteworthy that the function at the mesopic condition showed clear reduction of sensitivity at higher frequency regions also, underscoring the difficulty for people with low vision to see details of objects in inadequately illuminated environments.



NOTE 1 Data of young (dotted line) and older (solid line) people with normal vision shown in both graphs for comparisons are obtained from the above described study (Ujike and Sagawa, 2002). In the mesopic case (upper graph (a)) these data were measured at an adaptation luminance of 0,45 cd·m^{-2}, i.e. at a lower level than for the 30-, 50-, 70-, and 90-percentile values (measured at 1,5 cd·m^{-2}). In the photopic case (lower graph (b)) the adaptation luminance was the same for all cases (45 cd·m^{-2}). The viewing time was 1 000 ms in all cases.

NOTE 2 Contrasts in these charts are given as Michelson contrasts.

Figure 21 – Contrast sensitivity for (a) mesopic condition (1,5 cd·m^{-2}) and (b) photopic condition (45 cd·m^{-2})

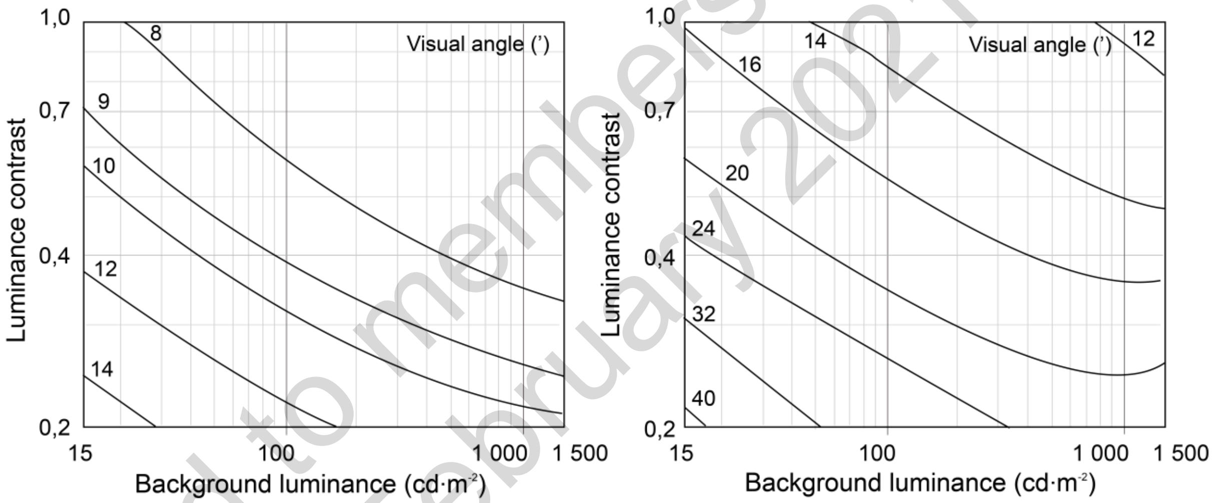
3.5 Illuminance preference for older adults with normal vision to perform visual tasks

As described above, it is possible for lighting practitioners to estimate an appropriate illuminance on a given task for a person with a certain age by using visual models derived from laboratory experiments. However, to confirm the correctness of what the visual models suggest, it is also important to understand which illuminance level people prefer for a given visual task.

One of the above described studies (Okajima and Iwata, 1998) conducted an experiment by employing 16 young subjects (22 years old on average) and 28 older subjects (69 years old on average). In this experiment each of the subjects were asked to select preferred illuminances under two lighting conditions (fluorescent lamps with 3 000 K and 5 000 K). The results indicated that older people needed a 1,5 times higher illuminance than young people in the case of 3 000 K lamps. In the case of 5 000 K lamps, older people needed twice the illuminance of young people. This demonstrates that age-related reduction in retinal illuminance calculated by the five-template model and the unified formula in 3.2.3 works well.

In order to identify preferred illuminances, several other studies conducted simulations and experiments. A study of Iwata et al. (2001) suggested that several times higher illuminance levels are required for older people compared to young people to have a visual acuity of 0,5 and over, even in bright environments. This study also suggested that older people require the same illuminance levels as young people for the visual acuity of approximately 0,1. This finding implies that young and old people require similar illuminance levels to read font sizes of 32 points (requiring the visual acuity of 0,1) and above. However, in order to read font sizes of 7 points (requiring the visual acuity of 0,5) and below, older people require at least twice as much light compared to young people.

Another study investigated preference of illuminance by asking subjects to evaluate readability of printed characters. Based on the study, Satoh et al. (1999) provided the equivalent visibility diagrams of three visual factors (background luminance, target size and contrast) for typical young observers. The data were collected from 10 young subjects. Although this study employed only young subjects, this study created a framework showing the relationships between background luminance and luminance contrast for certain readability levels at 50-% certainties (Figure 22).



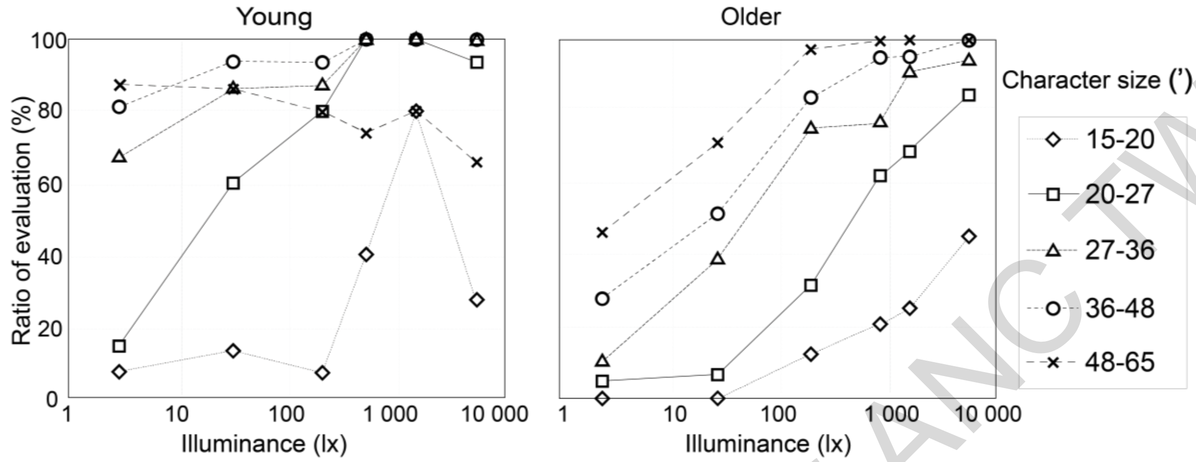
(a) Boundary condition of “just readable” (b) Boundary condition of “readable without stress”

NOTE 1 Curves indicate 50-% results of 10 young subjects.

NOTE 2 Contrasts in these charts are given as Weber contrasts.

Figure 22 – Relationship between background luminance, luminance contrast and target size to equivalent visibility

Inoue and Akizuki (1998) added the age effect to the above described curves in Figure 22 by examining how illuminance and character size on a document affected the readability of the characters for young and older subjects. The study employed 46 subjects: 15 young subjects (average age: 23 years; average near-vision visual acuity at 220 cd·m^{-2}: 1,7) and 31 aged subjects (average age: 69 years; average near-vision visual acuity at 220 cd·m^{-2}: 0,9). For the visual acuity measurements in this experiment, each of the aged subjects looked at a test chart at the shortest distance at which he/she can see the test chart while each of the young subjects looked at the test chart at a fixed distance of 30 cm. Figure 23 depicts the results. The vertical axis of the figure represents the percentage of subjects who regarded readability of given characters as better than the level of “normally readable”. For young subjects, readability of documents decreases when illuminance becomes too high, for instance over 5 000 lx, or when character sizes are too large. For aged subjects however, higher illuminances and larger character sizes resulted in easier reading.



NOTE The vertical axis represents the percentage of responses as better than "normally readable".

Figure 23 – Effects of illuminance and character size on readability

3.6 Illuminance effects on people with low vision

There have been many studies on the effects of light level on visual acuity, contrast sensitivity and visual performance of people with low vision. Many studies support that increasing illuminance improved visual functions and visual performance of patients suffering from age-related macular degeneration (ARMD) (Sloan et al., 1973; Cornelissen et al., 1995). Recent research supported these findings (Kuyk and Elliott, 1999; Fosse et al., 2001; Wood and Owens, 2005; Haymes and Lee, 2006). However, it is also true to say that too much light may often impair the visual function of a patient with ARMD (Bailey and Lovie, 1976). In addition, patients with astigmatism, cataract and juvenile macular degeneration had maximal acuity at low lighting levels (Hartmann et al., 1980).

3.6.1 Illuminance requirements for people with low vision

CIE 123 (CIE, 1997) concluded that it is difficult to specify the visual performance of low vision as a group because there are large individual differences within any sample and between samples. This is true even for people suffering from ARMD; individual differences make generalization difficult. To a large extent the study of low vision must be the study of the individual.

The present report follows the above described conclusion of CIE 123, and does not provide any illuminance recommendations for people with low vision as a group. However, since an increased task illuminance improves visual capability of people with certain causes of low vision, it is still important for lighting practitioners to have luminaires with dimmers so as to tune task illuminance to the level that each individual needs.

3.6.2 Effect of correlated colour temperature of a lamp on visual performance of people with low vision

A study compared effects of lamps with different spectral power distributions on visual performance of people with low vision (Hymes and Lee, 2006). However, there have not been significant differences in the degree of effectiveness. Another study investigated visual performance of 13 subjects with ARMD under four spectral conditions: standard (clear envelope) incandescent, daylight simulation (blue tint envelope) incandescent, compact cool white fluorescent and halogen incandescent (Eperjesi et al., 2007). This study confirmed that a clinically significant effect of spectral radiance on reading for people with ARMD is unlikely. This implies that lighting practitioners may not have to take spectral power distributions of lamps into account when selecting a lamp for people with low vision more carefully than for fully sighted people.

3.6.3 Colour similarity recognized by people with low vision: Effects of illuminance

To design visual environments appropriate for people with low vision, it is important to consider how colours appear to people with low vision. Figure 24 represents subjects' span of colour similarity under photopic and mesopic conditions expressed as values of five planes in the Munsell Colour System for two colours: 5R4/14 (red) and 5B5/8 (blue). The contour lines show the percentages of subjects (10 % and 50 %) who considered the colour to be similar or the same. In general, the probability of colour being judged as similar was higher when the test colours were close to the fundamental colour and low or zero when test colours were sufficiently distinct from one another. Some low-similarity distributions were observed in the broader area.

Comparing the data obtained for unimpaired subjects (Sagawa and Takahashi, 2003), spans of similarity for low vision were broader under both photopic and mesopic conditions. Under mesopic conditions (3 lx), each span of fundamental colour was broader than it was for the photopic condition (500 lx), with the same tendency found among unimpaired young subjects. However, the span of colour expanded in young unimpaired subjects (e.g. from green to bluish in the photopic condition towards green or bluish colour for the same value and not toward the yellowish or purplish colour), whereas the span for low vision subjects was broader (e.g. into the yellowish to purplish area).

From this study, high levels of similarity were found in colours that were close to the fundamental colour. This result implies that colour discrimination will be enhanced when two colours are highly dissimilar.

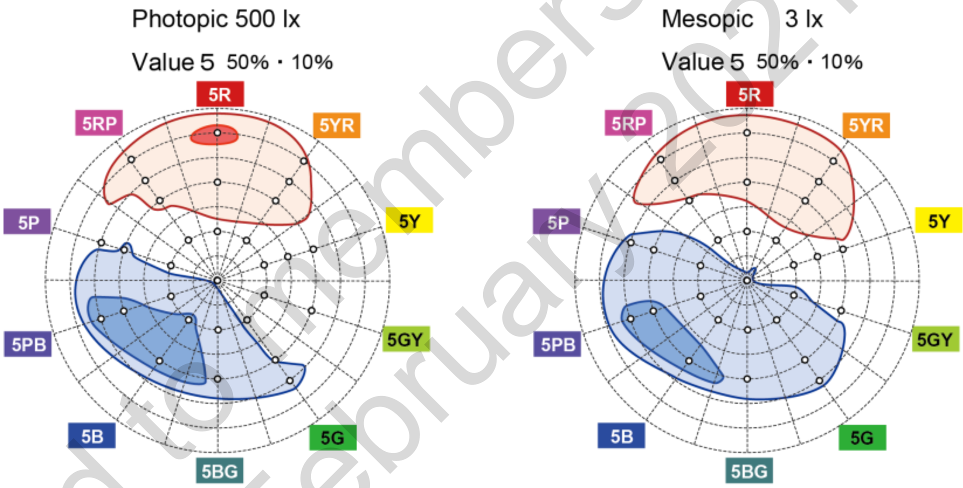
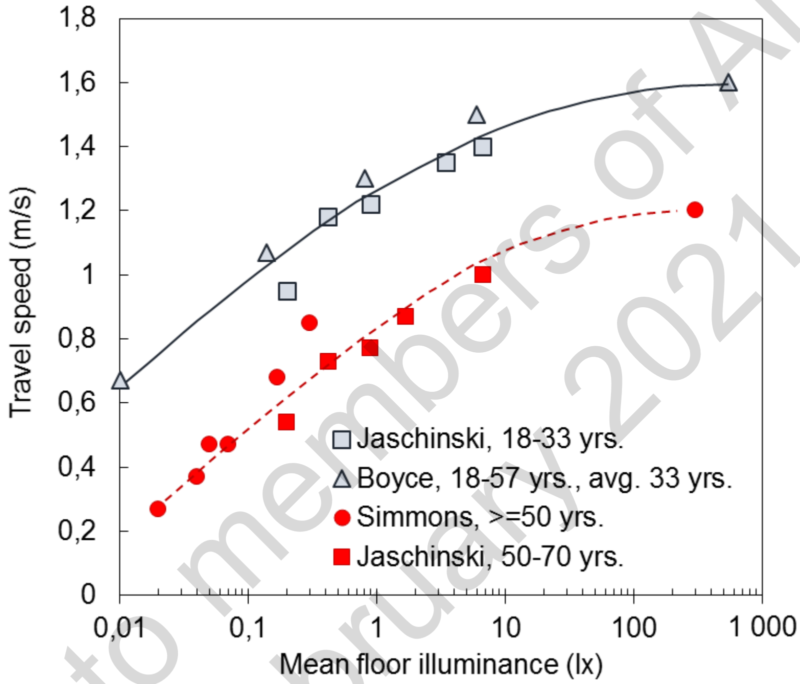


Figure 24 – Colour similarity under photopic condition (500 lx) and mesopic condition (3 lx) (figures provided by Nana Itoh)

4 Lighting requirements for older people to move through escape routes

Even in an interior space, a minimum acceptable illuminance should be considered under an emergency situation. Boyce organized relevant studies on escape lighting in his textbook (Boyce, 2003). There have been several important studies on evacuation performance by using speed of movement over escape routes. Simmons (1975) studied the relationship between illuminance and travel speed of evacuees who are 50 years or older. The result was referenced by the ISO/CIE Standard on emergency lighting (ISO/CIE, 2007), which set the standard floor illuminance to 1,0 lx for a travel speed of 1,0 m·s^{-1}. Jaschinski (1982) compared travel speeds between young and older subjects, and found that older people walked more slowly than young people. Boyce (1985) carried out evacuation examinations at an open-plan workplace, and indicated lighting requirements for evacuation under power outage and fire. Boyce (2003) concluded from the above described studies including older subjects that a mean illuminance on the floor of the escape route of at least 0,5 lx was sufficient to ensure movement over the escape route without collisions with objects.

However, in order to understand differences in travel speed between young and older people, it is useful for lighting practitioners to consult diagrams provided by Webber (1984), and Ouellette and Rea (1989). These diagrams depict the relationship between travel speed and floor illuminance. For instance, Ouellette and Rea (1989) showed an age-related decline in travel speed by comparing the results of Simmons (1975), Jaschinski (1982), and Boyce (1985). Although Boyce's data include middle-age subjects in the young subject group, they are treated as young subject data. This is because their average age was 33 years. Figure 25 shows the relationship between the speed of movement and the mean illuminance on the floor of the escape route. The figure shows that there is a steep decline in movement speed as illuminance is reduced from the highest mean illuminance which is used in normal offices. It is also clear that older people are slower in speed by 0,4 $m \cdot s^{-1}$ than young people. This figure shows that older people need about a hundred times higher illuminance than young people in order to move as fast as young people when the floor illuminance is low. However, that is not applicable for office lighting because the maximum mean speed of older people is already saturated at typical office illuminances.



NOTE The regression curves have been fitted by eye.

Figure 25 – Mean speed of movement in cluttered and furnished spaces by young and older people for different mean floor illuminances (after Ouellette and Rea, 1989)

4.1 Travel speed when walking considering luminance condition and visual acuity

Akizuki et al. (2008) addressed floor luminance requirements for corridors, and elucidated age-related differences in travel speed in conjunction with subjects' visual acuities. Figure 26 shows the relationship between travel speed and floor illuminance for young and older subject groups. At a floor illuminance of 1,0 lx and lower, the average speed of the young group was faster than the aged group. If the floor illuminance is higher than 3,0 lx, the travel speeds are similar in both age groups. The relationship between visual acuity and travel speed for each of the two age groups is shown in Figure 27. Each of the visual acuities was calculated by first converting the floor illuminance of the travel space into floor luminance by using Equation 6, and second substituting the obtained floor luminance for L_b in Equation 2.

In Figure 27, any age difference is not evident, implying that travel speed is not varied by age as long as visual acuity is constant. The relationship shown in Figure 27 suggests that travel speed, v, of an observer who completely adapts to a floor luminance in a corridor seems to be correlated with visual acuity regardless of age as expressed by Equation 11 (coefficient of determination R^2=0,80 for young and R^2=0,86 for older age groups respectively). If visual acuity under a visual condition in an emergency situation (e.g. with fire and smoke) can be estimated, travel speed of a subject can be predicted by the following equation:

$$v = \begin{cases} 1{,}56 \cdot V^{0{,}12} & \text{if } V < 0{,}25 \\ 1{,}32 & \text{if } V \geq 0{,}25 \end{cases} \tag{11}$$

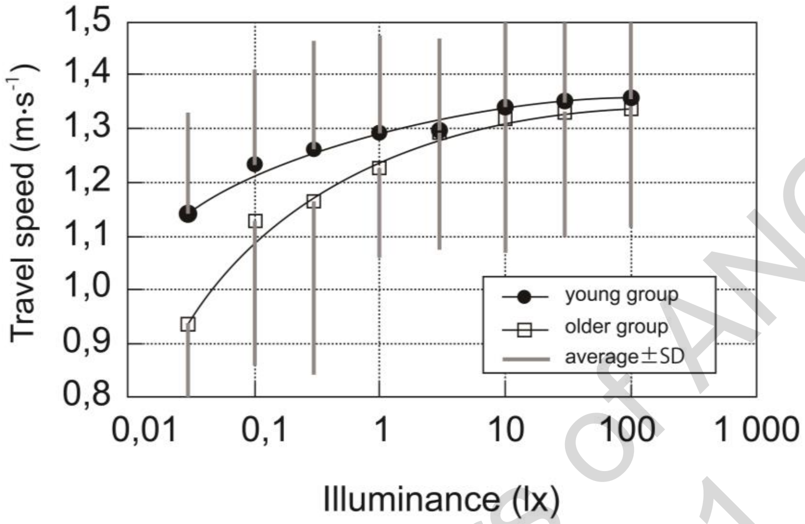


Figure 26 – Travel speed as a function of illuminance

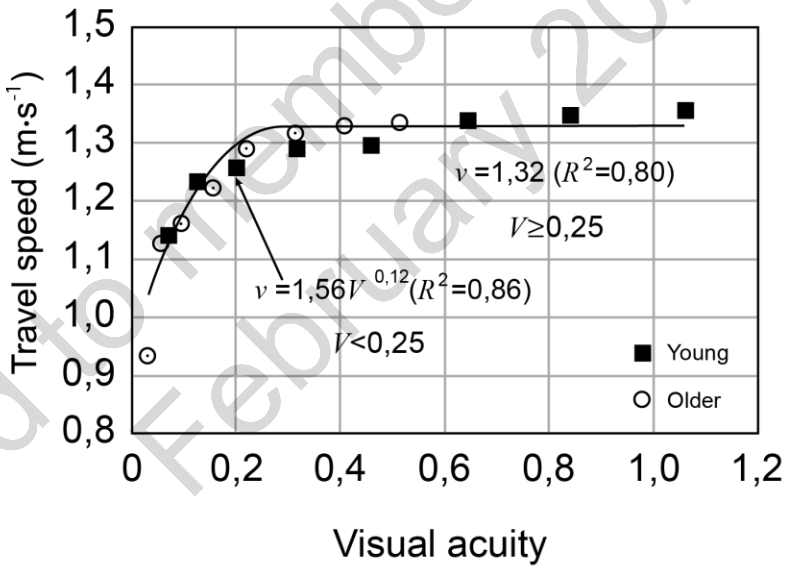


Figure 27 – Travel speed as a function of visual acuity

Table 6 shows a case study that calculates travel speeds of young and aged subjects for four surface finish types on the floor by using Equations 1 and 11. After the travel speed reaches 1,32 m·s⁻¹, any increase in floor illuminance, E_f, does not improve the travel speed.

Travel speeds of young subjects can reach 1,32 m·s⁻¹ at a floor illuminance of 3,0 lx for any floor type. In contrast travel speed of aged subjects is slower under the same illuminance (3,0 lx), and a floor illuminance of 10 lx is needed in order for the aged subjects to reach the same travel speed of 1,32 m·s⁻¹. Table 6 also suggests that the surface finish type on the floor (i.e. its reflectance, ρ) affects the travel speed of subjects.

Table 6 – Case study for calculating travel speeds of young and older subjects for different surface finish types on the floor

Floor type	ρ	E_f / lx	0,3	1	3	5	7,5	10	15
wood	0,43	travel speed of young subject m·s⁻¹	1,25	1,31	1,32	1,32	1,32	1,32	1,32
red brick	0,35		1,22	1,29	1,32	1,32	1,32	1,32	1,32
concrete	0,30		1,19	1,27	1,32	1,32	1,32	1,32	1,32
asphalt	0,20		1,07	1,21	1,30	1,32	1,32	1,32	1,32
wood	0,43	travel speed of aged subject m·s⁻¹	1,15	1,21	1,26	1,30	1,32	1,32	1,32
red brick	0,35		1,12	1,19	1,24	1,29	1,31	1,32	1,32
concrete	0,30		1,09	1,17	1,23	1,28	1,30	1,32	1,32
asphalt	0,20		0,99	1,11	1,20	1,25	1,28	1,31	1,32

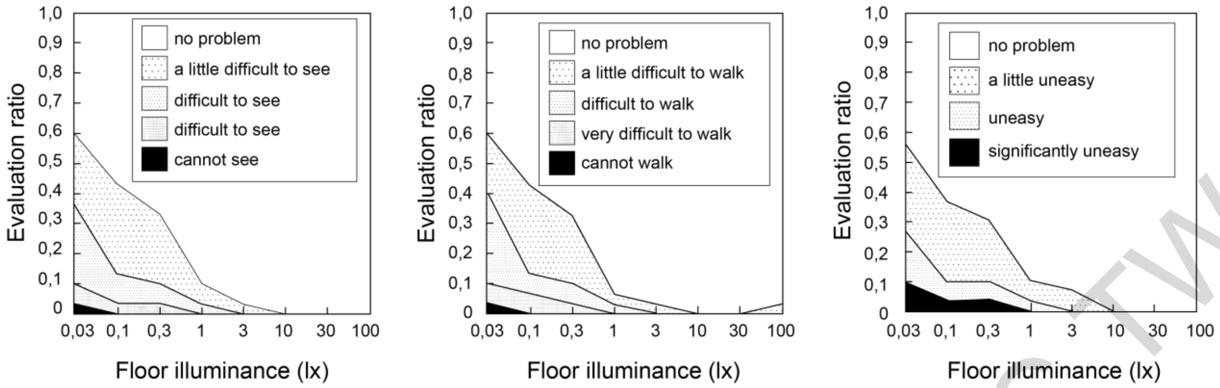
Under an emergency situation in an interior space, electric power often fails and the light level within the space rapidly decreases. Since such a rapid change in light level reduces an evacuee's luminance adaptation level, the evacuee's visual ability will decrease, too. When the illuminance in an adaptation space, E_a, is much higher than the illuminance in an adjacent travel space, E_t, the evacuee's travel speed in the travel space seems to be very slow initially, but it may increase until it reaches the maximum travel speed at the completely adapted state as the evacuee travels farther. To further analyse this, the relationship between the ratio of adaptation illuminances of the two spaces, $R_{E,\text{adapt}}$ (=E_a/E_t), and the ratio of travel speeds in the two spaces, $R_{v,\text{adapt}}$, was examined. The larger the value of $R_{E,\text{adapt}}$ the larger the adaptation transition and physiological load and therefore the larger the deterioration in visibility. With a ratio of adaptation illuminances, $R_{E,\text{adapt}}$, of 10 (i.e. illuminance in the adapting space was 10 times that in the travel space), the ratio of travel speeds, $R_{v,\text{adapt}}$, was nearly 1, meaning no deterioration in visibility. Regression analyses were applied for cases in which $R_{E,\text{adapt}}$ values were higher than 10. The results showed that the same formula as Equation 11 can be applied for evacuees' travel speeds when $R_{v,\text{adapt}}$ is lower than 100. However, a different regression curve between visual acuity, V, and the travel speed, v (in m·s⁻¹), should be applied for such incomplete adaptations when $R_{v,\text{adapt}}$ is higher than 100 as given by Equation 12.

$$v = \begin{cases} 1{,}56 \cdot 1{,}12^{\lg(R_{E,\text{adapt}})} \cdot V^{\left(0{,}08 \cdot \lg(R_{E,\text{adapt}}) + 0{,}12\right)} & \text{if } R_{v,\text{adapt}} \geq 100; V < 0{,}25 \\ 1{,}56 \cdot V^{0{,}12} & \text{if } R_{v,\text{adapt}} < 100; V < 0{,}25 \\ 1{,}32 & \text{if } R_{v,\text{adapt}} < 100; V \geq 0{,}25 \end{cases} \quad (12)$$

4.2 Subjective assessments of satisfaction with lighting on escape routes

Jachinski (1982) and Boyce (1985) obtained subjective assessments of satisfaction with lighting on escape routes, and found that mean floor illuminances of 3 lx and 7 lx were sufficient for young and older subjects respectively.

Akizuki et al. (2008) explored the relationship between travel speeds and subjects' subjective assessments for young and older subjects. Figure 28 shows an example of the relationship between floor illuminance and the results of psychological evaluations for three questions, i.e. (a) visibility of travel space, (b) easiness to walk, and (c) anxiety while walking, from 30 aged subjects. For all the evaluations, the ratio of negative responses became smaller while the ratio of "no problem" responses became greater with increases in floor illuminance. In order to focus on analysing what conditions create negative states, responses of "no problem" were eliminated from further consideration.



(a) Visibility of travel space (b) Easiness to walk (c) Anxiety while walking

Figure 28 – Relationship between floor illuminance and evaluation ratio (aged group)

Figure 29 shows the relationship between travel speed and negative response ratio. Without regard to conditions, the general tendency was that as visibility and travel speed increased, negative response decreased. This tendency seems to show that subjective evaluation has a linear relationship with travel speed. Equation 13 indicates the relationship between travel speed and negative response ratio for each of the three questions. Each of the evaluations showed a strong correlation with travel speed. The frequency of negative response was highest to the question of “visibility of travel space”, and lowest to the question of “anxiety while walking”, possibly because anxiety was an outcome of various factors. Under travel speeds of less than 1,05 m·s⁻¹, all subjects responded negatively to at least one of the questions.

$$P = \begin{cases} k_1 - 2,2\,v & \text{if } v < k_2 \\ 1 & \text{if } v \geq k_2 \end{cases} \qquad (13)$$

where

- P is the ratio of negative responses to each of the questions, meaning the ratio of cumulative negative responses (e.g. “a little difficult to walk”, “difficult to walk”, “very difficult to walk”, and “cannot walk”) to all responses;
- v is the travel speed in $m{\cdot}s^{-1}$;
- k_1 is a coefficient for each of the psychological states. The coefficient k_1 is 3,3 for “visibility of travel space”, 3,1 for “easiness to walk”, and 2,9, for “anxiety while walking”;
- k_2 is a coefficient of the threshold speed for each of the psychological states. The coefficient k_2 is 1,05 $m{\cdot}s^{-1}$ for “visibility of travel space”, 0,95 $m{\cdot}s^{-1}$ for “easiness to walk”, and 0,86 $m{\cdot}s^{-1}$ for “anxiety while walking”.

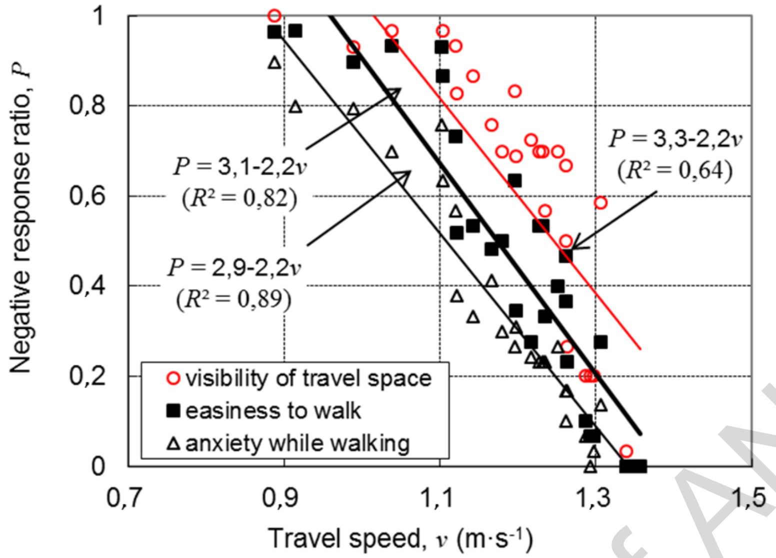


Figure 29 – Relationship between travel speed and negative response ratio for each evaluation

5 The impact of disability and discomfort glare

What kinds of measures are useful to ease the impact of glare caused by high-luminance light sources on visual performance and visual comfort for older people? To answer this question, this clause reviews how the effects of high-luminance light sources on both disability glare and discomfort glare change with age. Since there have been few studies about the effect of glare on the visually impaired, this clause does not consider any measures of glare reduction for people with visual impairments.

5.1 Disability glare

People experience increased intraocular scatter with age due mainly to increased proteins in the crystalline lens. The cornea, vitreous humour, and sclera also contribute to this intraocular scatter. Intraocular scatter reduces the amount of light on the image and increases the amount of light on the background (Boyce, 2003). The amount of light covering both the image and the background reduce the luminance contrast of the retinal images. This is known as disability glare. Disability glare is quantified by comparing it to the reduction in contrast caused by adding a certain luminance to both a task and its background. This luminance is known as equivalent veiling luminance and quantified by Equation 14 (Vos, 1984). The mechanisms of disability glare are well known, and therefore the ageing factor reflects the mechanisms of disability glare appropriately. Equation 14 was derived from experiments employing young subjects, while Equation 15 considers the effect of age on equivalent veiling luminance (Vos, 1995). Further details regarding the calculation of equivalent veiling luminance can be found in CIE Collection 1999 (CIE, 1999).

$$L_{\mathrm{v}} = \frac{k\,E}{\theta^2} \qquad (14)$$

$$L_{\mathrm{v}} = 10\left(1+\left(\frac{A}{70}\right)^4\right)\sum\frac{E_n}{\theta_n^2} \qquad (15)$$

where

L_{v} is the equivalent veiling luminance (cd·m⁻²)

E is the illuminance at the eye caused by the light source (lx)

Θ is the angle between the light source and the line of sight (°)

k coefficient (=10)

A	is the age of the observer (years)
E_n	is the illuminance at the eye caused by the nth light source (lx)
θ_n	is the angle between the nth light source and the line of sight (°)

In interior lighting, disability glare (or veiling luminance) is usually not listed in lighting requirements. However, older adults may frequently experience difficulty in reading books and seeing computer displays near bright light sources as shown in Figure 30. This is especially true when there are large unshaded windows near a visual task or behind a computer screen. Therefore, it is important for lighting practitioners to understand how much veiling luminance exists in the field of view especially when designing lighting installations for older people and people with low vision. Recent image processing techniques help calculate veiling luminance by using Equation 15, and convert a photographed image with luminance information into a retinal image, seen by young (22 years) and older people (65 years) Figure 30 is an example of such calculations. The difference in the retinal image may not appear to be large except for a larger halo around the task light for a young observer (22 years) than for an older observer (65 years).

However, how much veiling luminance is acceptable for interior spaces has not been determined yet. In any case, any bare lamps should be completely shielded from older adults and people with low vision, and windows treated with window coverings, exterior shades and awnings, or other architectural treatment to mitigate glare. Although architects and interior designers have tended to select white interior surfaces in order to maximize utilization factors recently, such white interior surfaces may become bright surfaces that can result in veiling reflections for older users. These light-colour surfaces should be carefully applied in interior spaces.

Figure 30 – Computer simulated scene including veiling luminance seen by young (left) and older (right) adults

5.2 Discomfort glare

Discomfort glare is one of the psychological effects of high-luminance light sources that cause discomfort. For the evaluation of discomfort glare the CIE established the Unified Glare Rating (UGR) system as an international standard (CIE, 1995; CIE, 2010). Many countries have employed the UGR system to set national standards. The UGR rates the degree of discomfort caused by high-luminance light sources in the visual field based on the luminances, sizes, and positions of the light sources, as well as the luminance of the background. Unfortunately, the UGR has not taken into account the effect of age on glare sensation, because the UGR is not a theoretical model based on the visual mechanisms of discomfort glare sensation, but rather an empirical model based on experimental results. In addition, the mechanisms of discomfort glare are not well understood. Therefore, it is difficult for scientists to include an ageing factor in the UGR formula:

$$R_{\mathrm{UG}} = 8 \log \left[\frac{0{,}25}{L_{\mathrm{b}}} \sum_i \frac{L_i^2\, \omega_i}{p_i^2} \right] \qquad (16)$$

where

- R_{UG} is the glare rating in the UGR system;
- L_b is the background luminance (cd·m^{-2});
- L_i is the luminance of the i^{th} light source (cd·m^{-2});
- ω_i is the solid angle of the i^{th} light source (sr);
- p_i is the position index of the i^{th} light source.

The luminance contrast between a light source and the background is the basis of the UGR formula. This means that as the luminance contrast increases, the degree of discomfort also increases. Light scatter in the eyes increases with age, and therefore the luminance contrast between the light source and the background is reduced with age. This implies that the degree of discomfort glare may be reduced as people age. However, light scatter may directly increase the degree of discomfort glare by increasing the apparent size of the light source. The UGR formula suggests that the larger the size of the light source, the higher the degree of discomfort glare caused by the light source. The current UGR metric does not consider the luminance distributions across a luminaire surface and therefore might underestimate glare for certain (LED) fixtures. Studies show mixed results with regard to the effects of age on discomfort glare.

One discomfort glare index that has an ageing factor is the Borderline between Comfort and Discomfort (BCD). The factor determining the degree of discomfort from a light source is the average luminance of the light source that produces a sensation between comfort and discomfort. This threshold luminance (L_{BCD}) is defined as a BCD luminance. Bennett (1977) quantified the effect of age on discomfort glare by the formula:

$$L_{BCD} = \frac{85{,}750}{A} \tag{17}$$

where A is the age in years.

Considering this formula, it might be concluded that older adults are more sensitive to a high luminance stimulus than young people. However, this formula (17) was derived from an experiment employing limited experimental conditions. Bennett presented only a 1° diameter circular target located in the centre of the visual field against a 5,5-cd·m^{-2} background. These conditions are different in size and background luminance from real interior spaces. Additionally, Bennett employed incandescent lamps as light sources for the target. Incandescent lamps reduce the proportion of short-wavelength radiation as the lamp output decreases. Such a limitation in the experiment might have influenced the experimental results.

Other studies found age-related changes in glare sensitivity to be different from what Bennett found: (Rex and Franklin, 1960; Tsongos and Schwab, 1970; Theeuwes et al., 2002; Mochizuki et al., 2000). For instance, Rex and Franklin asked 49 subjects with various ages to select BCD luminances in a roadway lighting context and found no correlation between BCD luminance and age. The other studies listed above found that older people were less sensitive to glare than young people. Vos (1999) proposed to define different types of glare more strictly and suggested segregating discomfort glare from dazzling glare. Vos believed that such segregations might solve the contradiction between Rex and Franklin (1960) and Bennett (1977) on the presence of age effect: they just talked of different things in the well-defined glare structure.

5.3 Visual mechanisms of discomfort sensitivity

Kimura and Ayama (2010) challenged Vos (1984) to investigate the mechanisms of discomfort glare. They asked young and older subjects to select BCD luminances of LED light sources with different spectral power distributions. They found that older subjects chose higher BCD luminances than young subjects for short wavelength LEDs, but selected similar BCD luminances for long wavelength LEDs (Kimura and Ayama, 2011). Kimura and Ayama found that both young and older subjects felt increased glare sensation as the peak wavelength of LED lamps became shorter. Such a tendency is supported by evidence obtained by another recent study (Bullough, 2009). Bullough attempted to identify the mechanisms of discomfort glare. The results showed that the discomfort glare response to high-luminance lights has greater short wavelength spectral sensitivity than originally implied by the photopic luminous efficiency function, $V(\lambda)$. Bullough (2009) and Kimura and Ayama (2010) attributed the above described spectral sensitivity to S-cone contributions to discomfort glare responses.

Akashi et al. (2013) also measured BCD luminances for three kinds of LEDs, white, amber, and cyan, presented at different eccentricity angles in the peripheral visual field. The results suggested that the degree of discomfort glare caused by the cyan LED with the peak wavelength of 510 nm (near the peak wavelength of S-cones) did not correlate well to the glare estimations according to the models derived from Bullough (2009) and Kimura and Ayama (2011). Therefore, it may be reasonable to consider rods, contributing to the brightness perception with cones at mesopic light levels, as major contributors to the discomfort glare sensation. Recent studies suggest that intrinsic photosensitive retinal ganglion cells (ipRGCs) are also involved in brightness encoding (e.g. Brown et al., 2012). Therefore, ipRGCs may also be expected to contribute to (discomfort) glare.

The human crystalline lens absorbs more short-wavelength radiations with age. Therefore, short-wavelength radiation stimulates S-cones (as well as rods and/or ipRGCs) less aggressively in older people than in young people. This may be the reason why older subjects are less sensitive to bright lights emitted by blue and green LEDs. To reduce discomfort glare, it is still important to use light sources with more long-wavelength radiations, which do not stimulate short-wavelength-sensitive photoreceptors (S-cones, rods, and/or ipRGCs) strongly regardless of an observer's age.

In order to identify appropriate measures to ease discomfort glare, it is still important to define the mechanisms of discomfort glare. To achieve this goal, further research is needed.

5.4 Measures to reduce glare

LED luminances have increased because of recent innovation in LED technology. It has become important to reduce glare from LEDs and LED luminaires.

As stated above, one component of glare, disability glare, and age-related change in disability glare are well defined while no recommendations for disability glare in interior spaces are available. Age-related change in discomfort glare has not been well defined yet. However, the degree of discomfort glare in an interior lighting installation can be evaluated based on UGR standardized by CIE. This report aims at guiding lighting practitioners to reduced glare lighting environments based on UGR as described in Clause 7.

6 Non-visual effect of light on older people and people with low vision

Light is a powerful biological stimulus that can do much more than enabling vision. Light has the ability to energize, relax, increase alertness, cognitive performance and mood. Light is the most powerful regulator of the day-night rhythm of people. Every day, light exposure adjusts and stabilizes the duration, and timing, of our sleep-wake cycle. Moreover, light is known to be an effective treatment for a variety of conditions that include various sleep disorders (Campbell et al., 1995; Terman et al., 1995) and mental disturbances such as depression and Seasonal Affective Disorder (SAD) (Lieverse et al., 2011; Wirz-Justice et al., 2009; Wirz-Justice et al., 2004).

The ability of light to achieve these various non-visual effects depends on the spectrum (Lucas et al., 2014), intensity (Cajochen et al., 2000; Zeitzer et al., 2000), and temporal pattern of the light (Chang et al., 2012), as well as the light-exposure history (Chang et al., 2011; Hebert et al., 2002; Jasser et al., 2006; Smith et al., 2004; Zeitzer et al., 2011) and preceding sleep behaviour of the individual (Burgess, 2010).

Residents of long-term elderly care institutions frequently suffer from symptoms of circadian disruption including depression, sleeping problems, daytime napping, and compromised cognitive performance. Evidence from randomized controlled trials indicates that a regular pattern of light and darkness (with sufficient light exposure contrast between day and night) can mitigate these symptoms by restoring a stable circadian rhythm (White et al., 2013).

6.1 Sleep efficiency

Does exposure to bright light in the daytime help older people improve their sleep efficiency? Since older adults tend to have less access to daylight than young adults (ANSI/IES, 2007), exposure to bright light during the day helps to improve night-time sleep quality. For instance, providing two hours of exposure to bright white light in the morning for about two weeks improved sleep efficiency in a study conducted by Fetveit et al. (2003).

Short-wavelength light, however, does not always have positive effects. The spectral region between 450 nm and 550 nm provides the strongest stimulation to the circadian and neuroendocrine systems (Brainard and Provencio, 2006). ANSI/IES RP-28-07 (ANSI/IES, 2007) describes that blue light (400 nm–440 nm) is one of the risk factors for macular degeneration (Roberts, 2001), and should therefore be filtered out. However, epidemiologic studies have provided conflicting results regarding the relationship between sun exposure (specifically the blue component of sunlight) and retinal pathologies like age related macular changes, age related macular degeneration, and also other retinal and macular pathologies (SCENIHR, 2012). This is mostly due to the fact that dosimetry is difficult to evaluate during long-term exposure and is highly dependent on geometric factors. Whether exposure from artificial light could have effects related to age-related macular degeneration is uncertain (SCENIHR, 2012). High quality epidemiologic studies are needed to evaluate the real impact of light on retinal diseases (SCENIHR, 2012). At the same time, brief exposures to the blue light from LEDs are obviously less than the daylight, and therefore accepted as safe by the American Conference of Government Industrial Hygienists (Bullough, 2000; ANSI/IES, 2007).

Recently White et al. (2013) published a review of prospective, randomized controlled clinical trials executed within senior living environments to investigate effects of indoor lighting on the health and well-being of senior residents. They conclude that:

1) valid and actionable data are available about circadian rhythms, sleep and human health and well-being that can inform the design of lighting for long-term care;
2) evidence-based architectural design of a 24-hour light/dark environment for residents may mitigate symptoms of circadian disruption;
3) evidence-based management of darkness is as important as evidence-based management of light.

Further research into the long-term circadian health needs of night staff is needed in order to understand the effects of shift work while at the same time providing the highest level of care for hospital and care facility patients. General lighting conditions can be used to create care environments that provide sufficient daytime light to strengthen the circadian rhythm (Mishima et al., 2001; Obayashi et al., 2012; Obayashi et al., 2013), and enable for sufficient vision to keep the residents engaged in daytime activities. In the evening and at night-time reducing light levels and blue content is desirable in order to prevent disruption of nocturnal sleep (Santhi et al., 2011).

Several studies indicate that the circadian system is sensitized to light by prior dim light exposure and desensitized by prior bright light exposure (Chang et al., 2011; Hebert et al., 2002; Jasser et al., 2006; Smith et al., 2004; Zeitzer et al., 2011). Many long-term care facilities are lit with relatively low light intensities (Shochat et al., 2000). These relatively modest daytime light levels in elderly care facilities might inadvertently increase the sensitivity for phase resetting upon exposure to an examination light that is used by caregivers in the late evening or at night-time. The relative dim light level in facilities during the day can make the residents more susceptible to (circadian) disruption from light exposure during the late evening or night.

In order to minimize such (circadian rhythm) disruptions it is important to have high levels of daylight and electric light during daytime, while in the evening during the last 1-2 hours prior to habitual bedtime light levels need to drop to lower values, preferably also shifting the spectrum towards warm (red/amber) tones of light (see also 6.2). During the night residents need to sleep in as much darkness as possible, minimizing stray light from corridors and adjacent spaces. Night-time orientation lighting preferably is directed to the floor and has a spectrum that is rich in longer wavelengths (red/amber) with a minimal content of short (blue) wavelengths. During the night, restrooms and toilets preferably are illuminated with warm light (low colour temperatures or even red or amber light) and should avoid exhibiting brightness/luminance that the resident can see directly.

6.2 Spectral power distributions useful for older adults

It is well established that short wavelengths are a very effective and strong input for the circadian system (Brainard et al., 2001; Thapan et al., 2001; Lucas et al., 2014; CIE, 2015). This input is largely mediated by ipRGCs that contain melanopsin and by themselves are light responsive, with a peak sensitivity at 480 nm (Lucas et al., 2014). However, ongoing research shows that classical photoreceptors (rods and cones) also can play a role in melatonin suppression and circadian responses to light. From the above-described literature, short-wavelength light also seems to be more effective at melatonin suppression for older adults, although they may have a reduced responsiveness when compared to young people (Sletten et al., 2009). This is true for monochromatic light. In the case of using polychromatic light, however, there is as yet little proof that short-wavelength light is more effective than long-wavelength light.

The human lens transmits less blue light to the retina, and intra-ocular scatter increases in the blue with age (Sliney, 2006). The chromophores in the human lens begin to change at around 50 years of age or later. At a higher age, the amount of light that reaches the retina decreases in amplitude by as much as 50 %, and simultaneously for wavelengths below 450 nm even more light is removed. A reduction of short-wavelength light reaching the retina may affect human circadian rhythms (Roberts, 2001; ANSI/IESNA, 2007). Thus, the action spectrum for the effects of light on the human circadian rhythm of a person, normally will vary with age. It is important to consider such changes in spectral transmittance with age when using standardized action spectra (Sliney, 2006). The Lucas et al. paper (2014) has proposed the spectral weighting functions for the five photoreceptor inputs that are relevant for the visual and non-visual effects of light (rods, red-cones, green-cones, blue-cones and ipRGCs). These weighting functions can be multiplied with factors to account for pre-receptoral filtering in the eye at a given age. In this way action spectra which consider different ages can be generated for each of the five photoreceptor inputs.

From the above, it is possible to develop descriptive guidelines of effective lighting for older adults in order to improve sleep efficiency, by maximizing the intensity, duration, spectrum, and timing of light exposure.

6.3 Light useful for people with visual impairments to improve sleep efficiency

Complete blindness generally results in the loss of synchronization of circadian rhythms to the 24-hour day and in recurrent insomnia. The absence of photic input to the circadian system, is known to be associated with periodic insomnia, and afflicts most patients with no conscious perception of light (Czeisler et al., 1995).

Lockley et al. (1997) assessed melatonin rhythms in 49 blind subjects by measuring the urinary metabolite of melatonin. The subjects were classified as having light perception or better, or having no perception of light. The majority of subjects with light perception had normally entrained melatonin rhythms. Most subjects with no perception of light had abnormal circadian rhythms (Lockley et al., 1997). Conversely, Czeisler et al. (1995) pointed out that a visual subsystem mediates the light-induced suppression of melatonin. This subsystem can remain functionally intact in people without (conscious) light perception. The absence of photic input to the circadian system is different from having no light perception (Czeisler et al., 1995). The majority of visually impaired individuals who maintain some degree of light perception have normally phased circadian rhythms. Primary loss of the visual fields is also not associated with circadian rhythm disorders (Lockley et al., 1997).

Whether daytime exposure to bright light improves the sleep efficiency of people with visual impairments or not depends on the individual. However, in most cases, daytime bright light exposure seems to be useful to improve nocturnal sleep efficiency in people with and without visual impairments.

7 Recommendations for practical lighting solutions for older people and people with low vision

Current lighting recommendations and designs are predominantly based on visual aspects derived from studies employing young subjects. Therefore, they often do not address the particular light needs of people who are older than 50 years and start experiencing some gradual decline in bodily functions including vision. How much light is actually needed for older people to see and perform well and to execute tasks comfortably and in a safe way? To respond to this question, this report makes some recommendations for practical light solutions based on the insights discussed in the previous clauses.

Most of the above described lighting recommendations do not consider the non-visual impact of light on human wellbeing, health and performance. It is important to have dimming capabilities with lighting systems and/or supplementary lighting systems so that occupants can obtain a high enough amount of light at the eyes for their biological clocks to be stimulated in the early morning. However, in this report, suggestions on such lighting systems or the target light levels measured at the eye are not provided.

7.1 Light for the visual task

Visual tasks do vary largely in complexity and smallest detail size. Not every person requires the same amount of light for a given visual task, even when they have the same age. Visual task performance depends on (i) the luminance of the object, (ii) the critical detail (the smallest detail size that one needs to see), (iii) the luminance contrast between the object/task and its background, and (iv) the duration of the task.

The critical detail is the smallest detail in the visual task that has to be perceptible. Lighting quality has to be adapted to this critical detail. The higher the illuminance of the visual task becomes, the smaller the size of the perceptible visual task can be. The effect of minimizing the critical detail in a visual task can be compensated with a higher adaptation level. Conversely enlarging the critical detail makes is possible to use lower illuminance levels. Even when the contrast is high a critical detail size of 2′ is recommended and it never may be smaller than 1′. In practice this means that on a distance of 0,40 m the real detail size is 0,1 mm which equals 0,9′ and 0,2 mm is a critical detail of 1,7′.

Examples of activities that require seeing small critical details are: e.g. sawing, needle work and embroidery, repair of watches, reading, drawing, and assembling electronics. Tasks that involve larger critical details include storage and rough carpentry.

7.1.1 Illuminance level

The illuminance level has to be adapted to the needs of the visual task. The luminance levels which occur in different parts of the visual field should not differ too much from the adaptation level.

The adaptation level can usually be regarded as the average luminance on the visual task and its surrounds on which the eye adapts. One has to take into account that the frequency and time this luminance is perceived is of importance. In fact it is the adaptation level that determines the contrast sensitivity, i.e. the possibility of seeing small details and the opportunity to distinguish colours (CIE, 1981a; CIE, 1981b).

7.1.2 Contrast

Luminance and/or colour contrast are essential for the visibility of details in the visual task area.

For visual tasks with contrasts below 3, a higher luminance (or illuminance) level is needed to enable good vision, see also Equations 5 and 7 in 3.3.1.

Some examples of contrast values (in Michelson contrast) in practice are

1) Hard pencil on white paper $C = 0,2$ *
2) Soft pencil on white paper $C = 0,5$

3) Black ink on white paper C = 0,82

4) Text on very bright displays C = 0,98 **

* Too low for comfortable vision

** Excessively high for comfortable vision

It is hardly possible to compensate for poor (low) contrast completely by increasing the luminance level alone.

When designers determine luminance contrast of a coloured object against its background, it is important for them to consider the difference in spectral sensitivity between young people and older people. Two studies (Kraft and Werner, 1994; Sagawa and Takahashi, 2003) measured luminous efficiency functions for different age groups. Based on the measurement results, CIE 196 (CIE, 2011) provides luminous efficiency functions for seven age groups, i.e. 10–19, 20–29, 30–39, 40–49, 50–59, 60–69, and 70–79 years. These data help designers select colours of public signs appropriately. It is possible for them to understand how the luminance contrast of the coloured sign is possibly changed by lamps with different spectral power distributions. This design process is important especially for a sign with blue letters on brown background (e.g. wooden walls). The luminance contrast of the blue letters to the brown background perceived by older people is likely to be lower than that by young people. This is because the luminous efficiency functions clearly show the decrease of efficiency with age in the shorter wavelength region between about 400 nm to 500 nm.

ISO 9241-303 (ISO, 2011) provides a model to calculate the minimum required luminance contrasts of characters against their background with different luminances on a computer display for a 20-year-old person and introduces a set of age-related multipliers which increases the required luminance contrasts for older people. For instance, a 20-year-old person needs a contrast value of 0,4 (in Michelson contrast) for letters against the background with a luminance of 200 cd/m^2, while a 60-year-old person needs a contrast value of 0,7 (in Michelson contrast). Since computer displays are self-luminous light sources, it should be noted that extremely high contrasts may cause glare for older people and for those with low vision, and therefore care is needed when applying this model to the updated LED computer screens.

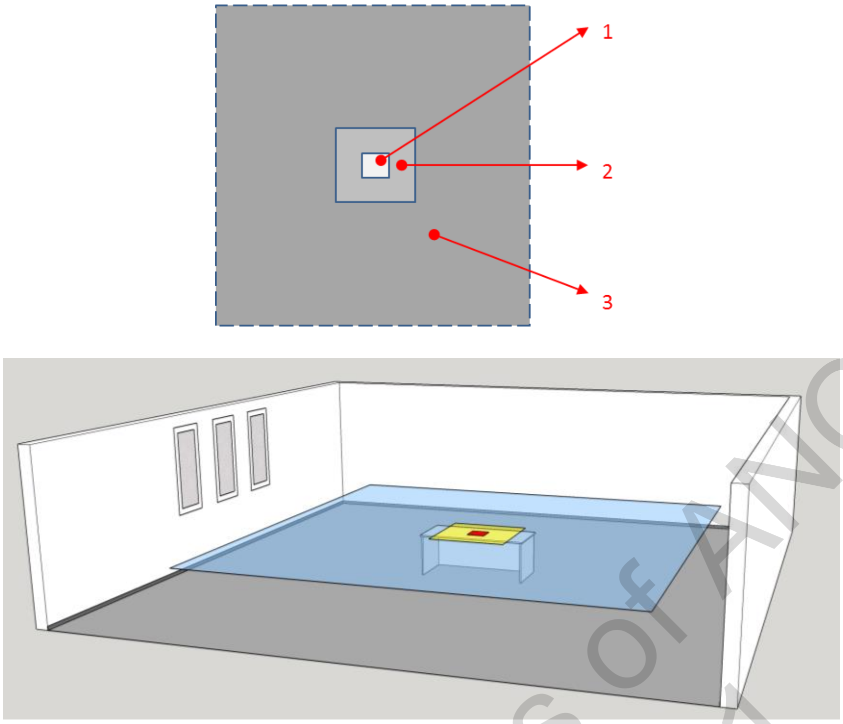
DIN 32975:2008-06 (DIN, 2008) suggests the minimum contrast for visual information in public areas for accessible use. To maintain the visibility of potential hazards and emergency information, marks of obstacles, curbs, and road edges as well as signs consisting of letters and pictographs, e.g. timetables and signs on information boards, the modulation contrast of the visual information against its background should be kept at least 0,7 (in Michelson contrast). To maintain the visibility of visual information without letters or pictographs in orientation and guiding systems, such as marks and markings on the floors, the modulation contrast should be kept at least 0,4 (in Michelson contrast).

7.1.3 Visual task with colour

When the visual task requires distinguishing small differences in colour, a high illuminance level is needed if the luminance contrast between the visual task and background is less than 0,5 (in Weber contrast). Under the conditions where the colour visual task varies with white background and the contrast is 0,5 (in Weber contrast) or above, the chroma and hue do not affect recognizable threshold of form perception. The only factor that needs to be considered to assess visibility of the visual task is lightness (Akizuki and Inoue, 2009). In industry, comparing samples of paint needs an illuminance level of at least 1 000 lx (see EN 12464-1 (CEN, 2011)).

7.2 Recommendations

Recommendations and codes for workplace lighting provide lighting design parameters (such as illuminance, uniformity, unified glare rating), not just for the task area (examples of the task area include a piece of printed paper, a computer screen, or a kitchen cutting board), but also for its immediate surroundings and the background (more remote surroundings such as a desk and floor area surrounding the printed paper, a wall behind a computer screen, or the countertop beyond the kitchen cutting board), see Figure 31.



NOTE The background area (remote surrounding) is at least 3 m wide, adjacent to the immediate surrounding area and within the limits of the space.

Figure 31 – Schematic representation of the task area (1), immediate or near surroundings (2) at least 50 cm around the task area, and the background area or remote surrounding (3)

7.2.1 Illuminance levels

Although the relation between the three different lighting zones in luminances is given as a ratio of 10:3:1, it is important to realize that the ratio of the average horizontal illuminances between the three lighting zones for a comfortable working environment is recommended to be 5:3:1 (CIE S008/E). This is because usually luminance patterns are perceived in the field of view. For instance, a white paper on a black desk will not be very comfortable to look at, even when both of them are illuminated at an illuminance of 1 000 lx. It is hardly possible to control these luminance ratios because the luminance varies depending on the reflection properties of furniture and decoration on the floors and the walls. But people must be aware that very dark walls, white paper, a white monitor and a dark wooden desk do not make an ideal match to work comfortably for eight hours a day. The contrasts in the field of view become too high in such conditions.

A good lighting practice for work places implies more than just providing a good task visibility. It is essential that tasks are performed easily and comfortably. Lighting should ensure good visual performance, so that people are able to perform their visual tasks, speedily, safely and accurately during prolonged periods. Such lighting will also be beneficial to enable a good productivity, reduce error rates and safety incidents, irrespective of age (ISO/CIE, 2002).

7.2.2 Illuminance requirements for young and older people

The difference in capability of eye sight is enormous among human beings. This has been presented by many studies. For example, Figure 16 in 3.3.1 shows a large spread in visual acuity among individuals, but also the overlap between young and older age groups. These studies comparing capability of visual acuity among different age groups were done for reading tasks or so-called critical visual tasks in indoor applications under photopic conditions. The results of these tests are applicable for this clause which discusses visual tasks and lighting conditions in indoor applications.

In Table 7, the recommended average illuminance level on the task area, as given in the current standard ISO 8995-1:2002(E)/CIE S 008/E:2001 (ISO/CIE, 2002), is provided in the first grey column. Within the lifetime of the lighting installation, the average illuminance over the task area may never be lower than the mentioned level. E_{av} denotes the average maintained illuminance, and U_o denotes a quality parameter for the uniformity of the overall illuminance distribution (E_{min}/E_{av}). The second (blue) column gives a new proposal for task lighting, and specifies a range for lighting conditions where more aged people and/or more complex visual tasks are involved. For those cases, it is desired to go higher than the minimum value given in current recommendations (see first column). All people, and especially older people and people with low vision, should have the possibility to choose a higher lighting level at their workplace. To create a well-balanced luminance distribution Column 3 presents the ratio between average illuminance on the immediate surrounding to that on the task area (ISO/CIE, 2002) while Column 4 presents the ratio between average illuminance on the background and that on the task area, as recommended in EN 12464-1:2011 (CEN, 2011). These columns also show uniformity values for the surrounding and the background, derived from ISO 8995-1/CIE S 008 and EN12464-1. In practical calculations of the uniformity of the background, a strip of 50 cm adjacent to the surrounding walls can be disregarded. It is useful to recommend finish material reflectances for ceiling, walls and floor. Recommended reflectances, ρ, for major diffuse surfaces are:

- Ceiling: 0,7 – 0,9
- Walls: 0,5 – 0,8
- Floor: 0,2 – 0,4

Illuminance recommendations in Table 7 were selected based on the studies reviewed in 3.3.1. By implementing these illuminance recommendations into real lighting applications, for example, it is possible to achieve the same retinal illuminance for different age groups as described in 3.2. The illuminance recommendations will not help older people to obtain the same visual acuities as young people do. However, older people can obtain visual acuities required for visual tasks safely. To confirm this, the equations derived from studies reviewed in 3.3.1 are useful. As an example, Equation 1 in 3.3.1 has been used to calculate the visual acuity for each of the age groups from 10 to 80 years. The results of such calculations were already shown in Table 3.

Table 7 – Recommended illuminance levels and illuminance ratios between the task area, immediate surrounding, and remote surrounding

		Illuminance on the task area depending on age, visual task complexity, and failure risk		Ratio 1: Ratio of average illuminance on the immediate surrounding of the task area to average illuminance on the task area		Ratio 2: Ratio of average illuminance of the background to average illuminance on the task area	
E_{av}	U_o	E_{av}	U_o	Ratio 1	U_o	Ratio 2	U_o **
750	0,60	750 -1 000 -1 500*	0,60	0,65	0,50	0,20	0,30
500	0,60	500 - 750 – 1 000*	0,60	0,65	0,50	0,20	0,30
300	0,60	300 - 500 -750*	0,60	0,65	0,50	0,20	0,30
200	0,60	200 - 300*	0,60	0,75	0,50	0,20	0,30
150	0,50	150	0,50	1,00	0,50	0,20	0,10
100	0,40	100	0,40	1,00	0,40	0,20	0,10
≤50	0,40	≤50	0,40	1,00	0,40	0,20	0,10

* Range of higher levels depending on factors like age or risk of falls which will influence the light level.

** Illuminance in peripheral areas of a room tends to be less uniform than that in the other area. To avoid the use of extra luminaires in the peripheral areas including the corners, a strip of 50 cm adjacent to the surrounding walls may be disregarded in uniformity calculations.

Visual acuities for various age groups can also be calculated by using Equation 2. Table 8 shows the result of visual acuities for a young group with a mean age of 22,9 years, a middle-age group with a mean age of 50 years, and an aged group with a mean age of 71,6 years for the various illuminance levels within Table 7. The task luminance is derived from the task illuminance by means of Equation 5 in 3.3.1, using 0,8 for the reflectance, ρ. The result is given in Table 8.

Table 8 – Visual acuity at a viewing distance of 1,5 m and a luminance contrast of 0,94 (in Weber contrast) of young, middle-aged, and older people as calculated from the luminance by means of Equation 2 and Table 4 in 3.3.1

Illuminance on the task area E_{task} (lx)	Luminance (cd·m^{-2}) $L = E_{task} \times \rho / \pi$ (see Equation 6 in 3.3.1) (ρ = 0,80)	VA Young group (~23 years)*	VA Middle-aged group (~50 years)	VA Older group (~71 years)**
1 500	382	1,51	1,02	0,75
1 000	255	1,45	0,98	0,72
750	191	1,40	0,95	0,70
500	127	1,34	0,91	0,67
300	76	1,27	0,86	0,63
200	51	1,21	0,82	0,60
150	38	1,17	0,79	0,58
100	25	1,11	0,75	0,55
≤50	≤13	≤1,00	≤0,68	≤0,50

* For the calculations of the young group data a value γ of 0,34 (for 25 years) was used.

** For the calculations of the older group data a value γ of 0,17 (for 70 years) was used.

7.2.3 Implementations of illuminance recommendations

The older group needs higher illuminance for good visibility because of their lower visual acuity. In terms of energy savings and at the same time good quality lighting for these older users, visual environments should be designed as follows:

- Use an approach of providing separate task lighting and ambient lighting. That is, provide focused lighting on difficult visual tasks, such as reading lamps, focused lighting on desk tops, accent lighting on signs and artwork, under cabinet lighting for kitchen counters and stove tops, etc. Provide ambient lighting throughout a room on a separate switch or dimmer control. Ambient lighting is best when at least some of the light is washed onto wall and ceiling surfaces, allowing the reflected light to produce shadow-free soft light at all areas of the room. Luminaires with large, low-brightness diffusers can also deliver pleasant, soft ambient light.
- Specify room surfaces, especially walls and ceilings, with higher reflectance. Lighter coloured surfaces allow more reflected light in the room, and this indirect light produces more uniform light levels and improves visibility of objects including in the corners of the room.
- Consider using larger size and contrast to improve visibility. Use larger letters for signage and room numbers, for example, and make sure those numbers are light (e.g. white) colour letters on a dark (e.g. black) colour background with high contrasts. Make handrails a contrasting colour so it stands out visually. Make important edges visible by using high-contrast markings. A dark-coloured baseboard can help the senior see a clear edge to the corridor when the floor tile and wall paint are medium-coloured, for example.

7.3 Colour temperature

The preference for correlated colour temperature (CCT) depends on lighting levels, appearance, and culture. People in the Middle East tend to prefer a cold appearance of light between 5 000 K and 7 000 K, while in European countries a range of CCT between 3 000 K and 4 000 K is common. The CCT is of course also depending on the application context.

In 3.2 it is explained that a lower CCT, and hence a warmer tone of light, reduces the relative difference in retinal illuminance between young and old individuals. This is at least partially due to the yellowing of the crystalline lens with increasing age (see Figure 11 and 3.2.3) (Iwata et al., 2001).

7.4 Discomfort glare

Glare can be caused by bright areas within the field of view and may be experienced either as discomfort glare or as disability glare. Glare can also occur by reflections in specular surfaces.

Disability glare is more common in outdoor lighting, but indoors it may also be experienced from bright spots, bare LEDs or from large bright surfaces, such as a window (ISO/CIE, 2002). Glare is caused by excessive luminance or contrasts in the field of view and can impair vision. It should be avoided for example by suitable shielding of lamps or shading of the windows by blinds. Using the requirements of shielding angles, which were developed for luminaires equipped with tubular fluorescent lamps, will probably not give satisfactory results for LED luminaires, which may have different luminous intensity distributions. This is because LED luminaires are usually composed of multiple small light sources, which may have higher luminance than fluorescent lamps, and therefore have a non-uniform luminance distribution over its luminous surface.

As mostly indoor installations are considered in this clause, the discomfort glare rating of the lighting installation should be determined by the CIE Unified Glare Rating (UGR) tabular method, in which the background luminance as well as the luminance of the luminous parts of each luminaire, in the direction of the observer’s eye, are considered. Details of the UGR method are given in CIE 117-1995 (CIE, 1995) and CIE 190:2010 (CIE, 2010).

UGR can be applied for limited ranges of applications and for luminaires with luminous surfaces up to a limited degree of non-uniformity. Lighting designers should revisit lighting installations that they have designed, to understand what installations with different UGR numbers (e.g. 16, 19, and 22) look like. There are often supplementary luminaires such as sconces and chandeliers in the same room. Although these luminaires are not included in UGR calculations, they may cause glare.

The recommended limiting values of the UGR form a series of glare scales whose steps represent noticeable changes in glare. The series of UGR values mainly used is 13, 16, 19, 22, 25, and 28. The lowest values represent the most comfortable lighting installation in terms of glare.

In lighting recommendations for indoor lighting a combination of quality parameters is used. The relevant parameters include the average maintained illuminance on the task area, E_{m}, the uniformity of the illuminance, U_{o}, the general colour rendering index, R_{a}, and also the UGR limit. As described earlier in 5.2, UGR does not take ageing with respect to glare into account. However, LED luminaires may have a higher luminance than conventional luminaires, depending on the luminaire design. Such a higher luminance will cause higher veiling luminance. The degree of veiling luminance for older people is higher than for young people. Therefore, it is important to provide a guideline for glare control based on UGR for older people until a better CIE glare standard applicable for LED luminaires is established.

In the meantime, it is advisable to decrease the UGR value with one step, e.g. from 19 to 16 for older people with higher risk of errors. See also the example of Table 9 below, which is based on the UGR limits given in CIE S 008 (ISO/CIE, 2002).

Table 9 – Current lighting recommendations according to CIE S 008 and proposed lighting recommendations for older people

Type of area, task or activity	$\bar{E}_m$ lx	UGR_L	U_o	R_a	Specific requirements
Filling, copying and etc.	300	19	0,40	80	
Writing, typing, reading, data processing.	500	19	0,60	80	
	750*	16**	0,60	80	older people
	1 000*	16**	0,60	80	older people and risk of errors higher
Technical drawing	750	16	0,70	80	
	1 500*	13**	0,70	80	older people and risk of errors higher
The blue cells show the current recommendations. * Higher illuminance level ** Stricter UGR					

7.5 Task and ambient lighting

As mentioned in 7.4, stricter cares for discomfort glare are needed for older occupants. To avoid discomfort glare, any measures to prevent luminaires from causing discomfort glare are preferable. For instance, general lighting often employs recessed and ceiling-mounted luminaires in normal offices. In such cases, an appropriate louvre or lens designed to reduce luminance at angles larger than 60° from the nadir should be used with each of the luminaires so that it does not appear glaring. It should be noted that this kind of optics can shield lamps from the view of a standing person, but do not function well when viewed from a reclining backward-tilted position. These luminaire archetypes are mentioned as an example only and other technical solutions are also possible.

A combination of direct and indirect lighting is most suitable to control discomfort glare while maintaining sufficient illuminance on visual tasks. For instance, task and ambient lighting (TAL) is used to satisfy the conflicting requirements of increasing task illuminance while reducing lighting energy. Ambient lighting should provide uniform illuminance distribution for safety of older people and low vision people. Figure 32 illustrates such a TAL system. The use of indirect lighting is the most appropriate solution for ambient lighting, as indirect lighting can perfectly conceal bare lamps and high-luminance luminous elements (such as LEDs) from any viewing angles. Indirect lighting can be achieved in several ways, e.g. using floor stands with 100 % upward light, cove light luminaires, and pendant luminaires. Task lighting can achieve higher illuminance on smaller areas where specific visual tasks are performed. Task lighting luminaires should have capabilities to dim and control light colour temperature to meet individual needs. There are many variations in how to apply TAL for offices as illustrated in Figure 33. TAL is only an example solution and other solutions are also possible.

Figure 32 – TAL system with indirect ambient luminaires (illustrated by Yukio Akashi)

Figure 33 – Variations of TAL systems (illustrated by Kana Yamamoto)

8 Design guides for lighting practitioners to improve their design skills

Many buildings in the world are equipped with information boards in braille, tactile tiles, and verbal announcement so that people with visual loss can move around independently and safely. However, those installations may not function well for people with low vision. International and national codes require an increase in the luminance contrast of the step edges and tactile tiles to the backgrounds while increasing illuminance uniformity over corridor floor surfaces. In order to make the best use of these codes in practical applications, however, it is necessary to pay attention to details of the whole visual environment.

For improved safety interior designers often select saturated colours on potential hazards to increase their colour contrast compared to the background. However, such an effort results in a noticeable but distracting design appearance as illustrated in Figure 34. Such a result may discourage interior designers from taking older people and people with visual impairments into account. In most cases, moderate but careful designs without using special installations or saturated colours can meet both functional and aesthetic requirements.

First, this clause demonstrates how to implement fundamental research findings into the real world in order to maintain safety and design aesthetics for older people and people with visual impairments. Second, this clause provides design guidelines for lighting practitioners and interior designers to design appropriate visual environments for people with low vision. The latter part is written based on a committee report of the Illuminating Engineering Institute of Japan (IEIJ, 2006).

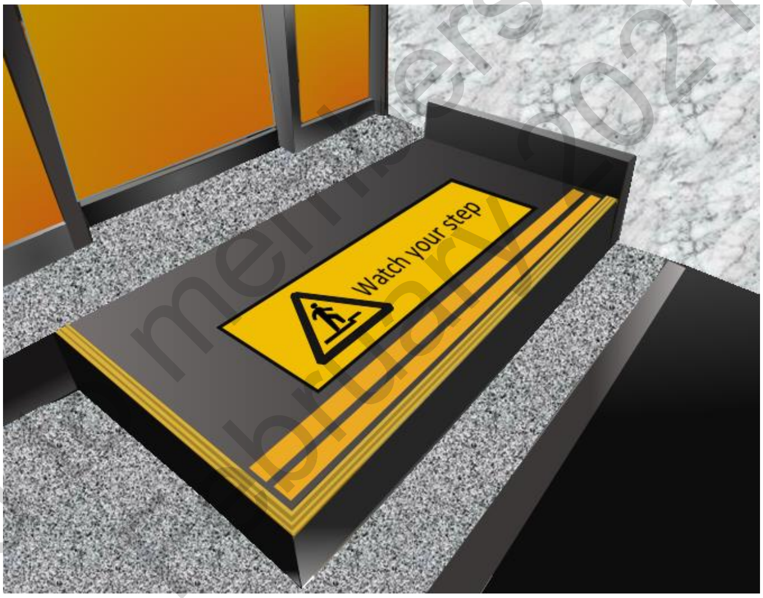


Figure 34 – A design solution outlining a hazardous step (illustrated by Yukio Akashi)

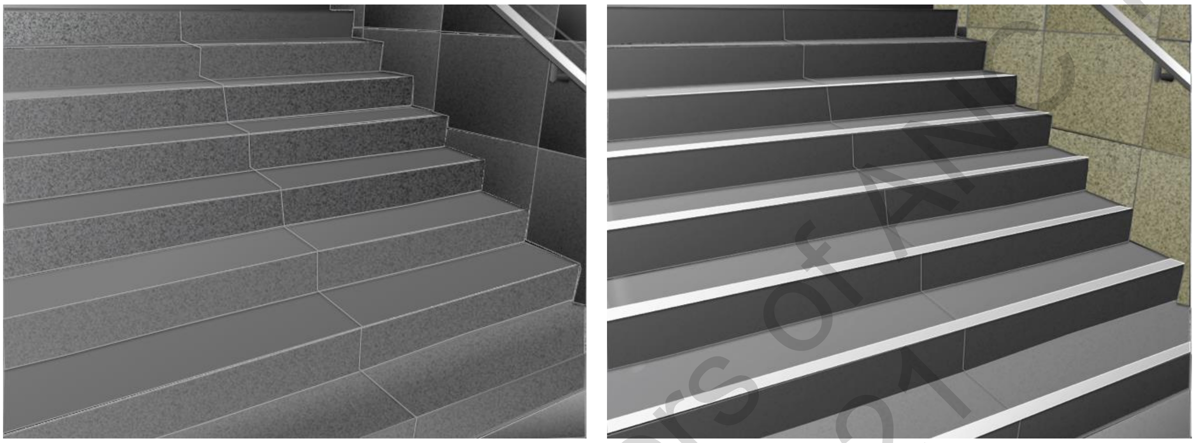
8.1 Increase the luminance contrast of the hazards

People with low vision may collide with independent columns and poles if they are inconspicuous and do not stand out in the scene. Those obstacles should be more conspicuous by increasing the luminance and colour contrasts to the backgrounds so that people with visual impairments can identify the columns and poles easily. For instance, using metallic material is one of the solutions to increase the conspicuity of the obstacles, as long as that metallic finish is not shiny. Shiny materials can introduce veiling reflections that can be disorienting.

8.1.1 Increase the contrast of stair nose to the background

In order to avoid falls at staircases, it is important for older people and people with low vision to increase the luminance contrast of a stair nose to its background (i.e. tread board and step rise). Figure 35 (a) shows an illustration of a real staircase in a public station building, made of artificial marble for all parts of the stairs including tread boards, risers, and stair noses. Three lines are engraved in the stair nose to mark the edge of the tread board and increase the friction of the stair nose with pedestrians' shoe soles. However, they are not visible to pedestrians. The chief architect of the station may have intended to coordinate all the parts of steps with a single material.

Figure 35(b) illustrates the same staircase, but with enhanced contrasts among tread boards, risers, and stair noses by selecting a light coloured material for the stair noses. The white stair noses stand out over the grey tread boards and risers. It is easy for rail passengers to distinguish the stair noses from the other parts. The width of the stair noses should be determined based on the contrast sensitivity for low vision reported in 3.6.



(a) (b)

Figure 35 – Steps with low contrast (a) and high contrast (b) (by Yukio Akashi)

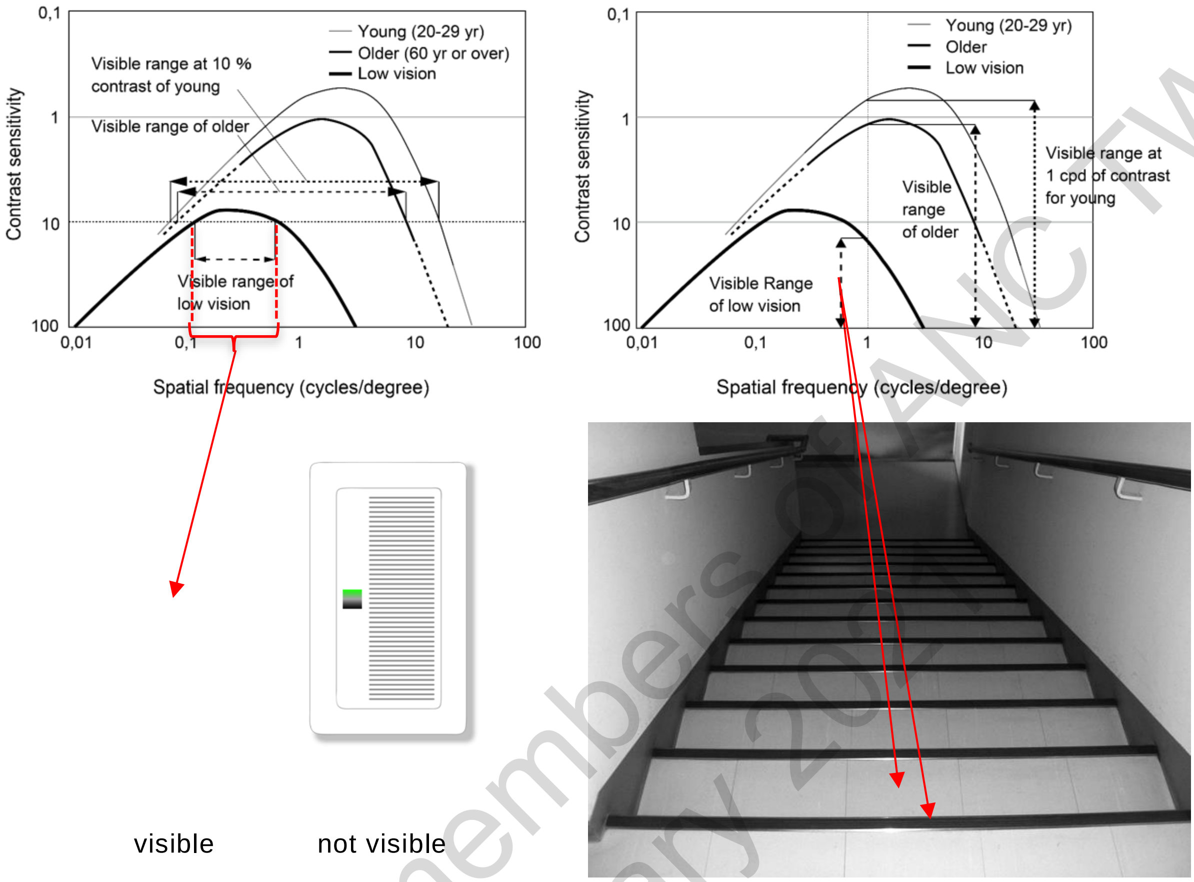
The above-described practical requirements can be theoretically supported by contrast sensitivity for low vision (see 3.4.2). Contrast sensitivity is an important consideration in the visibility of low vision individuals. The contrast sensitivity function can be applied in two ways for product and environmental design. The first is to design the fineness of the stripe pattern. Figure 36 (a) shows a case study for the design of a control panel for luminaires. After selecting the contrast of the highest luminance to the lowest luminance for the stripe pattern of the control panel, one can determine the visible range of spatial frequency for the stripe pattern. In this case, the contrast sensitivity of 10 was finally selected.

The second way is to design the contrast of stair nose and tread (Figure 36 (b)). After calculating the spatial frequency of the stair nose and tread by setting the visual distance of the stairs and the actual sizes of the stair nose and tread, the visible range of contrast of stair nose and tread will be determined.

In Figure 36 (a) and (b), the curves for low vision represent the mean (50-percentile) contrast sensitivity curves. It is also possible to select different percentile values according to the level of disability for intended users with low vision.

For both cases, it must be noted that low vision makes it difficult to see high-frequency visual information. Therefore, the edge of the stripe and nosing are not as clear as those seen by normal vision, even though contrast can be discriminated. In addition, discriminability depends on the apparent size of stripes and nosing. Therefore, appropriate settings for the position and direction of users are important.

It should also be noted that such a striped design technique should be carefully implemented since it can stimulate migraines and extreme neurological responses in children and adults (Wilkins et al., 1984; Wilkins, 2016).



(a) (b)

NOTE Contrasts in these charts are given as Michelson contrasts.

Figure 36 – Examples of using contrast sensitivity for product design (a) and environmental design (b) (figures provided by Nana Itoh)

8.1.2 Maintain appropriate luminance contrasts of tactile tiles and the background floor

The visibility of yellow tactile tiles is influenced by luminance and colour contrast of the tile to its background, higher luminance and greater colour contrast improving visibility. For instance, yellow tactile tiles on yellowish floor tiles are difficult to distinguish from the floor as illustrated in Figure 37 (a). Conversely, yellow tactile tiles on black floor tiles are easy to identify as illustrated in Figure 37 (b).

8.1.3 Maintain an appropriate contrast between tactile tiles and the floor

In order to move safely, it is important for people with low vision to increase visibility of not only tactile tiles but also other pedestrians. At rush hours in winter, pedestrians wearing dark-coloured clothes fill station corridors and concourses. Then, the situation described in 8.1.2 is reversed. At the concourse illustrated in Figure 37 (c), pedestrians wearing dark-coloured clothes are mixed with the dark background. People with low vision cannot distinguish the pedestrians from the floor, and therefore may collide with the pedestrians.

Therefore, in order for people with low vision to move safely and confidently, it is important to increase the visibility of not only tactile tiles but also other obstacles and pedestrians against the floor. For instance, at the concourse in Figure 37 (d), pedestrians wearing dark clothes appear to stand out from the light-coloured background. In this case low vision people can avoid colliding with the pedestrians.

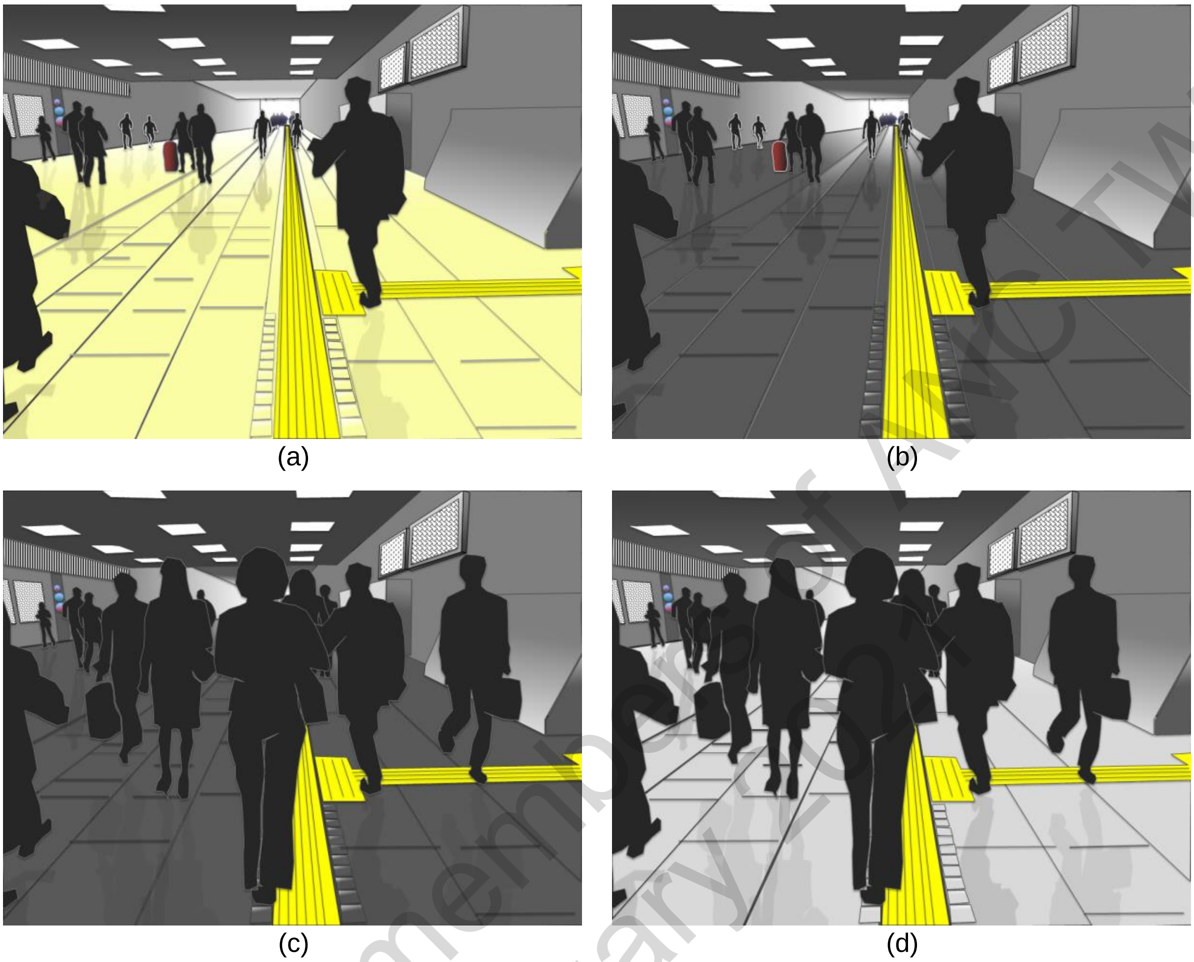


Figure 37 – Tactile tiles and floor colours in a station concourse under different pedestrian conditions
(illustrated by Yukio Akashi)

8.2 Apply the model of colour similarity for low vision to practical design

To consider the combinations of colours for low vision, it is important not to choose similar colours (ISO, 2014; JIS, 2010). First, select two or more colour categories for which the areas of similarities are not overlapped (e.g. red and blue in Figure 38). Select a colour that is included in each of the categories. The higher the level of similarity of the area which each of the selected colours belongs to becomes, the higher the conspicuity of the combination of the selected colours becomes. For instance, a blue colour should be selected from the dark blue area rather than from the light blue area to increase the conspicuity of the blue pictograph against the red pictograph as depicted in Figure 38.

It should be noted that for low vision, the area being named as the same colour in the colour chart is generally smaller than that of being recognized as similar colours. Therefore, even by categorizing colours by different namings, some colours might appear to be similar for people with low vision.

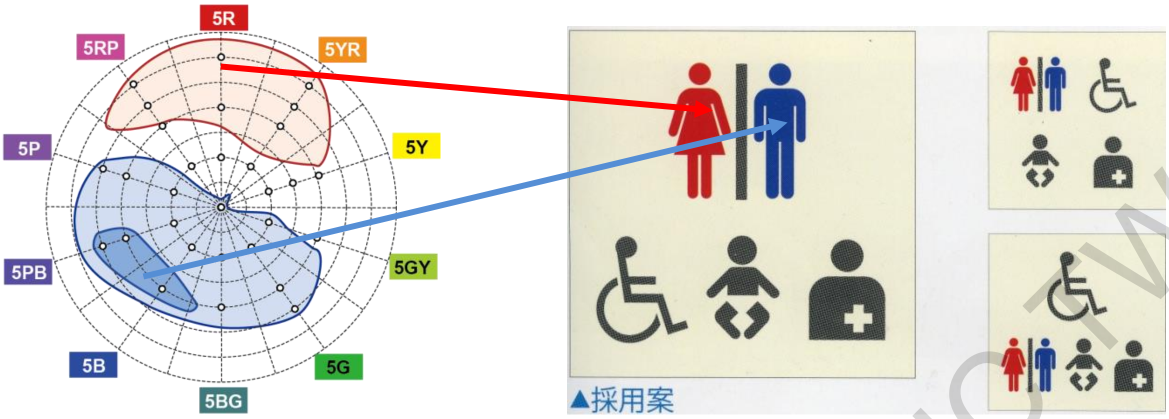


Figure 38– Examples of using colour similarity data for product and environmental design (figures provided by Nana Itoh)

8.3 Help recognize the depth of a space easily

8.3.1 Do not use the same colour for ceiling, walls, and floor

Colour coordination is one of the essential design requirements. In addition, light colours are often used for interior elements to increase reflected light and improve energy efficiency. For this reason, in the past interiors were often designed in similar colours on all room surfaces, i.e. ceiling, walls, and floor, as illustrated in Figure 39 (a). In such a space, people with low vision may have difficulties in recognizing the outlines, positions of corridor entrances, or the structure of the space. Instead, different colours should be used between the ceiling and the walls, and between the walls and the floor as illustrated in Figure 39 (b) so that people can recognize the structure of the interior space easily. Otherwise, it is important to outline the borderlines between the walls and the floor and between the walls and the ceiling by using baseboards and/or borders. Even more important specular (shiny) surface finishes should be avoided. A mirror-like reflecting surface can often be confusing or glaring to a viewer with low vision.

(a) (b)

Figure 39 –Spaces with colour variations (illustrated by Yukio Akashi)

8.3.2 Do not use decorative band patterns that may induce visual illusions in which the band patterns appear to be steps

If there are decorative band patterns lying perpendicular to pedestrians' walking direction on the floor of a corridor, the band pattern often induces an illusion in which the band patterns look like real steps with a certain rise as illustrated in Figure 40.

Such an illusion often affects pedestrians' behaviours. A recent study conducted by the committee of universal design for the Central Japan International Airport observed behaviours of six subjects with low vision (Taniguchi et al., 2007). Each of the subjects was asked to walk across decorative band patterns, consisting of two dark-coloured stripes with a white stripe between them, which lay perpendicular to the pedestrians' walking direction. In reality the band patterns had no real bumps. The study found that all the subjects confirmed by canes and/or their feet that there were no real bumps on the band patterns. This is because the widths of the stripes in the band patterns were equivalent to those of a tread board and a rise, and therefore the band patterns induced an illusion in which the band patterns appeared to be a white tread board between two shaded step risers. Therefore, it is important to avoid using decorative band patterns that are perpendicular to pedestrians' walking directions in a corridor in order to avoid such illusions for people with low vision.

Figure 40 – Decorative band patterns perpendicular to pedestrians' walking orientations may cause illusions for people with low vision (illustrated by Nana Yanagawa)

Another reason why designers should avoid using such decorative band patterns is that they can disturb neurological responses and therefore may induce headaches in some observers (Wilkins et al., 1984; Wilkins, 2016). Visual images from nature have a unique spatial feature. In these images, the Fourier spectrum decreases in amplitude as the spatial frequency of the images increases. This decrease in amplitude is approximately proportional to the reciprocal of spatial frequency. The brain processes such natural images efficiently and therefore comfortably. On the other hand, artificial images, which usually don't have the above-described spatial feature, are often proceeded inefficiently and uncomfortably.

Fernandez and Wilkins (2008) found that the degree of discomfort caused by various images can be predicted from the energy at a certain range of spatial frequency as measured by the Fourier amplitude spectrum of the luminance pattern. Comfortable images show the regression of Fourier amplitude against spatial frequency common in natural scenes. Uncomfortable images show a regression with disproportionally greater amplitude at spatial frequencies within two octaves of 3 cpd, i.e. between 1,5 cpd and 6 cpd. On the other hand, O'Hare and Hibbard (2011) found that a peak centred between 0,38 cpd and 1,5 cpd of spatial frequency was consistently evaluated as more uncomfortable than a peak at a higher spatial frequency.

Striped patterns caused by periodic layouts of ceiling luminaires may also induce discomfort. For instance, if linear luminaires with fluorescent lamps or LEDs are placed at a spacing of 3 m in a large wholesale store with a ceiling height of 4,5 m, luminaires between the fifth line and the 19th line fit in the range between 0,38 cpd and 6 cpd of spatial frequency and therefore appear to be uncomfortable.

Although reports on difference in sensitivity to such periodic patterns between young people and older people are unavailable, it is safe to avoid using periodic luminaire layouts in a large space to prevent older people and people with low vision from feeling discomfort.

8.3.3 Provide visual information effective to recognize the depth of a space

It is important to provide useful visual information to people with low vision in an appropriate manner. Media providing such information include not only signs but also various design solutions to avoid colliding with obstructions and other pedestrians, to identify corners and stairs, and therefore to recognize the depth of the space correctly. In some cases, special installations or devices may not be needed. However, it is more important to plan and design the interior elements carefully.

8.3.4 Draw stripes to make people become aware of the depth of a space

Walls and partitions often screen a washroom from pedestrians passing along the corridor. The entrance of the washroom, surrounded by the walls, forms an irregular space. If an identical white material is used for all the walls surrounding the entrance, people with low vision coming to use the washroom may have difficulty in identifying the space depth. Such a difficulty is often eased by putting dark coloured stripes on the walls below waist height as illustrated in Figure 41. Since people perceive that the apparent geometrical relationship between the closer stripe and the farther stripe keeps being changed dynamically while moving around, people can identify the depth of the space easily. A traditional interior element, waist-high partition wall, also provides a similar cue to the above-described stripes.

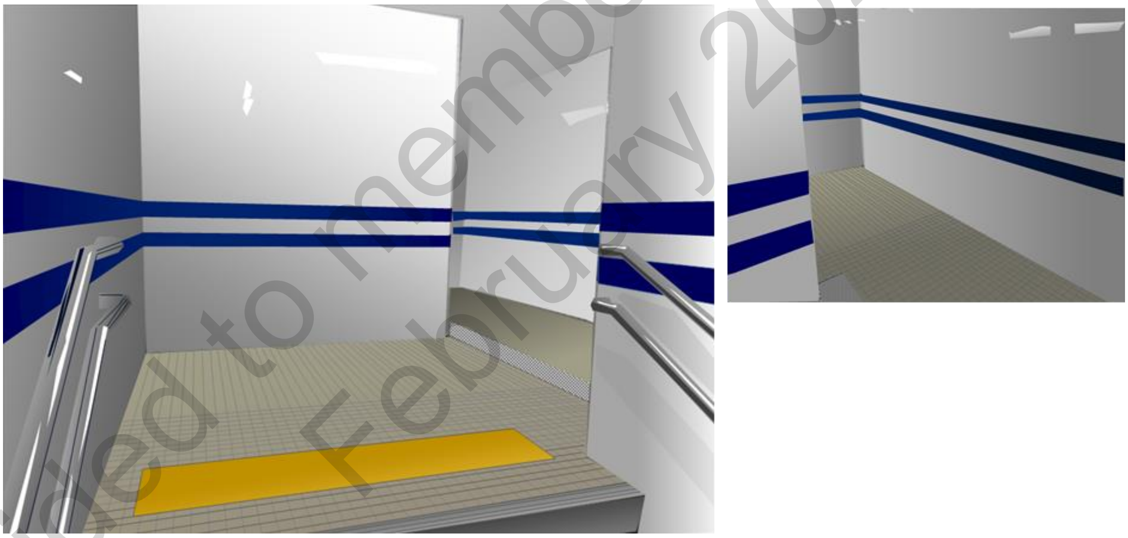


Figure 41 – An irregular entrance to a washroom surrounded by striped walls (illustrated by Yukio Akashi)

8.3.5 Install indirect lighting luminaires in the baseboard along a corridor and in the borderlines between the ceiling and the walls

The major purpose of luminaires is to illuminate visual tasks. Luminaires, if they are appropriately placed, also play another important role, i.e. providing cues for pedestrians to perceive the depth and configuration of the space. It is possible for luminaires to warn pedestrians about hazards and guide pedestrians to safer areas whilst maintaining lighting effects and aesthetics. For instance, indirect lighting luminaires installed in the baseboard along a corridor lengthwise help pedestrians identify the width of the corridor. Additionally, such indirect lighting helps pedestrians identify other pedestrians as silhouettes over the indirect lighting and therefore avoid colliding with the pedestrians. LEDs are especially appropriate light sources to achieve this purpose. In the same way, indirect lighting installed along the borderlines between the ceiling and the walls will help pedestrians perceive the size of the space easily. It should be noted that it is important to make sure that the baseboard lighting does not create a glaring or confusing reflections on a shiny floor.

8.3.6 Draw a line on the floor to guide pedestrians

Placing luminaires in a line parallel to the direction of a corridor helps pedestrians identify which direction they should go in. In such a case, care should be taken regarding the luminance and size of the luminaire to avoid glare. To this end, indirect lighting systems may be the most appropriate method to guide pedestrians in appropriate directions as illustrated in Figure 42.

In the same way, drawing band patterns along pedestrians' walking directions on the floor of the corridor may achieve the same purpose. However, it is important to cut off the band patterns on an intersection or a doorway where there is a line of flow perpendicular to the band patterns. Such a cut-off notifies pedestrians who follow the band patterns that there is an intersection or a doorway. This solution can prevent pedestrians walking across the band patterns from having an illusion in which the band patterns appear like real steps. In the same manner, if there is an obstruction in a corridor or a concourse, it is necessary to cut off the band patterns in order to warn pedestrians about the hazards.

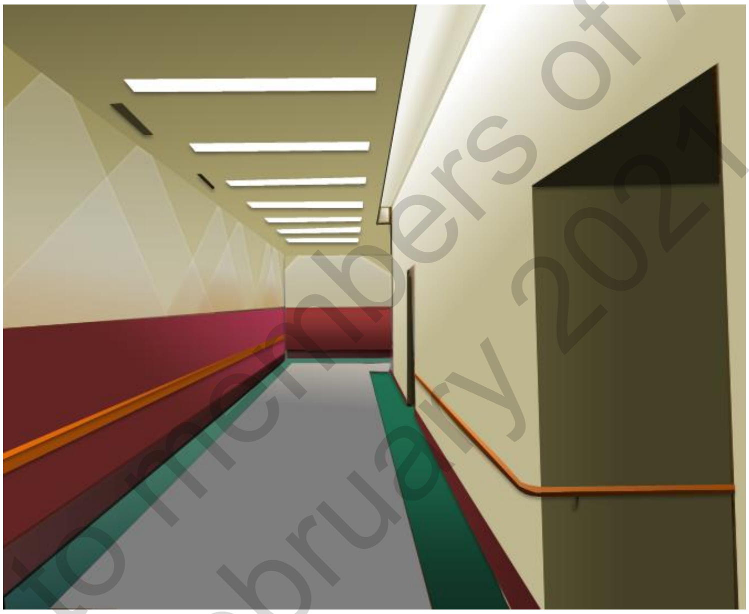


Figure 42 – Luminaires and floor band patterns parallel to the direction of corridor guide pedestrians
(illustrated by Yukio Akashi)

8.3.7 Increase local illuminance at hazardous areas

Illuminance levels at hazardous areas such as an intersection of corridors, an entrance to a moving sidewalk, and an elevator hall should be higher than at the other areas. This helps mark potentially hazardous areas for low vision people.

8.3.8 Use larger font sizes for signs located at high places

It is important to adjust the height of a sign, depending on the information context of the sign as illustrated in Figure 43. Signs positioned at high places are difficult to read for low vision individuals. A sign to provide information on zoning and orientation may be located at a high place if appropriate letter size, contrast, and colours are selected to make it visible to distant pedestrians. On the other hand, detailed information such as timetables and maps should be located at normal eye height.

Information boards using large monitors (e.g. flight information boards) should use high-luminance glare-free monitors. Information provided on the information boards should be simplified so people can read easily.

Figure 43 – Appropriate heights and sizes of signs (illustrated by Yukio Akashi)

8.3.9 Use night lighting to control posture and avoid falls

Night lighting should be provided to bed rooms and pathways to bathrooms and kitchens for older people and people with low vision to avoid falls. It is important to use night lights with low luminous flux activated by a motion sensor. The night lights should be located low on the wall to light the pathway, and provide only low light levels (ANSI/IES, 2007).

Ambient illumination may help to obtain visual information to recognize details of the space and therefore avoid falls better than conventional night lights. This is especially true when drowsing off while walking to bathrooms after awaking in the midnight. However, such ambient illumination may compromise subsequent sleep efficiency and quality for older people.

Figueiro et al. (2008) proposed to use a novel night lighting system that provides horizontal and vertical cues that could positively affect postural control in older people. Such a night lighting system can be provided by three linear arrays of amber LEDs that are attached to a door frame with the same dimension as the door frame as shown by a photograph in Figure 44.

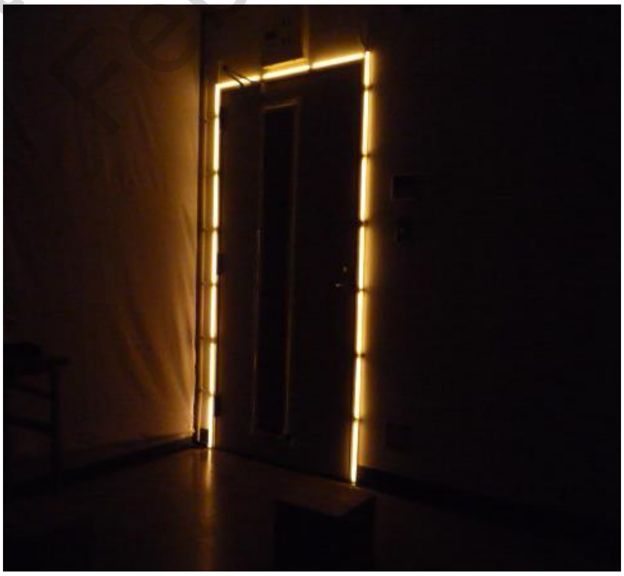


Figure 44 – An example of the night lighting system (photographed by Yukio Akashi)

Annex A

Definitions of contrasts

A.1 Weber contrast

The Weber contrast, C_W, is defined as follows:

$$C_W = \frac{|L_t - L_b|}{L_b} \qquad \text{(A.1)}$$

where L_t is the luminance of the target and L_b is the luminance of its background.

This contrast formula is often used where small features are present on a large uniform background.

A.2 Michelson contrast

The Michelson contrast, C_M, is defined as follows:

$$C_M = \frac{L_{max} - L_{min}}{L_{max} + L_{min}} \qquad \text{(A.2)}$$

where L_{max} is the maximum luminance and L_{min} is the minimum luminance of one cycle of dark and light pattern of the grating respectively.

This form of contrast is used to quantify contrast for periodic striped luminance patterns.

Annex B

Demonstrations of how to apply the Visual Acuity Model (Inoue and Akizuki, 1998)

Figure B.1 is identical to Figure 19. The broken lines/arrows and the solid lines/arrows demonstrate how to use the diagrams to identify necessary luminances and/or target sizes for desired readability levels in Figure B.1.

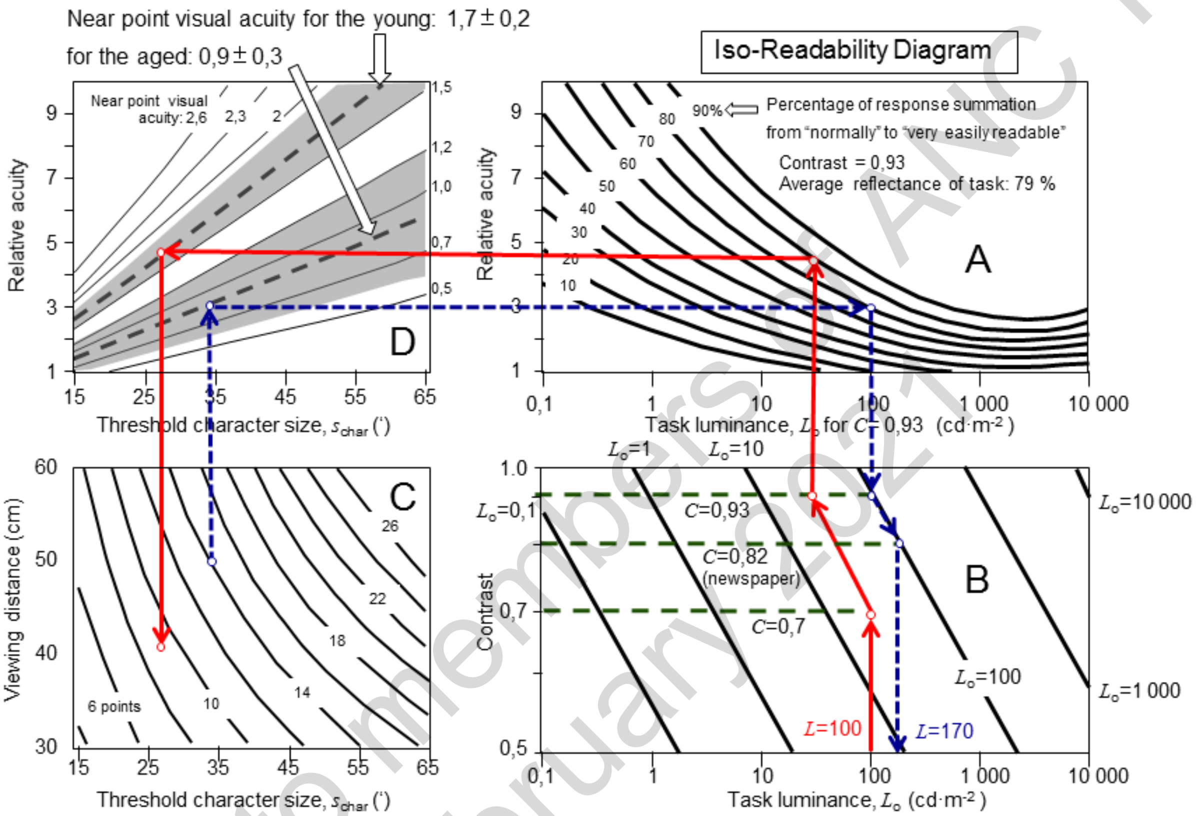


Figure B.1 – Demonstration of how to use diagrams proposed in the visual acuity model of Inoue and Akizuki (1998)

(1) Procedure to determine a proper task luminance, depicted by blue dashed lines and arrows

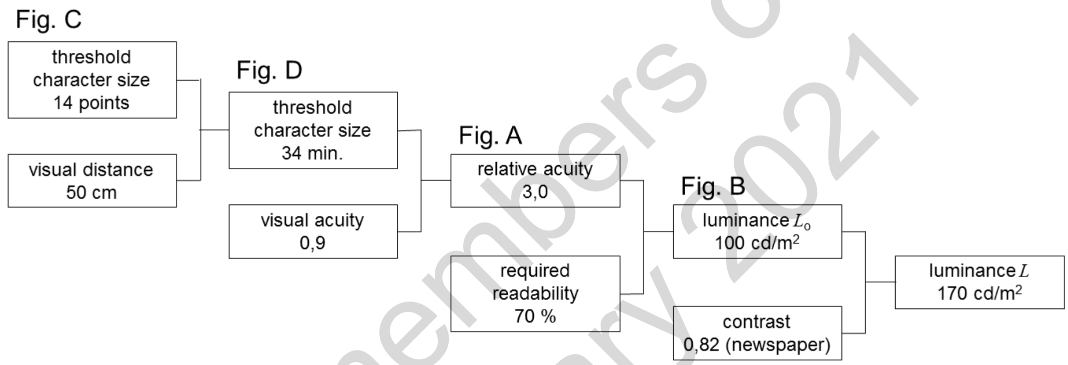
The first case demonstrates how a lighting practitioner can determine an appropriate task luminance for a given letter size of 14 points, a given visual distance of 50 cm, a given visual acuity of 0,9 (for an older person), a given readability level of 70 %, and a given task luminance contrast of 0,82 (in Weber contrast) by using Figure B.1.

- First, a threshold character size of 34′ is determined, based on given conditions with a letter size of 14 points and a viewing distance of 50 cm by using Figure B.1-C.
- Second, a relative acuity (RA) of 3,0 is selected, based on the threshold character size of 34′ (determined by using Figure B.1-C) and a given visual acuity of 0,9 for an older person by using Figure B.1-D.
- Third, a task luminance (L_o) for a default task contrast of 0,93 (in Weber contrast) as 100 cd·m⁻² is determined, based on the selected RA of 3,0 and a given readability level of 70 % by using Figure B.1-A.
- Forth, a task luminance of 170 cd·m⁻² is determined, based on the selected task luminance of 100 cd·m⁻² and a given task contrast of 0,82 (in Weber contrast) equivalent to the letter contrast on newspaper.

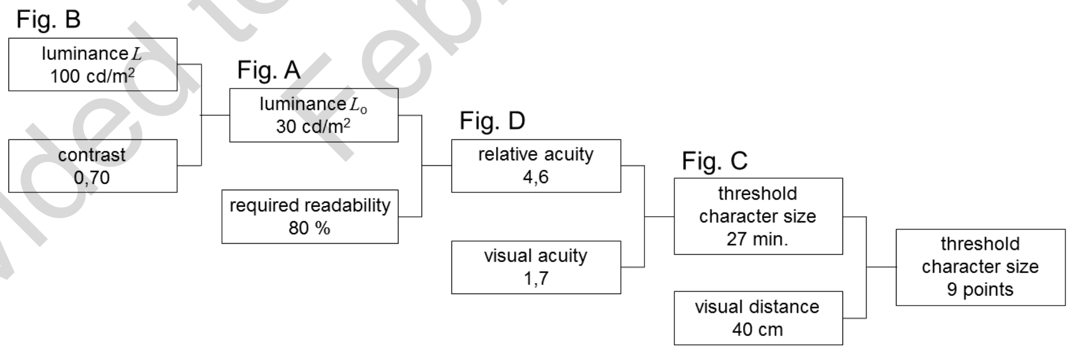
(2) Procedure to determine a proper letter size, depicted by red solid lines and arrows

The second case demonstrates how a lighting practitioner can determine an appropriate letter size for a given target luminance of 100 cd·m^{-2}, a given visual distance of 50 cm, a visual acuity of 1,7 (for a young person), a given target contrast of 0,7 (in Weber contrast), a required readability level of 80 %, a given visual acuity of 1,7 for a young adult, and a given visual distance of 40 cm by using Figure B.1.

- First, a task luminance for a default target contrast of 0,93 (in Weber contrast) as 30 cd·m^{-2} is determined, based on given conditions for a task luminance, L, of 100 cd·m^{-2} and a task contrast of 0,7 (in Weber contrast) by using Figure B.1-B.
- Second, a proper RA of 4,6 is determined, based on the selected task luminance for a default task contrast of 0,93 (in Weber contrast) and a required readability level of 80 % by using Figure B.1-A.
- Third, a proper apparent threshold character size of 27′ is determined, based on the selected RA of 4,6 and a given visual acuity of 1,7 by using Figure B.1-D.
- Forth, a proper letter size of 9 points is determined, based on the selected threshold character size (in arcminutes) and a given viewing distance of 40 cm by using Figure B.1-C.



(1) Procedure to obtain a proper task luminance, depicted by blue dashed lines and arrows



(2) Procedure to obtain a proper letter size, depicted by red solid lines and arrows

Figure B.2 – Example of task surface luminance evaluation using the relative acuity

References

ADRIAN, W. 1993. Visual performance, acuity and age, *Proceedings of Lux Europa 1993*:278–290.

AKASHI, Y., ASANO, S., KAKUTA, Y. 2013. Visual mechanisms of discomfort glare sensation caused by LEDs, *CIE x038:2013 Proceedings of the CIE Centenary Conference “Towards a New Century of Light”, 15–16 April 2013, Paris, France*, 43–47. Vienna: Commission Internationale de l’Eclairage.

AKIZUKI, Y., INOUE, Y. 2004. The Concept of Visual Acuity Ratio to the Maximum Level of Individual Visual Acuity: The Evaluation Method of Background Luminance and Visual Distance on Visibility Taking into Account of Individual Visual Acuity, *Journal of Light & Visual Environment*, Vol. 28, 35–49.

AKIZUKI, Y., INOUE, Y. 2009. Effects of Three Color Factors on Recognizable Threshold of Form Perception Taking into Account Individual Differences of Visual Ability, *Journal of Light & Visual Environment*, Vol. 33, 88–100.

AKIZUKI, Y., TANAKA, T., YAMAO, K., 2008, Calculation Model for Travel Speed and psychological State in Escape Routes considering Luminous Condition, Smoke Density, and Evacuee's Visual Acuity, *Proceedings of the 9th International Symposium of Fire Safety Science*, International Association of Fire Safety Science, 365–376.

ANSI/IES, 2007. RP-28-07: *Lighting and the visual environment for senior living*, New York: Illuminating Engineering Society of North America.

BAILEY, I.L., LOVIE, J.E. 1976. New design principles for visual acuity letter charts. *Am. J. Optom. Physiol. Opt.* 53, 740–745.

BARTEN, P.G.J. 1999. *Contrast sensitivity of the human eye and its effects on image quality*. Bellingham, WA: SPIE Optical Engineering Press.

BENNETT, C.A. 1977. The demographic variables of discomfort glare, *Lighting Design and Applications*, 7, 22–24.

BERMAN, S.M., JEWETT, D.L., FEIN, G., SAIKA, G., ASHFORD, F. 1990. Photopic luminance does not always predict perceived room brightness, *Lighting Research & Technology*, Vol. 22, No. 3, 37–41.

BIRCH, D.G., HOOD, D.C., LOCKE, K.G., HOFFMAN, D.R., TZEKOV, R.T. 2002. Quantitative electroretinogram measures of phototransduction in cone and rod photoreceptors: normal aging, progression with disease, and test-retest variability. *Arch Ophthalmol.* 120(8): 1045–1051.

BLACKIE, C.A., HOWLAND, H.C. 1999. An extension of an accommodation and convergence model of emmetropization to include the effects of illumination intensity. *Ophthalmic & Physiological Optics*, 19(2), 112–125.

BLACKWELL, H.R. 1970. Development of procedures and instruments for visual task evaluation, *Illuminating Engineering*, 65(4), 317–353.

BOYCE, P.R. 2003, *Human factors in Lighting, Second Edition*. London: CRC Press.

BOYCE, P.R., 1985 Movement under emergency lighting: Effect of illuminance, *Lighting Research & Technology.* Vol. 17, No. 2, 51–71.

BOYNTON, R.M., GORDON, J. 1965. Bezold-Brucke hue shift measured by color-naming technique, *Journal of the Optical Society of America A*, 55, 78–86.

BRAINARD, G. C., HANIFIN, J. P., GREESON, J. M., BYRNE, B., GLICKMAN, G., GERNER, E., ROLLAG, M. D. 2001. Action spectrum for melatonin regulation in humans: evidence for a novel circadian photoreceptor, *J. Neurosci.*, Vol. 21, No. 16, 6405–6412.

BRAINARD, G.C., PROVENCIO, I. 2006. Photoreception for the neurobehavioral effects of light in humans, *CIE x031:2006 Proceedings of the 2nd CIE Expert Symposium "Lighting and Health", 7–8 September 2006, Ottawa, Ontario, Canada*, 6–21. Vienna: Commission Internationale de l’Eclairage.

BROWN, T.M., TSUJIMURA, S., ALLEN, A.E., WYNNE, J., BEDFORD, R., VICKERY, G., VUGLER, A., LUCAS, R.J. 2012. Melanopsin-based brightness discrimination in mice and humans. *Curr. Biol.* 22 (12):1134–1141.

BULLOUGH, J.D. 2000. The blue-light hazard: A review, *Journal of the Illuminating Engineering Society*, 9 (2), 6–14, 141.

BULLOUGH, J.D. 2009. Spectral sensitivity for extra-foveal discomfort glare, *Journal of Modern Optics*, 56, 13, 1518–1522.

BURGESS, H.J. 2010. Partial sleep deprivation reduces phase advances to light in humans, *J. Biol. Rhythms*, Vol. 25, No. 6, 460–468.

CAJOCHEN, C., ZEITZER, J.M., CZEISLER, C.A., DIJK, D.J. 2000. Dose-response relationship for light intensity and ocular and electroencephalographic correlates of human alertness, *Behavioural Brain Research*, Vol. 115, No. 1, 75–83.

CAMPBELL, S.S., TERMAN, M., LEWY, A.J., DIJK, D.J., EASTMAN, C.I., BOULOS, Z. 1995. Light treatment for sleep disorders: consensus report. V. Age-related disturbances, *J. Biol. Rhythms*, Vol. 10, No. 2, 151–154.

CEN. 2011. *EN 12464-1 Light and lighting – Lighting of work places – Part 1: Indoor work places*. European Committee for Standardization.

CHANG, A.M., SANTHI, N., ST HILAIRE, M., GRONFIER, C., BRADSTREET, D.S., DUFFY, J.F., LOCKLEY, S.W., KRONAUER, R.E., CZEISLER, C.A. 2012. Human responses to bright light of different durations, *J. Physiol.*, Vol. 590, Pt 13, 3103–3112.

CHANG, A.M., SCHEER, F.A., CZEISLER, C.A. 2011. The human circadian system adapts to prior photic history, *J. Physiol.*, Vol. 589, Pt 5, 1095–1102.

CIE. 1981a. CIE 19.21-1981. *An Analytic Model for Describing the Influence of Lighting Parameters upon Visual Performance – Technical foundations*. Vienna: Commission Internationale de l'Eclairage.

CIE. 1981b. CIE 19.22-1981. *An Analytic Model for Describing the Influence of Lighting Parameters upon Visual Performance – Summary and application guidelines*. Vienna: Commission Internationale de l'Eclairage.

CIE. 1995. CIE 117-1995. *Discomfort glare in interior lighting*, Vienna: Commission Internationale de l'Eclairage.

CIE. 1997, CIE 123-1997. *Low vision – Lighting needs for the partially sighted*, Vienna: Commission Internationale de l'Eclairage.

CIE. 1999. CIE 135:1999. *CIE Collection 1999: Vision and Colour, Physical Measurement of Light and Radiation*, Vienna: Commission Internationale de l'Eclairage.

CIE. 2010. CIE 190:2010. *Calculation and Presentation of Unified Glare Rating Tables for Indoor Lighting*. Vienna: Commission Internationale de l'Eclairage.

CIE. 2011. CIE 196:2011. *CIE Guide to increasing accessibility in light and lighting*, Vienna: Commission Internationale de l'Eclairage.

CIE. 2015. CIE TN 003:2015. *Report on the First International Workshop on Circadian and Neurophysiological Photometry.* Vienna: Commission Internationale de l'Eclairage.

CORNELISSEN, F.W., BOOTSMA, A., KOOIJMAN, A.C. 1995, Object perception by visually impaired people at different light levels, *Vision Research*, 35, 161–168.

CRASSINI, B., BROWN, B., BOWMAN, K. 1988. Age-related changes in contrast sensitivity in central and peripheral retina, *Perception*, 17, 315–322.

CRAWFORD, B.H. 1936. The dependence of pupil size upon external light stimulus under static and variable conditions. *Proceedings of the Royal Society of London, Series B, Biological Sciences*, 121(823), 376–395.

CURCIO, C.A., MILLICAN, C.L., ALLEN, K.A., KALINA, R.E. 1993. Aging of the human photoreceptor mosaic: evidence for selective vulnerability of rods in central retina. *Investigative Ophthalmology & Visual Science.* 34(12): 3278–3296.

CZEISLER, C., SHANAHAN, T.L., KLERMAN, E.B., MARTENS, H., BROTMAN, D.J., EMENS, J. 1995. Suppression of melatonin secretion in some blind patients by exposure to bright light, *The New England Journal of Medicine,* 332 (1), 6–11.

DE GROOT, S.G., GEBHARD, J.W. 1952. Pupil size as determined by adapting luminance. *Journal of the Optical Society of America A*, 42(7), 492–495.

DELAHUNT, P.B., WEBSTER, M.A., MA, L., WERNER, J.S. 2004. Long-term renormalization of chromatic mechanisms following cataract surgery. *Visual Neuroscience*, 21(3), 301–307.

DIN. 2008. DIN 32975: 2008-06, *Designing visual information in the public area for accessible use,* Deutsches Institut für Normung.

EISNER, A., FLEMING, S.A., KLEIN, M.L., MAULDIN, W.M. 1987. Sensitivities in older eyes with good acuity: cross-sectional norms. *Investigative Ophthalmology & Visual Science,* 28(11), 1824–1831.

ELLIOTT, D.B., WHITAKER, D., 1991. Changes in macular function throughout adulthood. *Documenta Ophthalmologica.* 76: 251–259.

EPERJESI, F., MAIZ-FERNANDEZ, C., BARTLETT, H.E. 2007. Reading performance with various lamps in age-related macular degeneration, *Ophthalmic and Physiological Optics,* 27 (1), 93–99.

FERNANDEZ, D., WILKINS, A.J. 2008. Uncomfortable images in art and nature, *Perception*, 37, 1098–1113.

FETVEIT, A., SKJERVE, A., BJORVATN, B. 2003. Bright light treatment improves sleep in institutionalized elderly—an open trial, *International Journal of Geriatric Psychiatry*, 18, 520–526.

FIGUEIRO, M.G., GRAS, L., QIA, R., RIZZO, P., REA, M., REA, M.S. 2008. A novel night lighting system for postural control and stability in seniors, *Lighting Research & Technology*, 40, 111–126.

FOSSE, P., VALBERG, A., ARNLJOT, H.M., 2001. Retinal Illuminance and the Dissociation of Letter and Grating Acuity in Age-Related Macular Degeneration, *Optometry & Vision Science*, 78(3), 162–168.

HARTMANN, E., SCHEFZYK-HAGL, A., LACHENMAYR, B. 1980. Der Einfluss von Beleuchtungsstärke, Leuchtdichte, Kontrast und Farbe auf das Sehvermögen von Patienten mit leichterer bis hochgradiger Sehbehinderung. *Klin. Mbl. Augenheilk.* 177, 304–318.

HAYMES, S.A., LEE, J. 2006. Effects of task lighting on visual function in age-related macular degeneration. *Ophthalmic and Physiological Optics*. 26 (2) 169–179.

HEBERT, M., MARTIN, S.K., LEE, C., EASTMAN, C.I. 2002. The effects of prior light history on the suppression of melatonin by light in humans, *J. Pineal Res.*, Vol. 33, No. 4, 198–203.

HIGGINS, K.E., JAFFE, M.J., CARUSO, R.C., DEMONASTERIO, F.M. 1988, Spatial contrast sensitivity: effects of age, test-retest, and psychophysical method, *Journal of the Optical Society of America*, A5, 2171–2180.

HOLLADAY, L. 1926. The fundamentals of glare and visibility. *Journal of the Optical Society of America*, 12(4), 271–319.

IEIJ. 2006. *Section 2.9 Practical examples of space design for lighting and colours (authored by Toshiaki Hara), Report of Research Committee of Visual Environment Design for Low Vision*, 29–32, Illuminating Engineering Institute of Japan.

Inoue, Y., Akizuki, Y. 1998. The optimal illuminance for reading–Effects of age and visual acuity on legibility and brightness, *Journal of Light and Visual Environment*, 22, 23–33.

Inoue, Y., Noguchi, T., Itoh, K. 1990. On effective luminance ratio of Landolt Ring, *Proceeding of the Kinki Branch Workshop of Architectural Institute of Japan*, Vol. 30, 9–12, in Japanese.

ISO. 2009. ISO 8596:2009 *Ophthalmic optics – Visual acuity testing – Standard optotype and its presentation*. International Organization for Standardization.

ISO. 2011. ISO 9241-303:2011 *Ergonomics of human-system interaction—Part 303: Requirements for electronic visual displays.* International Organization for Standardization.

ISO. 2014. ISO/DIS 24505 *Ergonomics — Accessible design — Method for creating colour combinations taking account of age-related change of human colour vision*. International Organization for Standardization

ISO/CIE. 2002. ISO 8995-1:2002(E)/CIE S 008/E:2001 *Lighting of Work Places – Part 1: Indoor*. Vienna: Commission Internationale de l'Eclairage.

ISO/CIE. 2007. ISO 30061:2007(E)/CIE S 020/E:2007 *Emergency lighting*. Vienna: Commission Internationale de l'Eclairage.

ISO/IEC. 2001. Guide 71:2001 *Guidelines for standards developers to address the needs of older persons and persons with disabilities*.

IES. 2008. 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* (2008).

ITOH, N., SAGAWA, K. 2010. Spatial resolution of people with low vision, Selected papers of the light and lighting conference with spatial emphasis on LEDs and solid state lighting, International commission on illumination, *CIE x034:2010 Selected Papers of the Light and Lighting Conference with Special Emphasis on LEDs and Solid State Lighting, 27–29 May 2009, Budapest, Hungary*, 49–53.

IWATA, M., OKAJIMA, K., UJIKE, H. 2001. Change in visual contrast sensitivity with age depends on illuminance level, *Journal of Illuminating Engineering Institute of Japan*, 85 (5), 352–360.

JACKSON, G.R., OWSLEY C., McGWIN, G. Jr. 1999. Aging and dark adaptation, *Vision Research*, 39, 3975–3982.

JASCHINSKI, W., 1982, Conditions of emergency lighting, *Ergonomics*, Vol. 25, 363–372.

JASSER, S.A., HANIFIN, J.P., ROLLAG, M.D., BRAINARD, G.C. 2006. Dim light adaptation attenuates acute melatonin suppression in humans, *J. Biol. Rhythms*, Vol. 21, No. 5, 394–404.

JIS. 2010. JIS/TR S 0005:2010. *Data on span of similar colors of low vision*.

JOHNSON, C.A., ADAMS, A.J., TWELKER, J.D., QUIGG, J.M. 1988. Age-related changes in the central visual field for short-wavelength-sensitive pathways. *Journal of the Optical Society of America A*. 5(12): 2131–2139.

KEUNEN, J.E., VAN NORREN, D., VAN MEEL, G.J. 1987. Density of foveal cone pigments at older age *Invest Ophthalmol. Vis. Sci.* 28: 985–991.

KIMURA, T., AYAMA, M. 2010. Evaluation of glare from colour LEDs for young and the elderly, *Journal of Illuminating Engineering Institute of Japan*, 94, 2, 120–123.

KIMURA, T., AYAMA, M. 2011. Evaluation of discomfort glare from colour LEDs and its correlation with individual variations in brightness sensitivity. *Colour Research and Application*, Vol. 36, Issue 4, 286–294.

KNOBLAUCH, K., VITAL-DURAND, F., BARBUR, J.L. 2001. Variation of chromatic sensitivity across the life span. *Vision Research.* 41(1): 23–36.

KRAFT, J.M., WERNER, J.S. 1994. Spectral efficiency across the life span: flicker photometry and brightness matching, *Journal of Optical Society America*, A, 11, 1213–1221.

KUYK, T., ELLIOTT, J.L. 1999. Visual factors and mobility in persons with age-related macular degeneration. *J Rehabil Res Dev* 36: 303–312.

LIEVERSE, R., VAN SOMEREN, E.J., NIELEN, M.M., UITDEHAAG, B.M., SMIT, J.H., HOOGENDIJK, W.J. 2011. Bright light treatment in elderly patients with nonseasonal major depressive disorder: a randomized placebo-controlled trial, *Arch.Gen.Psychiatry*, Vol. 68, No. 1, 61–70.

LOCKLEY, S.W., SKENE, D.J., ARENDT, J., TABANDEH, H., BIRD, A.C., DEFRANCE, R. 1997. Relationship between Melatonin Rhythms and Visual Loss in the Blind, *Journal of Clinical Endocrinology and Metabolism*, Vol. 82, No. 11, 3763–3770.

LUCAS, R.J., PEIRSON, S.N., BERSON, D.M., BROWN, T.M., COOPER, H.M., CZEISLER, C.A., FIGUEIRO, M.G., GAMLIN, P.D., LOCKLEY, S.W., O'HAGAN, J.B., PRICE L.L.A., PROVENCIO, I., SKENE, D.J., BRAINARD, G.C. 2014. Measuring and using light in the melanopsin age, *Trends Neurosci.*, Vol. 37, No. 1, 1–9.

MISHIMA, K., OKAWA, M., SHIMIZU, T., HISHIKAWA, Y. 2001. Diminished melatonin secretion in the elderly caused by insufficient environmental illumination, *Journal of Clinical Endocrinology and Metabolism*, Vol. 86, No. 1, 129–134.

MOCHIZUKI, E., IWATA, T., TSUKAMI, S., KIMURA, K. 2000. Experimental study on discomfort glare from large light source judged by elder and young people, *Journal of Architecture and Planning* (*Transactions of AIJ)*, Vol. 65, No. 528, 17–22.

MOON, P., SPENCER, D.E. 1944. On the Stiles–Crawford effect. *Journal of the Optical Society of America*, 34(6), 319–329

OBAYASHI, K., SAEKI, K., IWAMOTO, J., OKAMOTO, N., TOMIOKA, K., NEZU, S., IKADA Y., KURUMATANI, N. 2012. Positive effect of daylight exposure on nocturnal urinary, melatonin excretion in the elderly: a cross-sectional analysis of the HEIJO-KYO study, *Journal of Clinical Endocrinology and Metabolism*, Vol. 97, No. 11, 4166–4173.

OBAYASHI, K., SAEKI, K., IWAMOTO, J., OKAMOTO, N., TOMIOKA, K., NEZU, S., IKADA, Y., KURUMATANI, N. 2013. Exposure to light at night, nocturnal urinary melatonin excretion, and obesity/dyslipidemia in the elderly: a cross-sectional analysis of the HEIJO-KYO study, *Journal of Clinical Endocrinology and Metabolism*, Vol. 98, No. 1, 337–344.

O'HARE, L., HIBBARD, P.B. 2011. Spatial frequency and visual discomfort, *Vision Research*, 51, 1767–1777.

OKAJIMA, K., IWATA, M., 1998. Simulation of light efficiency for aged people and data-analysis of an optimal illuminance with aging models of the human lens, *Journal of Illuminating Engineering Institute of Japan*, 82, 8A, 564–572.

OKAJIMA, K., TSUCHIYA, N., YAMASHITA, K. 2002. Age-related changes in color appearance depend on unique-hue components, *Proc. SPIE*, 4421, 259–262.

OUELLETTE, M.J., REA, M.S., 1989, Illuminance requirements for emergency lighting, *J. Illum. Eng. Soc.,* 18 (1), 37–42.

OWSLEY, C. 2011. Aging and vision, *Vision Research*, 51, 1610–1622.

OWSLEY, C., SEKULER, R., SIEMSEN, D. 1983. Contrast sensitivity throughout adulthood, *Vision Research*, 23, 689–699.

POKORNY, J., SMITH, V.C., LUTZE, M. 1987, Aging of the human lens, *Applied Optics*, 26, 1437–1440.

REA, M.S., OUELLETTE, M.J. 1991. Relative visual performance: A basis for application, *Lighting Research & Technology*, 23(3) 135–144.

RESNIKOFF, S., PASCOLINI, D., ETYA'ALE, D., KOCUR, I., PARARAJASEGARAM, R., POKHAREL, G.P., MARIOTTI S.P. 2004. Global data on visual impairment in the year 2002, *Bulletin of the World Health Organization*, 82 (11), 844–851.

REX, C.H., FRANKLIN, J.S. 1960. Relative visual conform evaluations of roadway lighting, *Illuminating Engineering*, 55, 161–174.

ROBERTS, J.E. 2001. Ocular phototoxicity. *Journal of Photochemistry and Photobiology B: Biology*, 64, 136–143.

SAGAWA, K., TAKAHASHI, Y. 2003. Span of categorical colours measured by similarity of colours, *Proceedings of 25th Session of the CIE*, Vol. 1, D1-64–D1-67.

SAGAWA, K., UJIKE, H., SASAKI, T. 2003. Legibility of Japanese characters and sentences as a function of age, *Proceedings of the IEA 2003*, 7, 496–499.

SANTHI, N., THORNE, H.C., VAN DER VEEN, D.R., JOHNSEN, S., MILLS, S.L., HOMMES, V., SCHLANGEN, L.J., ARCHER, S.N., DIJK, D.J. 2011. The spectral composition of evening light and individual differences in the suppression of melatonin and delay of sleep in humans, *J. Pineal Res.*, Vol. 53, No. 1, 47–59.

SATOH, R., MOTOTSUGU, S., HARA, N. 1999. Curved Surfaces of Various Visibility Level in the Three Dimensional Space Composed of Three Visual Factors, *CIE 133-1999: Proceedings of the 24th Session of the CIE, 24–30 June 1999, Warsaw, Poland*, 1-2, 74–76, Vienna: Commission Internationale de l'Eclairage.

SCENIHR (Scientific Committee on Emerging and Newly Identified Health Risks). 2012. *Health effects of artificial light*, http://ec.europa.eu/health/scientific_committees/emerging/docs/scenihr_o_035.pdf, 19 March 2012.

SCHEFRIN, B.E., WERNER, J.S. 1990. Loci of spectral unique hues throughout the life span. *Journal of the Optical Society of America A*. 7(2), 305–311.

SCHEFRIN, B.E., WERNER, J.S. 1993. Age-related changes in the color appearance of broadband surfaces, *Color Research & Application,* 18, 380–389.

SHINOMORI, K., SCHEFRIN, B.E., WERNER, J.S. 2001. Age-related changes in wavelength discrimination, *Journal of the Optical Society of America A*. 18, 310–318.

SHINOMORI, K. 2003. Aging effects on color vision, *Journal of the Color Science Association of Japan*, 27(3), 216–223.

SHOCHAT, T., MARTIN, J., MARLER, M., ANCOLI-ISRAEL, S. 2000. Illumination levels in nursing home patients: effects on sleep and activity rhythms, *J. Sleep Res.*, Vol. 9, No. 4, 373–379.

SIMMONS, R.C., 1975, Illuminance, diversity and disability glare in emergency lighting, *Lighting Research & Technology*, Vol. 7, No.2, 121–132.

SLETTEN, T.L., REVELL, V.L., MIDDLETON, B., LEDERLE, K.A., SKENE, D.J. 2009. Age-related changes in acute and phase-advancing responses to monochromatic light, *J. Biol. Rhythms*, Vol. 24, No. 1, 73–84.

SLINEY, D.H. 2006. From photo-biological science to lighting applications, *x031:2006: Proceedings of the 2nd CIE Expert Symposium "Lighting and Health", 7–8 September 2006, Ottawa, Ontario, Canada*, 1–5, Vienna: Commission Internationale de l'Eclairage.

SLOAN, L.L., HABEL, A., FEIOCK, K. 1973. High illumination as an auxiliary reading aid in diseases of the macula, *American Journal of Ophthalmology*, 76,745–757.

SMITH, K.A., SCHOEN, M.W., CZEISLER, C.A. 2004. Adaptation of human pineal melatonin suppression by recent photic history, *Journal of Clinical Endocrinology and Metabolism*, Vol. 89, No. 7, 3610–3614.

STANLEY, P.A., DAVIES, A.K. 1995. The effect of field of view size on steady-state pupil diameter. *Ophthalmic & Physiological Optics*, 15(6), 601–603.

STEEN, R., WHITAKER, D., ELLIOTT, D.B., WILD, J.M. 1993. Effect of filters on disability glare, *Ophthalmic & Physiological Optics*, 13, 10 (October), 372–376.

TANIGUCHI, G., ISOBE, T., MORISAKI, Y., HARA, T. 2007. *Central Japan International Airport's Universal Design: From Processes to Design Testing.* Tokyo: Kajima Institute Publishing Co., Ltd. (ISBN: 978-4-306-07259-6 C3052).

TERMAN, M., LEWY, A.J., DIJK, D.J., BOULOS, Z., EASTMAN, C.I., CAMPBELL, S.S. 1995. Light treatment for sleep disorders: consensus report. IV. Sleep phase and duration disturbances, *J. Biol. Rhythms*, Vol. 10, No. 2, 135–147.

THAPAN, K., ARENDT, J., SKENE, D.J. 2001. An action spectrum for melatonin suppression: evidence for a novel non-rod, non-cone photoreceptor system in humans, *J. Physiol.*, Vol. 535, No. Pt 1, 261–267.

THEEUWES, J., ALFERDINCK, J.W.A.W., PEREL, M. 2002. Relation between glare and driving performance. *Human Factors*, 44(1): 95–107.

TSONGOS, N.G., SCHWAB, R.N. 1970. Driver judgments as influenced by vehicular lighting at intersections, *Highway Research Record*, 336: 21–32.

UJIKE, H., SAGAWA, K. 2002. CSF as a function of age and its application to visibility of letters, *x025:2003: Proceedings of the CIE Symposium 2002 on Temporal and Spatial Aspects of Light and Colour Perception and Measurement, August 2002, 81–86*, Vienna: Commission Internationale de l'Eclairage.

VAN DE KRAATS, J., VAN NORREN, D. 2007. Optical density of the aging human ocular media in the visible and the UV, *Journal of the Optical Society of America A*, 24(7), 1842–1857.

VAN SOMEREN, E.J., HAGEBEUK, E.E., LIJZENGA, C., SCHELTENS, P., DE ROOIJ, S.E., JONKER, C., POT, A., MIRMIRAN, M.M., SWAAB, D.F. 1996. Circadian rest-activity rhythm disturbances in Alzheimer's disease, *Biol. Psychiatry*, Vol. 40, No. 4, 259–270.

VOS, J.J. 1984. Disability glare – A state of the art report, *CIE Journal*, 3, 2, 39–53.

VOS, J.J. 1995. Age dependence of glare effects and their significance in terms of visual ergonomics, in W Adrian (ed.) *Lighting for Aging vision and health*, New York: Lighting Research Institute.

VOS, J.J. 1999. Glare today in historical perspective: towards a new CIE glare observer and a new glare nomenclature, *CIE 133-1999: Proceedings of the 24th Session of the CIE, 24–30 June 1999, Warsaw, Poland*, 38–42.

WATSON, A.B., YELLOTT, J.I. 2012. A unified formula for light-adapted pupil size, *Journal of Vision*, 12(10) 1–16.

WEALE, R.A. 1961. Retinal illumination and age, *Transaction Illuminating Engineering Society* (London), 26(2), 95–100.

WEALE, R.A. 1963. *The aging eye*, London: HK Lewis.

WEBBER, G.M.B., 1984, Emergency Lighting Recommendations. *Proceedings of the National Lighting Conference*, Cambridge, UK: 138–150.

WERNER, J.S., STEELE, V.G. 1988. Sensitivity of human foveal color mechanisms throughout the life span. *Journal of the Optical Society of America A*. 5(12): 2122–2130.

WERNER, J.S., SCHEFRIN, B.E. 1993. Loci of achromatic points throughout the life span, *Journal of the Optical Society of America A*. 10(7), 1509–1516.

WERNER, J.S., DELAHUNT, P.B., HARDY, J.L. 2004. Chromatic-spatial vision of the aging eye, *Optical Review*, 11(4), 226–234.

WESTON, H.C. 1945. The relation between illumination and industrial efficiency, the effect of brightness contrast, *London: Industrial Health Research Board, Great Britain Medical Research Council* pp1–35, Report No.87.

WHITE, M.D., ANCOLI-ISRAEL, S., WILSON, R.R. 2013. Senior living environments: evidence-based lighting design strategies, *HERD*, Vol. 7, No. 1, 60–78.

WHO 1993. *International statistical classification of diseases, injuries and causes of death, tenth revision*. Geneva: World Health Organization.

WHO, 2004a. *World Health Report 2004. Changing History*. Geneva: World Health Organization (Annex Table 3 Burden of disease in DALYs by cause, sex and mortality stratum in WHO regions, estimates for 2002, p. 130).

WHO, 2004b. *Global burden of diseases 2004 update*, Geneva: World Health Organization (Table 9: Estimated prevalence of moderate and severe disability (millions) for leading disabling conditions by age, for high-income and low- and middle-income countries, 2004, p. 35).

WHO, 2010. *Global data on visual impairments 2010*, Geneva: World Health Organization (Table 2: Global estimate of the number of people visually impaired by age, 2010, p. 5; and Table 3 Number of people visually impaired and corresponding percentage of the global impairment by WHO Region and country, 2010, p. 5.).

WILKINS A.J., NIMMO-SMITH M.I., TAIT A., MCMANUS C., DELLA SALA S., TILLEY A., ARNOLD K., BARRIE M., SCOTT S. 1984. A neurological basis for visual discomfort, *Brain,* 107, 989–1017.

WILKINS, A.J. 1986. What is visual discomfort? *Trends Neurosci*, 9(8), 343–346.

WILKINS, A.J. 2016. A physiological basis for visual discomfort: Application in lighting design. *Lighting Research & Technology,* 48, 44–54.

WINN, B., WHITAKER, D., ELLIOTT, D.B., PHILLIPS, N.J. 1994. Factors affecting light-adapted pupil size in normal human subjects, *Investigative Ophthalmology & Visual Science*, 35(3), 1132–1137.

WIRZ-JUSTICE, A., BENEDETTI, F., TERMAN, M. 2009. *Chronotherapeutics for Affective Disorders, A Clinician's Manual for Light and Wake Therapy*. Basel: Karger.

WIRZ-JUSTICE, A., TERMAN, M., OREN, D.A. 2004. Brightening depression, *Science*, Vol. 303, No. 5657, 467–469.

WOOD, J.M., OWENS, D.A. 2005. Standard measures of visual acuity do not predict drivers' recognition performance under day or night conditions. *Optom Vis Sci,* 82: 698–705.

XU, J., POKORNY, J., SMITH V.C. 1997. Optical density of the human lens, *Journal of the Optical Society of America*, A14, 953–960.

ZEITZER, J.M., DIJK, D.J., KRONAUER, R., BROWN, E., CZEISLER, C. 2000. Sensitivity of the human circadian pacemaker to nocturnal light: melatonin phase resetting and suppression, *J. Physiol.*, Vol. 526, Pt 3, 695–702.

ZEITZER, J.M., FRIEDMAN, L., YESAVAGE, J.A. 2011. Effectiveness of evening phototherapy for insomnia is reduced by bright daytime light exposure, *Sleep Med.*, Vol. 12, No. 8, 805–807.