Age-Dependent Impacts of Lighting Conditions on Contrast Sensitivity and Subjective Visual Perception Focusing on Pupil Size and Crystalline Lens Transmittance

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Age-dependent impacts of lighting conditions on contrast sensitivity and subjective visual perception focusing on pupil size and crystalline lens transmittance

The effects of different illuminances and correlated color temperatures (CCTs) of LED lighting on contrast sensitivity (log CS) and subjective visual perception (brightness and comfort) were compared in healthy children (n = 10, 9.9 ± 1.6 years old), middle-aged (n = 10, 40.7 ± 3.3 years) and older adults (n = 10, 68.3 ± 3.2 years). The six lighting conditions used were a combination of three illuminances (100, 300, and 750 lx) and two CCTs (3000 and 6000 K). Furthermore, we measured spectral crystalline lens transmittance and pupil size, and investigated relationships between visual-related measurements and ophthalmologic characteristics. Log CS significantly decreased in older adults, and increased with increasing illuminance, regardless of age group or CCT. Multiple regression analysis revealed that age-related changes in log CS are not due to pupil size ($\beta = 1.1*10^{-3}$, $p = 0.42$) or age ($\beta = 6.0*10^{-4}$, $p = 0.24$) but are influenced by a decrease in lens transmittance ($\beta = 1.72$, $p < 0.0001$). Subjective brightness and comfort increased with increasing illuminance, but comfort in children was not affected by illuminance and was a higher tendency at low CCT. These results show that the effects of the lighting environment, i.e., illuminance and CCT, on visual functions vary with age and ophthalmologic characteristics, especially crystalline lens transmittance, emphasizing the importance of designing a lighting environment considering these factors.

Keywords; aging, contrast sensitivity, pupil, crystalline lens, lighting environment

1. Introduction

Visual perception, a crucial element of human cognition, is significantly influenced by lighting conditions, particularly illuminance and correlated color temperature (CCT).(Tidbury et al. 2016; Cheng et al. 2016; Yang and Jeon 2020) Modern lighting technologies such as light-emitting diode (LED) lighting, offer extensive capabilities for adjusting both illuminance and CCT. This flexibility is associated with a diverse array of visual effects. For instance, studies using LED lighting have shown that high light intensity and CCT can improve color discrimination abilities and visual comfort in older adults.(Cheng et al. 2016) Understanding the effects of diverse LED lighting characteristics on visual function and perception is essential for the development of comfortable lighting environments.

Age-related physiological changes in pupil size (senile miosis)(Winn et al. 1994; Yang et al. 2002) and crystalline lens transmittance (nonhomogeneous decrease in transmittance with age),(Van den Berg and Felius 1995; Broendsted et al. 2011; Teikari et al. 2012; Najjar et al. 2016; Chaopu et al. 2018) can also affect visual function and modulate the impact of different lighting environments on such functions. Notably, blue-light transmittance of the lens declines by approximately 50% from young to older adults,(Broendsted et al. 2011) potentially diminishing stimulation of melanopsin, a photopigment sensitive to blue light wavelengths (~480 nm). While melanopsin is widely recognized for its role in non-visual functions, such as circadian clock regulation,(Berson et al. 2010) emerging evidence suggests that it also contributes to visual functions, including the enhancement of contrast sensitivity (CS) (Allen et al. 2019; Zele et al. 2019; Chien et al. 2023) and brightness perception.(Brown et al. 2012; Zele et al. 2018; Yamakawa et al. 2019) A recent study suggested that melanopsin alone supports the detection of coarse spatial and temporal patterns rather than discrimination of form or orientation,(Nugent and Zele 2024) highlighting the complexity of its role in visual perception. Although the precise mechanisms remain to be fully understood, accumulating evidence supports its contribution to human visual functions. Accordingly, age-related lens transmittance changes may reduce melanopsin excitation, potentially diminishing specific visual functions, such as CS and brightness perception, in older adults. Indeed, CS declines with age,(Owsley et al. 1983) and such a decline is suspected to be primarily due to increases in the optical density of the crystalline lens.(Owsley 2016) However, the quantitative effect of age-related changes in lens transmittance on visual function has not been thoroughly evaluated. Reduced CS in older adults leads to reduced reading speed, especially for small letters,(Akutsu et al. 1991) and can have significant impacts on the quality of life.

In contrast to older adults, children have larger pupils and higher lens transmittance, especially in blue light regions.(Eto et al. 2021; Eto and Higuchi 2023) This may be advantageous for maintaining high visual acuity and CS because it leads to increasing the excitation of melanopsin. The larger pupils and higher lens transmittance allow more light to reach the retina, which can facilitate larger pupil constriction. Generally, it is known that smaller pupil sizes, resulting from this constriction, improve visual acuity.(Campbell and Gregory 1960) Additionally, the characteristics of the pupil and lens transmittance of children, which are more stimulated melanopsin, may themselves affect visual functions, such as CS. However, this also makes them more susceptible to the non-visual effects of nighttime lighting. For example, it has been shown that nocturnal melatonin secretion is more strongly suppressed by light at night in children compared to adults.(Higuchi et al. 2014; Eto et al. 2021) Children’s learning and lifestyle habits further exacerbate this susceptibility as they often study under bright light during nighttime hours, whether for homework or extra classes. While studying, high illuminance and CCT lighting are sometimes preferred to improve the readability of text because they increases visual acuity(Berman et al. 2006; Tidbury et al. 2016); however, the use of high CCT lighting at night enhances melatonin suppression in children and adolescents(Lee et al. 2018; Nagare et al. 2019) and causes circadian rhythm disruptions.(Higuchi et al. 2016)

The trade-off between optimizing visual function and maintaining healthy circadian rhythms across the lifespan requires balanced lighting designs. However, to date, the individual or combined effects of illuminance and CCT on visual function in different age groups remain under-investigated, especially in the range of brightness that people routinely experience during visual tasks, such as during home study in children. Our study aimed to fill these gaps by investigating the effect of the illuminance and CCT of LED lighting on contrast sensitivity, subjective brightness perception and comfort 1) in the range of daily experience and 2) in different age groups, from children to older adults. In addition, to clarify the direct influence of age-related differences in ophthalmic characteristics on visual function, we investigated 3) the role of pupil size and crystalline lens transmittance on these visual functions. We have a technique to measure the spectral transmittance of the crystalline lens, which we used to clarify the role of ophthalmologic characteristics on age-related differences in the effects of light environmental conditions on visual functions.

2. Materials and methods

2.1. Participants

Ten healthy primary school children (mean age ± standard deviation (SD), 9.9 ± 1.6 years old; three boys and seven girls); 10 middle-aged (40.7 ± 3.3 years old; two men and eight women); and 10 older adults (68.3 ± 3.2 years old; three men and seven women) with normal red-green color vision as determined by the Ishihara color vision test participated in this study. Participant recruitment for this study was conducted from July 1, 2021, to March 31, 2022. Participants with corrected decimal visual acuity of 1.0 (0.0 logMAR) or higher were recruited. None of the participants had a history of ocular diseases such as cataracts or glaucoma. The information on visual acuity and history of ocular diseases was provided by self-reports from participants or their parents. All older adult participants did not require the use of presbyopia correction glasses, at least during the experiment. An oral and paper-based explanation of the study was provided to all participants before the experiment. All participants provided written informed consent to participate in this study, which was approved by the Ethical Committee of Kyushu University (Approval No. 391), Japan. Informed consent forms for the children were completed by their parents after confirming the children's consent to participate. This study was conducted in accordance with the principles of the Declaration of Helsinki.

2.2. Experimental conditions and procedures

Figure 1 shows a diagram of the experimental protocol. Participants repeatedly performed contrast sensitivity and answered questionnaires on the subjective visual perception of lighting environments (brightness and comfort) in six LED lighting environments with different illumination and CCTs. The pupil sizes of the right eye were repeatedly measured for each lighting condition, and crystalline lens transmittances of the right eye were measured once before or after the experiment to investigate the relationship between each visual index and ophthalmologic characteristics. The illuminance conditions were 100, 300, and 750 lx, and CCTs were 3000 and 6000 K; thus, six lighting conditions were used for all combinations using an LED ceiling light (HH-LC569A, Panasonic Inc., Minato-ku, Japan: Spectral irradiances are shown in S1A Fig). Daylight color (6500 K, color rendering: Ra = 83) and lamp color LED (3000 K, Ra = 83) are installed in the ceiling light and the CCTs of the ceiling light can be adjusted to four levels between 6500 and 3000 K. The brightness of the ceiling light is adjustable between 5 and 100%, with a maximum luminous flux of 4299 lm.

The illuminance and CCT of the LED ceiling lighting were measured at the working surface using an illuminance radiometer (CL-200A, KONICA MINOLTA Inc., Chiyoda-ku, Japan) and vertically at the eye level of the sitting participant using an illuminance spectroradiometer (CL-500A, KONICA MINOLTA Inc.). At eye level, the illuminances were 33, 97, and 240 lx, and CCTs were 2983 and 5629 K (spectral irradiances are shown in S1B Fig). Table 1 A shows the melanopic-EDI at eye level,(CIE System for Metrology of OpticalRadiation for ipRGC-Influenced Responses to Light 2018) a metric that evaluates the effect on the photoreceptor melanopsin, which contributes significantly to non-visual functions, including circadian phase-shift functions. This range of lighting conditions is experienced daily in real life.

Participants were explained each test, that is, the CS test and questionnaires, and were allowed to practice before starting the experiment. First, the participants waited in a dark room for 2 min and then moved to a measurement room, where the light environment was set to one of six LED lighting conditions. Next, the pupil size of the right eye was measured using an electronic pupillometer (FP-10000, TMI Inc., Niiza, Japan), and a CS test was performed using the right eye with the left eye covered. Finally, the participants answered a questionnaire on subjective evaluations of the light environments. This cycle was repeated under various LED lighting conditions. The order of the lighting conditions was randomized. If participants wore glasses or contact lenses, they were asked if they were spectrally corrected lenses, e.g., blue-filtering lenses, and all participants confirmed that they did not use spectrally corrected lenses. All participants performed the experimental procedure for a duration of about two hours within the time frame of 10:00 AM to 5:30 PM.

2.3. Measurement of contrast sensitivity

CS was evaluated using The Mars Letter Contrast Sensitivity Test (Mars Perceptrix

Corporation, NY, USA).(Dougherty et al. 2005) The charts of The Mars Letter Contrast Sensitivity Test consist of letters referred to as the Sloan letters "C, D, H, K, N, O, R, S, V, Z," which have been reported to be equally easy to recognize and not too similar to each other. The contrast between background and letters decreases from left to right and from top to bottom, with 0.04 log CS per letter, gradually decreasing from 0.04 log CS (the contrast is 91 %) to 1.92 log CS (the contrast is 1.2 %). The viewing distance of the participants from the chart and the viewing angle were 40 cm and 2.5 degrees, respectively. Under this viewing condition, the spatial frequencies of the letters in the Mars Letter Contrast Sensitivity Test were 0.4−1.6 cycles/degree. The letters in the chart are presented individually by masking the other letters. A lack of response within 3 s was considered incorrect. Each participant's CS score was defined as the log CS at the lowest contrast letter immediately before two incorrectly identified letters minus a scoring correction. The letter immediately before two consecutive misses was called the final correct letter, and a scoring correction was calculated by multiplying 0.04 by the number of errors before the final correct letter. If the participant reaches the end of the chart without making two consecutive errors, then the final correct letter is simply the final letter correctly identified. The chart of three different characters was presented randomly to reduce the learning effect.

2.4. Subjective evaluation of lighting environments

The questionnaire for evaluation of subjective impressions—"Brightness" and "Comfort"—of lighting environments was designed with six scales without a middle category response, e.g., "Neither." Participants were asked to check the most likely alternative to the questionnaire when studying the experimental desk under the lighting conditions. This evaluation was performed after measuring CS and pupil size under each lighting condition.

2.5. Spectral crystalline lens transmittance measurement

The spectral lens transmittance was measured using the Purkinje image-based system developed in our laboratory.(Eto et al. 2020) Purkinje images were formed by the reflections of light sources at different ocular interfaces (air-cornea, cornea-aqueous humor, aqueous humor lens, and lens-vitreous humor interfaces). The first and second Purkinje images are reflection images at the air-cornea and cornea-aqueous humor interfaces, respectively. The third and fourth Purkinje images are reflection images of the aqueous humor lens and lens-vitreous humor interfaces, respectively. The Purkinje-based system can measure the lens density spectrum by using the intensity and size of the fourth Purkinje image in the participant's eye for different wavelengths of visible light. The transmittance spectrum was obtained from the measured density spectrum and the ocular media model proposed by van de Kraats and van Norren.(van de Kraats and van Norren 2007) The participant's right eye lens was measured using the Purkinje-image-based system.

2.6. Data and statistical analyses

Statistical analyses were performed using R version 4.2.1 (R Core Team, Austria) with the "stats" package (v. 4.3.0)(R Core Team 2024) and the "anovakun" function.(Iseki 2023) To analyze the effects of age and light conditions (illuminance and CCT) on the log CS, subjective evaluation of lighting environments, and pupil size, mixed repeated measures analysis of variance (ANOVA) was performed. "Age" (children, middle-aged and older adults) was used as a between factor; and illuminance, defined as "lx" (100, 300, and 750 lx), and "CCT" (3000 and 6000 K) was used as within factors. Post-hoc analysis was performed using multiple comparisons of two-tailed paired or unpaired t-tests with modified sequentially rejective Bonferroni (MSRB) correction.(Shaffer 1986)

Crystalline lens transmittance was compared among the age groups using one-way

ANOVA with multiple comparisons of unpaired t-tests corrected by MSRB after calculating the area under the curve (AUC) of spectral lens transmittance in the wavelength range of 350–790 nm. The AUC of the crystalline lens transmittance spectrum was defined as T_AUC, which was transformed into a value relative to the AUC value, assuming that the lens transmittance was 1.0, over the wavelength range of 350–790 nm.

Pearson's correlation analysis was used to evaluate the relationship between log CS and T_AUC, pupil size, and age. Then, the contribution of ocular features (pupil size and crystalline lens transmittance) to the measurements (log CS, subjective "brightness" and "comfort") was examined using multiple regression analysis with age, illuminances, and CCTs as control variables. Note that pupil size and T_AUC were included in the multiple regression equation as control variable for each other. $p < 0.05$ was considered statistically significant in all statistical analyses.

3. Results

3.1. Contrast sensitivity

Figure 2 shows the results of the measurements of log CS in each age group, and Fig. 2 A and B show the results at 3000 and 6000 K, respectively. The mixed repeated measures ANOVA revealed the significant main effects of "Age" ($F_{2, 27} = 18.75$, $p < 0.0001$, $\eta_p^2 = 0.581$; the statistical results are summarized in S1 Table) and "lx" ($F_{1.75, 47.3} = 9.12$, $p < 0.001$, $\eta_p^2 = 0.253$). Post-hoc analysis for the main effect of "Age" showed that log CS in older adults was lower compared to children ($t_{27} = 4.94$, $p < 0.0001$, Cohen's $d = 1.52$) and middle-aged adults ($t_{27} = 5.60$, $p < 0.0001$, $d = 1.90$), and the main effect of "lx" showed that a lower illuminance reduces the log CS independent of age (S1 Table). There was no significant effect of "CCT" on log CS ($F_{1, 27} = 0.0061$, $p = 0.938$, $\eta_p^2 = 0.0002$) and there were no significant interactions of "Age*CCT," "Age*lx," "lx*CCT," and "Age*lx*CCT" (all p >0.05).

3.2. Subjective evaluation for lighting environments

3.2.1. Brightness

Figure 3 shows the results of subjective brightness and comfort when participants imagined studying on the experimental desk under each lighting condition, and Fig. 3 A and B show the results at 3000 and 6000 K, respectively. The ANOVA revealed that there were significant main effects of "Age" ($F_{2, 27} = 11.6$, $p < 0.001$, $\eta_p^2 = 0.463$) and "lx" ($F_{1.69, 45.8} = 45.6$, $p < 0.0001$, $\eta_p^2 = 0.628$), and significant interactions of "CCT*lx" ($F_{1.97, 53.1} = 3.79$, $p < 0.05$, $\eta_p^2 = 0.123$). There was no significant main effect of "CCT" ($F_{1, 27} = 0.371$, $p = 0.547$, $\eta_p^2 = 0.0136$). Statistical results are summarized in S2 Table.

Post-hoc analysis for the main effect of "Age" showed that children evaluated subjective brightness as higher compared to middle-aged ($t_{27} = 3.64$, $p < 0.01$, $d = 0.98$) and older adults ($t_{27} = 4.56$, $p < 0.001$, $d = 1.25$). For the main effect of "lx" post-hoc analysis showed that a lower illuminance reduced the subjective brightness independent of age.

Examining the interaction of "CCT*lx" again showed that a lower illuminance reduced subjective brightness perception in both 3000 ($F_{1.63, 44.1} = 27.0$, $p < 0.0001$, $\eta_p^2 = 0.50$) and 6000 K ($F_{1.88, 50.9} = 33.1$, $p < 0.0001$, $\eta_p^2 = 0.551$) conditions. Additionally, examining the effects of "CCT" on subjective brightness in each illuminance condition, we noted a tendency to rate 3000 K brighter than 6000 K at 100 lx ($F_{1, 27} = 3.74$, $p = 0.0638$, $\eta_p^2 = 0.123$), whereas there was no significant effect at 300 and 750 lx.

3.2.2. Comfort

Figures 3 C and D show the results for the subjective comfort at 3000 and 6000 K, respectively. The ANOVA revealed that there were significant main effects of "Age" ($F_{2, 27} = 16.9$, $p < 0.0001$, $\eta_p^2 = 0.556$) and "lx" ($F_{1.97, 53.2} = 46.4$, $p < 0.0001$, $\eta_p^2 = 0.632$), and significant interactions of “Age*CCT” ($F_{2, 27}$ = 3.47, p <0.05, η_p^2 = 0.205) and “Age*lx” ($F_{3.94, 53.2}$ = 4.56, p <0.001, η_p^2 = 0.253). There was no significant main effect of “CCT” ($F_{1, 27}$ = 3.69, p = 0.0655, η_p^2 = 0.120). Statistical results are summarized in S3 Table.

Post-hoc analysis for the main effect of “Age” showed that children evaluated subjective comfort higher than middle-aged (t_{27} = 4.14, p <0.001, d = 1.19) and older adults (t_{27} = 5.60, p <0.001, d = 1.42), and for the main effect of “lx” showed that a lower illuminance reduces the subjective comfort.

In a post-hoc analysis for the interaction of “Age*CCT,” examining the effects of “CCT” on subjective comfort in each age group, there was a non-significant tendency to rate 3000 K as more comfortable than 6000 K in children ($F_{1, 9}$ = 4.61, p = 0.0603, η_p^2 = 0.339), whereas there was no significant effect in middle-aged ($F_{1, 9}$ = 2.19, p = 0.173, η_p^2 = 0.200) and older adults ($F_{1, 9}$ = 0.69, p = 0.427, η_p^2 = 0.0714). Regarding the interaction of “Age*lx,” although “Ix” had significant effects in all age groups, the post-hoc analysis for the effect of “lx” showed that there were no significant differences in subjective comfort between each illuminance condition in children (all p >0.1), while a lower illuminance significantly reduces the subjective comfort in middle-aged and older adults.

3.3. Ophthalmic characteristics

3.3.1. Pupil size

Figure 4 shows the pupil sizes under each lighting condition, and Fig. 4 A and B show the results at 3000 and 6000 K, respectively. The mixed repeated measures ANOVA revealed that there were significant main effects of “Age” ($F_{2, 27}$ = 7.85, p <0.01, η_p^2 = 0.368), “lx” ($F_{1.86, 50.2}$ = 117.8, p <0.0001, η_p^2 = 0.814), and “CCT” ($F_{1, 27}$ = 13.8, p <0.001, η_p^2 = 0.338), and significant interactions of “Age*lx” ($F_{3.72, 50.2}$ = 2.91, p <0.05, η_p^2 = 0.177). Statistical results are summarized in S4 Table.

Post-hoc analysis for the main effect of "Age" shows that the pupil sizes in children were larger than middle-aged (t_{27} = 2.44, p <0.05, d = 0.67) and older adults (t_{27} = 3.92, p <0.01, d = 1.14), and there was no significant difference between middle-aged and older adults (t_{27} = 1.48, p = 0.15, d = 0.44). Pupil sizes under 6000 K light (mean ± SD: 9.95 ± 4.76 mm^2) were significantly smaller than those under 3000 K (11.4 ± 5.16 mm^2). The main effect of "lx" showed that a higher illuminance reduced pupil sizes ($F_{1, 27}$ = 13.8, p <0.001, η_p^2 = 0.338).

In a post-hoc analysis examining the interaction of "Age*lx," pupil sizes in children were significantly larger than that in middle-aged and older adults under all illuminance conditions (ps <0.05). In contrast, there were no significant differences in pupil size between middle-aged and older adults under any illuminance condition. Regarding the effects of "lx" on pupil sizes in each age group, pupil sizes were significantly smaller with increasing illuminance in all age groups (all p <0.01).

3.3.2. Lens transmittance

Figure 5 A shows the crystalline lens transmittance spectra for each age group measured using the Purkinje image-based system. The one-way ANOVA in the AUC of T_AUC (Fig. 5 B) on factor "Age" revealed significant main effects ($F_{2, 27}$ = 51.7, p <0.0001, η_p^2 = 0.793. Post-hoc analysis showed that the T_AUC in children was significantly larger than that in middle-aged (t_{27} = 4.25, p <0.001, d = 2.10) and older adults (t_{27} = 10.1, p <0.0001, d = 4.14). The T_AUC in middle-aged adults was significantly higher than that in older adults (t_{27} = 5.88, p <0.0001, d = 2.34).

Figure 5 C shows the estimated spectral irradiance distribution of light on the retina for each age group and lighting condition. The spectral irradiance distributions were calculated by multiplying the mean lens transmittance spectra in Fig. 5 A and the spectral irradiance at the eye level in S1B Fig. Table 1 B shows the melanopic EDI for each lighting condition corrected for actual lens transmittance for each age group according to CIE S 026/E:2018. The standard melanopic EDI shown in Table 1 A is corrected for lens transmittance of the 32-year-old standard observer (CIE System for Metrology of OpticalRadiation for ipRGC-Influenced Responses to Light 2018); therefore, the melanopic EDI in children is higher than that in Table 1 A and lower in middle-aged and older adults.

3.4. Relationships between ophthalmic characteristics and visual-related measurements

Table 2 shows the relationships between log CS, T_AUC, and pupil size, evaluated using Pearson's correlation analysis. No significant correlation was observed between pupil size and log CS under any of the lighting conditions (S2 Fig). In contrast, T_AUC significantly correlated with log CS under all lighting conditions (all p <0.01; S3 Fig). Additionally, because the correlation between age and log CS was found to be significant for all lighting conditions (all p <0.01; S4 Fig), multiple regression analysis was performed to investigate the relationship between log CS and ophthalmic characteristics in detail.

Table 3 shows the results of multiple regression analysis with age, lx, and CCT as control variables to assess the contributions of age-related variations in pupil size and lens transmittance to CS and subjective visual perception. Multiple regression analysis yielded a statistically significant model ($F_{5,174}$ = 27.2, adjusted R^2 = 0.42, p <0.0001), indicating that the regression model as a whole provided a meaningful fit to log CS (Table 3). Upon adjusting for the potential confounders of pupil size, age and lighting conditions, T_AUC emerged as the predictor that exhibited a statistically significant influence on log CS (β = 1.72, p <0.0001). Whereas pupil size ($\beta = 1.1*10^{-3}$, p = 0.42), age ($\beta = 6.0*10^{-4}$, p = 0.24) and CCT ($\beta = 2.0*10^{-3}$, p = 0.84) did not exhibit a statistically significant impact on log CS, lighting illuminance ($\beta = 6.8*10^{-5}$, p = 0.003) demonstrated a statistically significant association.

Multiple regression analysis was performed on the subjective visual perceptions and log CS to investigate the relationship between subjective brightness, comfort, pupil size, and lens transmittance. Statistically significant multiple regression models were obtained for subjective brightness and comfort (brightness: $F_{5,174} = 33.5$, adjusted $R^2 = 0.49$, $p < 0.0001$; comfort: $F_{5,174} = 29.2$, adjusted $R^2 = 0.46$, $p < 0.0001$). However, unlike the results for log CS, pupil size and T_AUC were not significantly associated with subjective visual perception, whereas age, lx, and CCT were (Table 3).

4. Discussion

In this study we show that log CS measured using the Mars Letter Contrast Sensitivity Test is significantly lower in older adults compared to children and middle-aged adults. These findings support a previous study, which investigated CS in participants from 22–77 years of age, showing that log CS decreases with aging, (Haymes et al. 2006) in addition to other findings.(Owsley et al. 1983) Although both senile miosis and attenuated lens light transmittance were expected to reduce CS in older adults, multiple regression analysis indicated that reduced lens transmittance was the main contributor to reduced CS. While it is well established that cataracts are associated with reduced CS,(Adamsons et al. 1992; Elliott and Situ 1998; Chua et al. 2004; Stifter et al. 2006; Shandiz et al. 2011) our findings highlight that alterations in lens transmittance throughout healthy aging can affect CS. In contrast, there were no significant differences in log CS between children and middle-aged adults, despite significant differences in pupil size and lens transmittance. CS is established throughout a child's eye development and appears to reach full maturity between the ages of 8 and 19.(Leat et al. 2009) A comparison of CS between children and adults aged approximately 8 and 25 years old shown that children have lower CS.(Liu et al. 2014)

Children in this study were approximately 10 years old and were considered to be at the same developmental stage as in the previous study,(Liu et al. 2014) while the middle-aged adults in this study were approximately 40 years old and were considered to have lower CS than 25 years old in the previous study.(Liu et al. 2014) This may have led to similar CS findings between children and middle-aged adult groups in our study.

In addition, here we also report that CS increases significantly with increasing illuminance. However, the change in the mean log CS was small, even amongst older adults who displayed the greatest change (i.e., the increase from 100–750 lx led to a change of only ~0.07 log CS). Log CS values in the Mars Letter Contrast Sensitivity were classified into the following five levels: profound (<0.48), severe (0.52–1.00), moderate (1.04–1.48), normal for those aged >60 years (1.52–1.76), normal for middle/young adults (1.72–1.92).(MarsLetterCSTestUserManual 2013) The range of change in mean log CS with illuminance increase in this study was 1.75–1.8 for children, 1.78–1.81 for middle-aged adults, and 1.63–1.7 for older adults, indicating that age-appropriate normal contrast sensitivity can be achieved according to the above classification. Therefore, the light environments in the illuminance range experienced on a daily basis (100–750 lx) would not significantly increase or, conversely, impair contrast sensitivity, regardless of age.

High CCT lighting, enriched with blue-light components, was suspected to contribute to improving CS. This is because melanopsin, which is sensitive to blue-light region, has recently been shown to contribute to CS.(Chien et al. 2023) However, no significant effect of CCT on CS was found in any age group. In other words, the CS might be independent of the CCT of LED lighting, at least under the specific conditions of this study. These conditions included the use of the Mars Letter Contrast Sensitivity Test, which is limited to low spatial frequencies and the lighting settings used in this study. This indicates that it may not be necessary to use high-CCT lighting during nighttime study hours. For any illuminance level, changing the CCT from 6000–3000 K reduced melanopic-EDI by approximately 53–56% according to Table 1 A and B. It should be noted that the relationship between melanopic-EDI and non-visual function is not linear,(Brown 2020; Giménez et al. 2022) but lowering the CCT and illuminance may be effective in reducing the negative effects on circadian rhythms while ensuring a certain level of visibility. However, the present study did not replicate the results of previous studies that reported improved CS under high melanopsin-stimulating light. This discrepancy underscores the need for the careful interpretation of our findings. To further evaluate the age-dependent effects of lighting conditions on CS, comprehensive approaches using a variety of measurement methods and spatial frequencies should be adopted.

The ratings in the questionnaire were significantly higher with increased illuminance in both subjective visual perception items, “brightness” and “comfort,” but as with CS, no significant main effect of CCT was shown in both items. Several studies have shown that higher melanopsin excitation light enhances brightness perception. (Brown et al. 2012; Zele et al. 2018; Yamakawa et al. 2019) However, the results of this study did not confirm a significant effect of CCT on brightness perception. Whereas previous studies evaluated brightness perception using strictly controlled psychophysical methods, the present study relied on a subjective scaling questionnaire. Subjective scaling has an upper limit, and ceiling effects were observed at 750 lx (Fig. 3 A and B). Therefore, the use of a subjective questionnaire with a limited measurement range and associated ceiling effects may have obscured the detection of CCT effects on brightness perception. However, the results of multiple regression analysis revealed a significant effect of CCT on brightness perception (Table 3). This finding suggests that controlling for confounding factors such as age as a continuous variable, pupil size and lens transmittance enabled the detection of CCT effects. In contrast, ANOVA did not show a significant effect of CCT, possibly because it did not account for these confounding factors. The inability to control for individual differences in the ANOVA may have reduced its statistical power, masking the effect of CCT on brightness perception.

Focusing on age differences of the subjective visual perception, children were more likely to report being bright and comfortable than middle-aged or older adults. Notably, for comfort, middle-aged and older adults increased their ratings with increasing illuminance, whereas no significant differences in ratings were observed among children across the illuminance conditions. This may indicate that children are subjectively comfortable in lighting environments of 100 or 300 lx when they spend time studying. The fact that there was no significant difference in comfort between low and high CCT supports previous research;(Yang and Jeon 2020) however, the present study showed that the effect of CCT varied with age, and there was a tendency to answer 3000 K more comfort questions than 6000 K in children. A previous study by Yang et al. included university students but did not examine age differences. The results of this study suggest the importance of considering a participant's age in the subjective evaluation of lighting environments.

This study has several limitations. First, the sample size is relatively small. Although the total number of participants was 30, there were 10 participants in each age group. Second, we did not measure any aging-related factors other than pupil size or lens transmittance. Cone sensitivity decreases with age,(Werner and Steele 1988) and age-related changes in cone absorptance decrease CS.(Braham Chaouche et al. 2020) Therefore, we cannot exclude the possibility that factors other than lens transmittance were involved in age-related changes in CS herein. Third, the spatial frequencies tested for CS were limited to low spatial frequencies, ranging from 0.4–1.4 cycles/degree. Previous studies have shown that the effects of age on CS vary with spatial frequency and become more pronounced at higher frequencies, particularly at frequencies greater than 1.0 cycles/degree.(Owsley et al. 1983) While some letters in this study corresponded to spatial frequencies above 1.0 cycles/degree, a more comprehensive evaluation of age-dependent effects on CS would require future studies using charts specifically designed to measure high spatial frequencies, e.g., (Adhikari et al. 2022). Fourth, subjective visual perceptions (brightness and comfort) was evaluated using a scaling questionnaire. As mentioned previously, evaluation using a method with a limited scaling range may obscure the detection of potential light effects. However, as the effects of illuminance and age were detectable, it is unlikely that the use of a scaled questionnaire would significantly compromise the reliability of the results. Finally, we did not ask about the lighting environment to which the participants were exposed daily or their lighting preferences. We attempted to unify the basis of the subjective visual perception evaluations by limiting the context in which we evaluated the situation. However, comfort may also depend on personal preferences and familiarity with the lighting environment.

Conclusion

This study investigated the effects of LED lighting environments with different illuminances and CCTs on age-related differences in CS and subjective visual perception. We also focused on age-related changes in pupil size and crystalline lens transmittance and examined their contribution to CS and subjective visual perception. It was found that CS decreased in older adults, increased with increasing illumination regardless of age, and that CCT had no effect. It was also found that age-related changes in CS are not due to pupil size or simply age but are strongly influenced by a decrease in lens transmittance, even in healthy aging. The subjective sense of brightness and comfort increased overall with increasing illuminance; however, comfort in the children's group was not affected by illuminance and was higher in the low-CCT condition. When considering nighttime lighting for children, the use of low-illuminance and low-color-temperature lighting may reduce non-visual effects without significantly reducing CS or subjective comfort. This study provides useful insights for the design of appropriate lighting environments for individuals of various ages.

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Disclosure statement

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Supplemental materials

S1 Fig. Spectral irradiance for each LED condition (A) at the working surface and (B) at the eye level.

S2 Fig. Scatter plots for relationships between log CS and pupil size in each lighting condition.

S3 Fig. Scatter plots for relationships between log CS and lens transmittance (T_AUC) in each lighting condition.

S4 Fig. Scatter plots for relationships between log CS and age in each lighting condition.

S1 Table. Results of ANOVA on contrast sensitivity (log CS) (A) and post-hoc analysis in main effects (B).

S2 Table. Results of ANOVA on subjective brightness (A), post-hoc analysis in main effects (B) and in interaction of CCT * lx (C).

S3 Table. Results of ANOVA on subjective comfort (A), post-hoc analysis in main effects (B), in interaction of Age * CCT (C) and in interaction of Age * lx (D).

S4 Table. Results of ANOVA on pupil size (A), post-hoc analysis in main effects (B) and in interaction of Age * lx (C).

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Figures

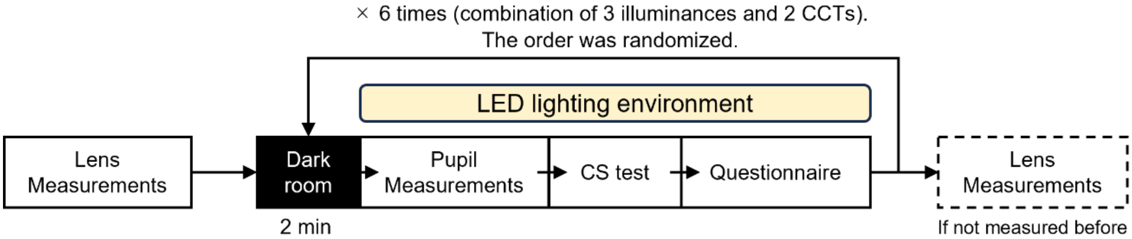

Figure 1. Diagram of the experimental protocol. CCT, correlated color temperature; CS, contrast sensitivity.

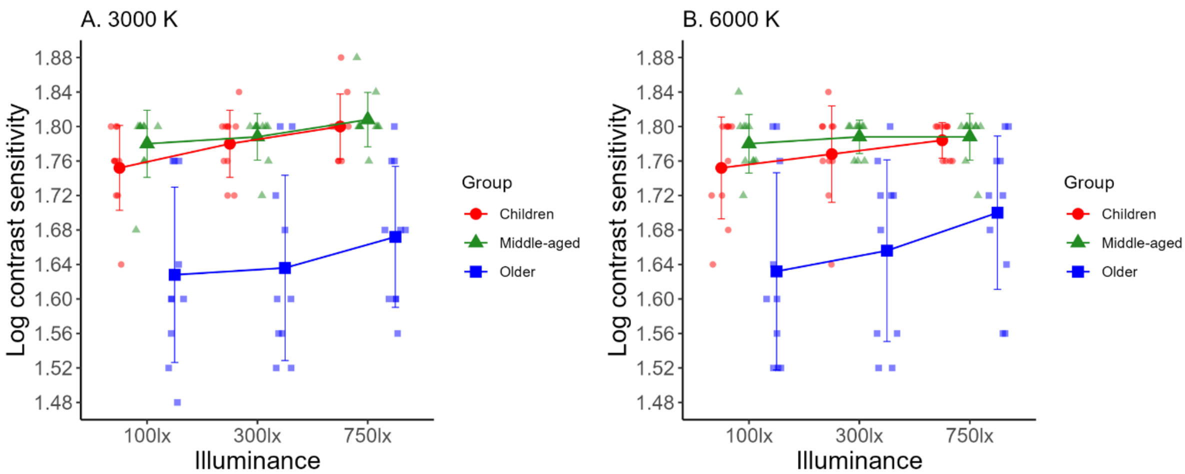

Figure 2. Log contrast sensitivity measured under different illuminance conditions in children, middle-aged and older adults at (A) 3000 K and (B) 6000 K. Results for the children group are shown as red circles and red lines, those for the middle-aged adults group are shown as green triangles and green lines, and those for the older adults group are shown as blue squares and blue lines. Results are presented as mean ± standard deviation.

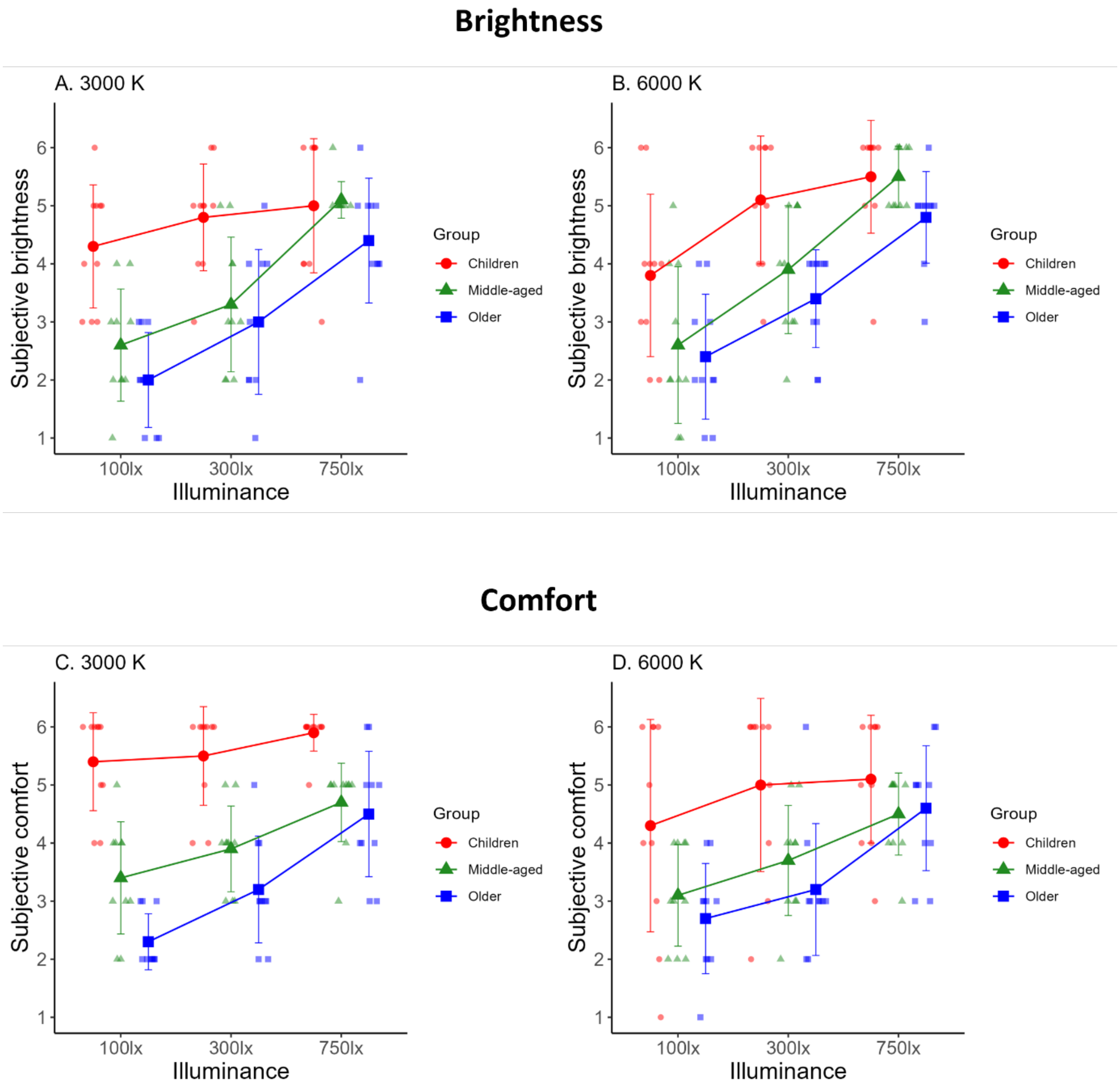

Figure 3. Subjective visual perception assessed under different illuminance conditions in children, middle-aged and older adults. (A) and (B) show subjective brightness assessed at 3000 K and 6000 K, respectively. (C) and (D) show subjective comfort assessed at 3000 K and 6000 K, respectively. Results for the children group are shown as red circles and red lines, those for the middle-aged adults group are shown as green triangles and green lines, and those for the older adults group are shown as blue squares and blue lines. The x-axis is shown in the log scale. Results are presented as mean ± standard deviation.

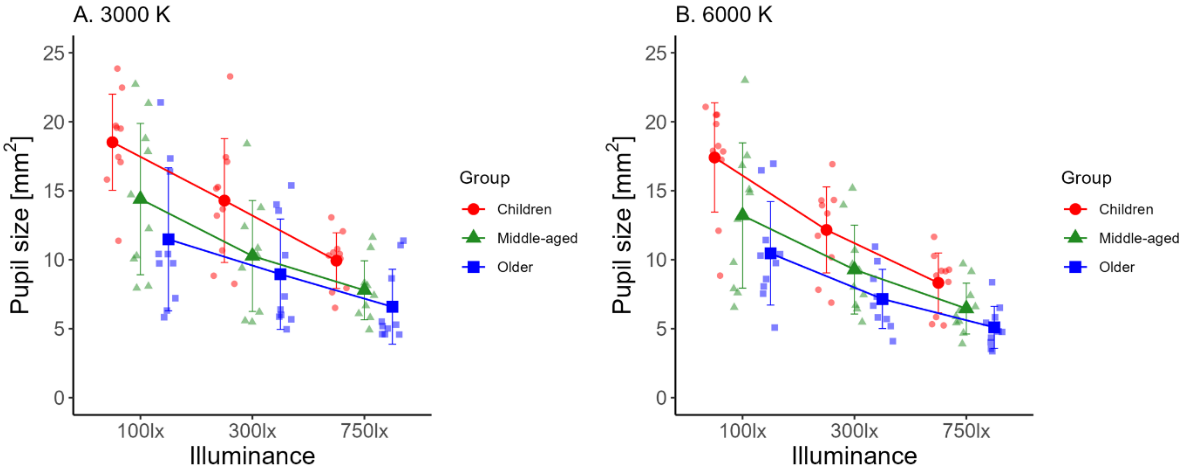

Figure 4. Pupil size measured under different illuminance conditions in children, middle-aged and older adults at (A) 3000 K and (B) 6000 K. Results for the children group are shown as red circles and red lines, those for the middle-aged adults group are shown as green triangles and green lines, and those for the older adults group are shown as blue squares and blue lines. The x-axis is shown in the log scale. Results are presented as mean ± standard deviation.

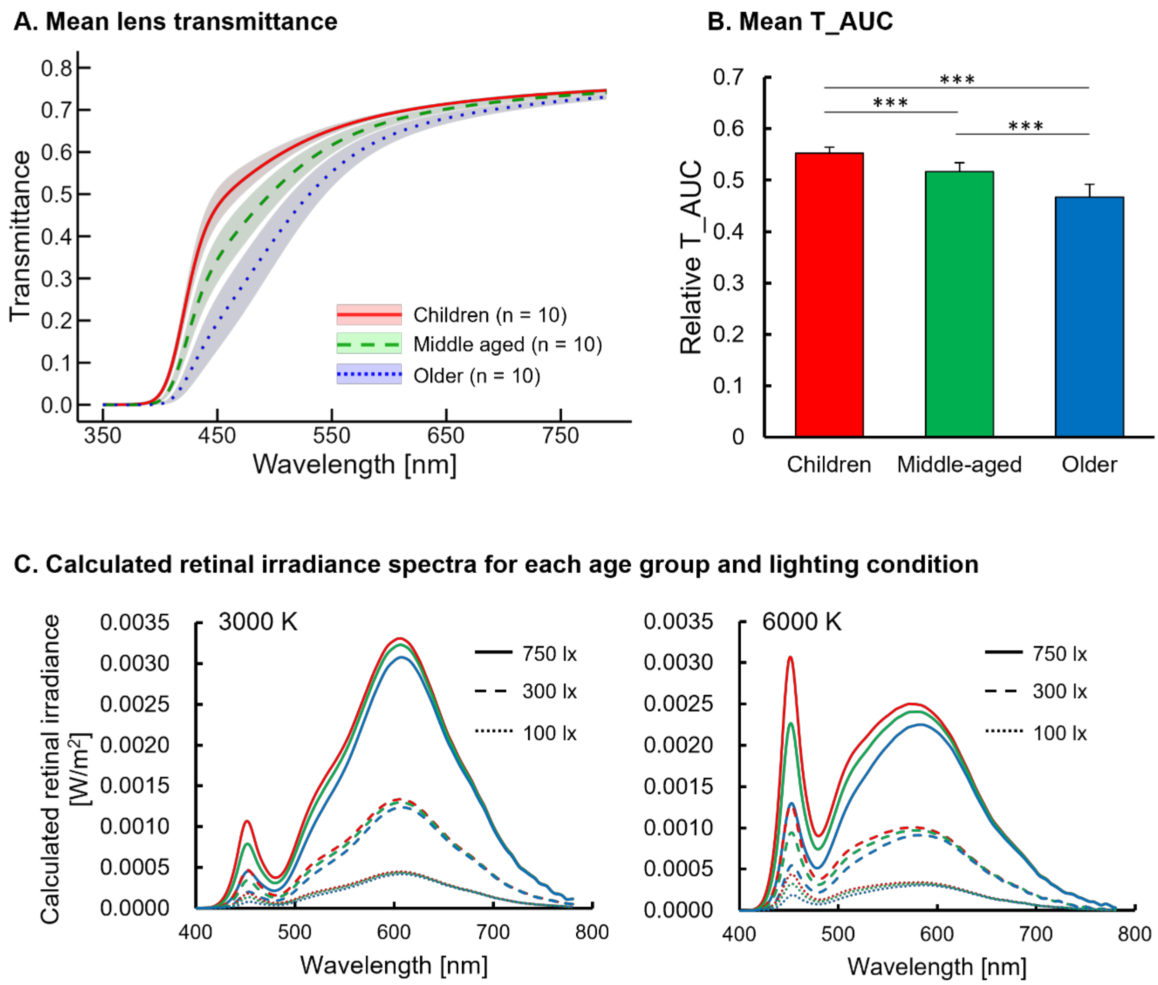

Figure 5. (A) Mean lens transmittance spectra of the right crystalline lens measured by the Purkinje image-based system.(Eto et al. 2020) The mean transmittance spectrum in the children group is shown by red lines, that in the middle-aged adults group is shown by green dashed lines, and that in the older adults group is shown by blue dotted lines. Each pale color area around the mean lens transmittance line depicts the standard deviation (SD) of lens transmittance in each age group. (B) The mean area under the curve of the crystalline lens transmittance spectrum defined as T_AUC. Error bars indicate SD. (C) The spectral irradiance of the retina for each age and lighting condition calculated by multiplexing the mean transmittance spectrum and spectral irradiance at the eye level (Fig S1B). Solid, dashed and dotted lines indicate 750, 300 and 100 lx illuminance conditions, respectively. Red, green and blue lines indicate children, middle-aged adults, and older adults, respectively. ***: *p*

<0.001.

Tables

Table 1. (A) Melanopic-EDI [lx] in the vertical plane in front of the eye for each lighting condition. (B) Crystalline lens transmittance-corrected melanopic EDI [lx] for each age group and each lighting condition. Values in parentheses indicate actual values of illuminance and correlated color temperature measured in the vertical plane in front of the eye. CCT: correlated color temperature.

A

		CCTs	
		3000 (2983) K	**6000 (5629) K**
	100 (33) lx	15.1	26.7
Illuminances	**300 (97) lx**	42.0	78.9
	750 (240) lx	102.0	193.9

B

		Age group	CCTs	
			3000 (2983) K	**6000 (5629) K**
	100 (33) lx	Children	15.7	28.0
		Middle-aged	13.4	23.3
		Older	10.2	16.9
Illuminance	**300 (97) lx**	Children	43.8	82.9
		Middle-aged	37.4	68.4
		Older	28.5	50.0
	750 (240) lx	Children	106.3	203.7
		Middle-aged	90.8	169.1
		Older	69.4	122.8

Table 2. Relationships between log contrast sensitivity and pupil size, lens transmittance, and age as evaluated by Pearson's correlation analysis.

Variables	**Lighting condition**		**Statistics**			
	CCT	**lx**	**Correlation coefficient (*r*)**	***t*-value**	***p*-value**	
Pupil size	3000	100	0.349	1.97	0.0589	
		300	0.356	2.02	0.0533	
		750	0.323	1.80	0.0821	
	6000	100	0.241	1.31	0.200	
		300	0.260	1.43	0.165	
		750	0.339	1.91	0.0668	
	3000	100	0.672	4.80	<0.0001	***

T_AUC		300	0.733	5.71	<0.0001	***
		750	0.697	5.14	<0.0001	***
	6000	100	0.536	3.36	0.00229	**
		300	0.649	4.52	<0.001	***
		750	0.607	4.04	<0.001	***
Age	3000	100	-0.561	-3.59	0.00123	**
		300	-0.625	-4.23	<0.001	***
		750	-0.629	-4.29	<0.001	***
	6000	100	-0.505	-3.10	0.00438	**
		300	-0.513	-3.16	0.00377	**
		750	-0.535	-3.35	0.00232	**

*: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$

CCT, correlated color temperature; T_AUC, area under the curve of lens transmittance.

Table 3. Results of multiple regression analysis for evaluating relationships between ophthalmic characteristics, that is, pupil size and lens transmittance, and visual measurements, that is, log contrast sensitivity and subjective visual perceptions.

Objective variable	Explanatory variable	Coefficient (β)	*p*-value	
Log CS	(Intercept)	0.792	<0.0001	***
	Pupil size	$1.1*10^{-3}$	0.424	
	T_AUC	1.72	<0.0001	***
	Age	$6.04*10^{-4}$	0.238	
	lx	$6.82*10^{-5}$	0.00368	**
	CCT	$9.56*10^{-3}$	0.844	
Subjective brightness	(Intercept)	5.63	0.0434	*
	Pupil size	0.0310	0.162	
	T_AUC	-4.64	0.328	
	Age	-0.0272	<0.001	***
	lx	$3.42*10^{-3}$	<0.0001	***
	CCT	0.321	0.0489	*
Subjective comfort	(Intercept)	7.85	0.00394	**
	Pupil size	0.0312	0.147	
	T_AUC	-6.49	0.160	
	Age	-0.0369	<0.0001	***
	lx	$2.34*10^{-3}$	<0.0001	***
	CCT	-0.245	0.121	

*: p <0.05, **: p <0.01, ***: p <0.001

CCT, correlated color temperature; CS, contrast sensitivity; T_AUC, area under the curve of lens transmittance.

Supplementary Figures

Figure S1

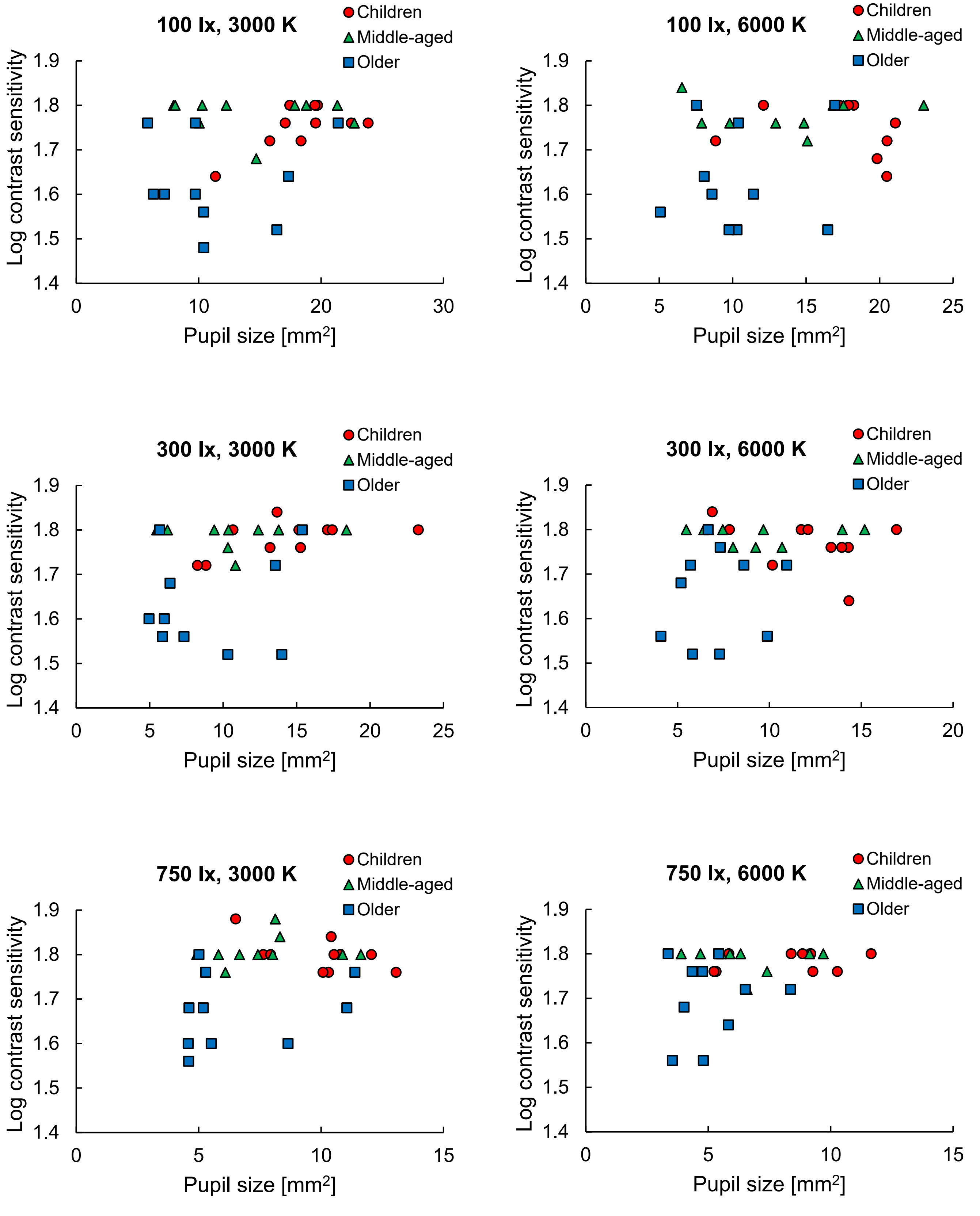

Fig S1. Scatter plots for relationships between log CS and pupil size in each lighting condition.

Figure S2

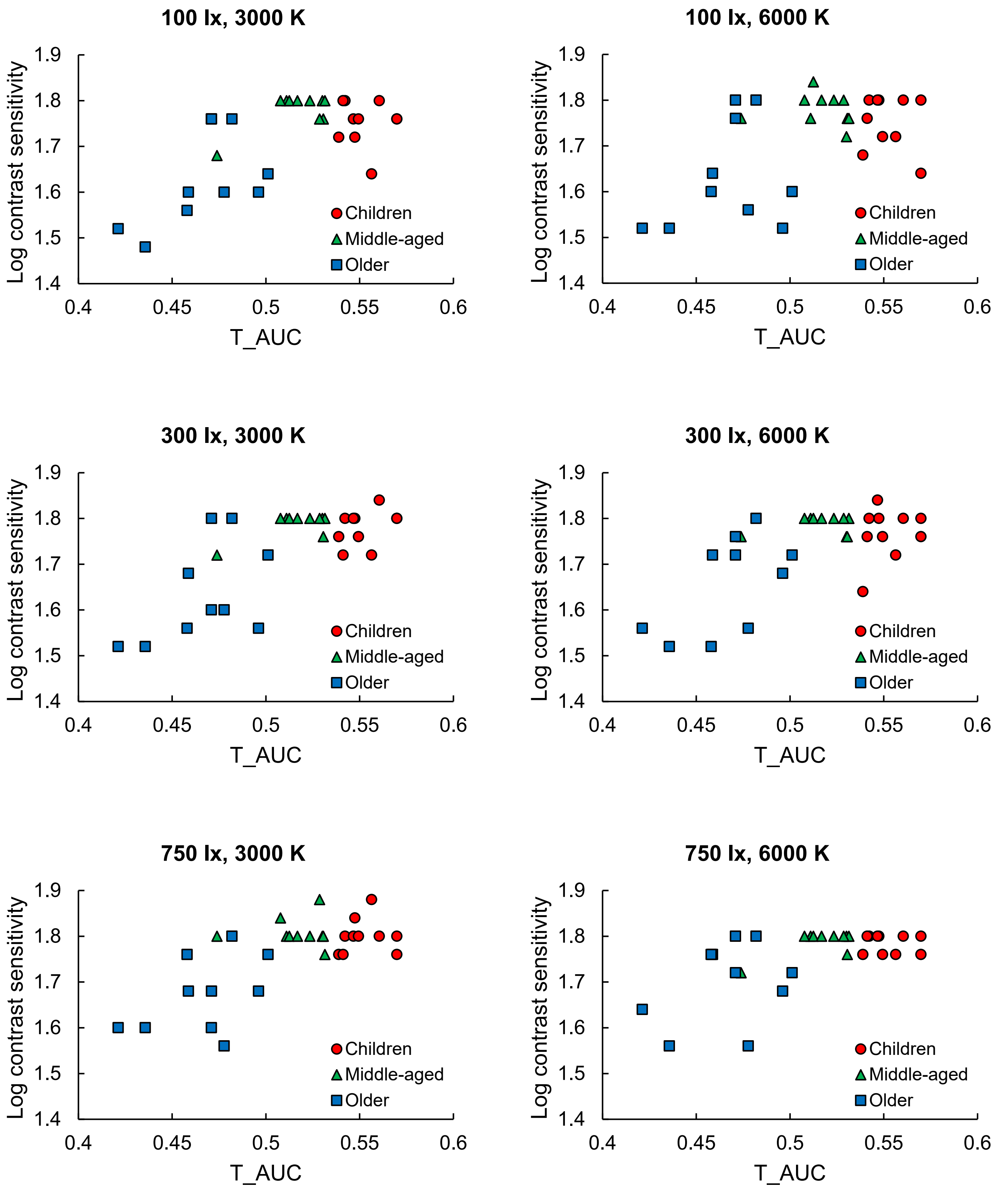

Fig S2. Scatter plots for relationships between log CS and lens transmittance (T_AUC) in each lighting condition.

Figure S3

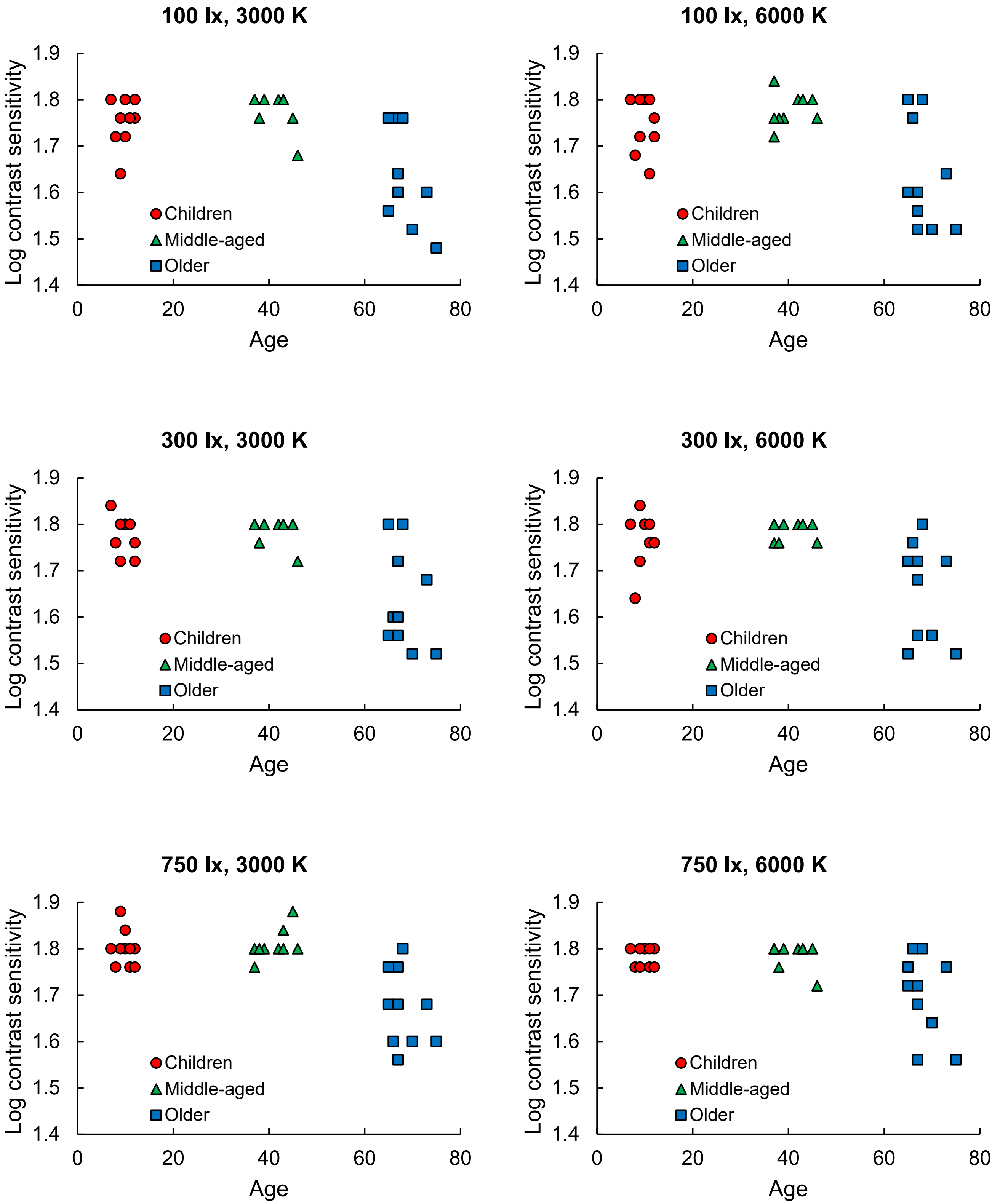

Fig S3. Scatter plots for relationships between log CS and age in each lighting condition.

S1 Table. Results of ANOVA on contrast sensitivity (log CS) (A) and post-hoc analysis in main effects (B).

(A)

Factor	F-value	Effect size(η_p^2)	p-value	
Age group (Age)	$F(2, 27) = 11.6$	0.581	< 0.0001	***
Correlated color temperature (CCT)	$F(1, 27) = 0.0061$	0.0002	0.938	
Illuminance (lx)	$F(1.75, 47.3) = 9.12$	0.253	0.0007	***
Age * CCT	$F(2, 27) = 2.23$	0.142	0.127	
Age * lx	$F(3.5, 45.8) = 0.908$	0.063	0.457	
CCT * lx	$F(1.87, 50.5) = 0.904$	0.0033	0.904	
Age * CCT * lx	$F(3.74, 50.5) = 0.634$	0.0448	0.631	

(B)

Factor	Comparison pair (Mean ± S.D.)	t-value	p-value	
Age	Children vs Middle-aged (1.77±0.05 vs 1.79±0.03)	$t_{27} = 0.666$	0.511	
	Middle-aged vs Older (1.79±0.03 vs 1.65±0.10)	$t_{27} = 5.60$	< 0.0001	***
	Children vs Older (1.77±0.05 vs 1.65±0.10)	$t_{27} = 4.94$	< 0.0001	***
lx	100 lx vs 300 lx (1.72±0.10 vs 1.74±0.10)	$t_{27} = 2.24$	0.0335	*
	300 lx vs 750 lx (1.74±0.10 vs 1.76±0.07)	$t_{27} = 2.48$	0.0197	*
	100 lx vs 750 lx (1.72±0.10 vs 1.76±0.07)	$t_{27} = 3.63$	0.0035	**

*: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$

S2 Table. Results of ANOVA on subjective brightness (A), post-hoc analysis in main effects (B) and in interaction of CCT * lx (C).

(A)

Factor	*F*-value	Effect size(η_p^2)	*p*-value	
Age group (Age)	$F(2, 27) = 11.6$	0.463	0.0002	***
Correlated color temperature (CCT)	$F(1, 27) = 0.371$	0.0136	0.547	
Illuminance (lx)	$F(1.69, 45.8) = 45.6$	0.628	< 0.0001	***
Age * CCT	$F(2, 27) = 1.25$	0.0849	0.302	
Age * lx	$F(3.39, 45.8) = 1.92$	0.125	0.132	
CCT * lx	$F(1.97, 53.1) = 3.79$	0.123	0.0295	*
Age * CCT * lx	$F(3.93, 53.1) = 1.94$	0.126	0.119	

(B)

Factor	Comparison pair (Mean ± S.D.)	*t*-value	*p*-value	
Age	Children vs Middle-aged (4.73±1.30 vs 3.48±1.24)	$t_{27} = 3.64$	0.0011	**
	Middle-aged vs Older (3.48±1.24 vs 3.17±1.20)	$t_{27} = 0.92$	0.365	
	Children vs Older (4.73±1.30 vs 3.17±1.20)	$t_{27} = 4.56$	0.0003	***
lx	100 lx vs 300 lx (3.10±1.42 vs 3.68±1.26)	$t_{27} = 5.02$	< 0.0001	***
	300 lx vs 750 lx (3.68±1.26 vs 4.60±1.14)	$t_{27} = 5.57$	< 0.0001	***
	100 lx vs 750 lx (3.10±1.42 vs 4.60±1.14)	$t_{27} = 8.06$	< 0.0001	***

(C)

Factor	Comparison pair (Mean ± S.D.)	*F*-value	Effect size(η_p^2)	*t*-value	*p*-value	
CCT * lx	-	$F(1.97, 53.1) = 3.79$	0.123	-	0.0295	*
CCT at 100 lx	3000 K vs 6000 K (3.33±1.52 vs 2.87±1.31)	$F(1, 27) = 3.74$	0.123	-	0.0638	
CCT at 300 lx	3000 K vs 6000 K (3.67±1.24 vs 3.70±1.29)	$F(1, 27) = 0.0299$	0.0011	-	0.864	
CCT at 750 lx	3000 K vs 6000 K (4.53±1.20 vs 4.67±1.09)	$F(1, 27) = 0.447$	0.0163	-	0.509	
lx at 3000 K	-	$F(1.63, 44.1) = 27.0$	0.500	-	< 0.0001	***
	100 lx vs 300 lx (3.33±1.52 vs 3.67±1.24)	-	-	$t_{27} = 2.76$	0.0102	*
	300 lx vs 750 lx (3.67±1.24 vs 4.53±1.20)	-	-	$t_{27} = 5.01$	< 0.0001	***

	100 lx vs 750 lx (3.33±1.51 vs 4.53±1.20)	-	-	$t_{27} = 5.95$	< 0.0001	***
lx at 6000 K	-	$F(1.88, 50.9) = 33.1$	0.551	-	< 0.0001	***
	100 lx vs 300 lx (2.87±1.31 vs 3.70±1.29)	-	-	$t_{27} = 4.66$	0.0001	***
	300 lx vs 750 lx (3.70±1.29 vs 4.67±1.09)	-	-	$t_{27} = 4.19$	0.0003	***
	100 lx vs 750 lx (2.87±1.31 vs 4.67±1.09)	-	-	$t_{27} = 7.24$	< 0.0001	***

*: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$

S3 Table. Results of ANOVA on subjective comfort (A), post-hoc analysis in main effects (B), in interaction of Age * CCT (C) and in interaction of Age * lx (D).

(A)

Factor	*F*-value	Effect size(η_p^2)	*p*-value	
Age group (Age)	$F(2, 27) = 16.9$	0.556	< 0.0001	***
Correlated color temperature (CCT)	$F(1, 27) = 3.69$	0.120	0.0655	
Illuminance (lx)	$F(1.97, 53.2) = 46.4$	0.632	< 0.0001	***
Age * CCT	$F(2, 27) = 3.47$	0.205	0.0454	*
Age * lx	$F(3.94, 53.2) = 4.56$	0.253	0.0032	**
CCT * lx	$F(2, 54) = 0.103$	0.0038	0.902	
Age * CCT * lx	$F(4, 54) = 0.857$	0.0597	0.496	

(B)

Factor	Comparison pair (Mean ± S.D.)	*t*-value	*p*-value	
Age	Children vs Middle-aged	$t_{27} = 4.14$	0.0003	***
	(5.20±1.23 vs 3.88±0.98)			
	Middle-aged vs Older	$t_{27} = 1.47$	0.154	
	(3.88±0.98 vs 3.42±1.27)			
	Children vs Older	$t_{27} = 5.60$	0.0003	***
	(5.20±1.23 vs 3.42±1.27)			
lx	100 lx vs 300 lx	$t_{27} = 4.15$	0.0003	***
	(3.53±1.47 vs 4.08±1.33)			
	300 lx vs 750 lx	$t_{27} = 6.26$	< 0.0001	***
	(4.08±1.33 vs 4.88±0.98)			
	100 lx vs 750 lx	$t_{27} = 8.43$	< 0.0001	***
	(3.53±1.47 vs 4.88±0.98)			

(C)

Factor	Comparison pair (Mean ± S.D.)	*F*-value	Effect size(η_p^2)	*t*-value	*p*-value	
Age * CCT	-	$F(2, 27) = 3.47$	0.205	-	0.0454	*
Age at 3000K	-	$F(2, 27) = 36.0$	0.727	-	< 0.0001	***
	Children vs Middle-aged	-	-	$t_{27} = 5.83$	< 0.0001	***
	(5.60±0.72 vs 4.00±0.95)					
	Middle-aged vs Older	-	-	$t_{27} = 2.43$	0.0221	*
	(4.00±0.95 vs 3.33±1.24)					
	Children vs Older	-	-	$t_{27} = 8.26$	< 0.0001	***
	(5.60±0.72 vs 3.33±1.24)					
Age at 6000 K	-	$F(2, 27) = 4.83$	0.264	-	0.0161	*
	Children vs Middle-aged	-	-	$t_{27} = 2.34$	0.0269	*
	(4.80±1.49 vs 3.77±1.01)					
	Middle-aged vs Older	-	-	$t_{27} = 0.604$	0.551	

	(3.77±1.01 vs 3.50±1.31)					
	Children vs Older (4.80±1.49 vs 3.50±1.31)	-	-	$t_{27} = 2.94$	0.0198	*
CCT at Children	3000 K vs 6000 K (5.60±0.72 vs 4.80±1.49)	$F(1, 9) = 4.61$	0.339	-	0.0603	
CCT at Middle-aged	3000 K vs 6000 K (4.00±0.95 vs 3.77±1.01)	$F(1, 9) = 2.19$	0.200	-	0.173	
CCT at Older	3000 K vs 6000 K (3.33±1.24 vs 3.50±1.31)	$F(1, 9) = 0.69$	0.0714	-	0.427	

(D)

Factor	Comparison pair (Mean ± S.D.)	*F*-value	Effect size(η_p^2)	*t*-value	*p*-value	
Age * lx	-	$F(2, 27) = 3.47$	0.205	-	0.0454	*
Age at 100 lx	-	$F(2, 27) = 18.0$	0.571	-	< 0.0001	***
	Children vs Middle-aged (4.85±1.50 vs 3.25±0.91)	-	-	$t_{27} = 4.00$	0.0004	***
	Middle-aged vs Older (3.25±0.91 vs 2.50±0.76)	-	-	$t_{27} = 1.87$	0.0720	
	Children vs Older (4.85±1.50 vs 2.50±0.76)	-	-	$t_{27} = 5.87$	< 0.0001	***
Age at 300 lx	-	$F(2, 27) = 15.1$	0.528		< 0.0001	***
	Children vs Middle-aged (5.25±1.21 vs 3.80±0.83)	-	-	$t_{27} = 3.78$	0.0008	***
	Middle-aged vs Older (3.80±0.83 vs 3.20±1.01)	-	-	$t_{27} = 1.57$	0.129	
	Children vs Older (5.25±1.21 vs 3.20±1.01)	-	-	$t_{27} = 5.35$	< 0.0001	***
Age at 750 lx	-	$F(2, 27) = 4.94$	0.268	-	0.0149	*
	Children vs Middle-aged (5.5±0.89 vs 4.60±0.68)	-	-	$t_{27} = 2.65$	0.0285	
	Middle-aged vs Older (4.60±0.68 vs 4.55±1.05)	-	-	$t_{27} = 0.15$	0.884	
	Children vs Older (5.5±0.89 vs 4.55±1.05)	-	-	$t_{27} = 2.79$	0.0285	*
lx at Children	-	$F(1.48, 13.3) = 4.82$	0.349	-	0.0348	*
	100 lx vs 300 lx (4.85±1.50 vs 5.25±1.21)	-	-	$t_{27} = 1.92$	0.117	
	300 lx vs 750 lx (5.25±1.21 vs 5.50±0.89)	-	-	$t_{27} = 1.86$	0.117	
	100 lx vs 750 lx (4.85±1.50 vs 5.50±0.89)	-	-	$t_{27} = 2.41$	0.117	

lx at Middle-aged	-	$F(1.5, 13.5) = 21.0$	0.700	-	0.0002	***
	100 lx vs 300 lx (3.25±0.91 vs 3.80±0.83)	-	-	$t_{27} = 2.91$	0.0174	*
	300 lx vs 750 lx (3.80±0.83 vs 4.60±0.68)	-	-	$t_{27} = 2.95$	0.0161	*
	100 lx vs 750 lx (3.25±0.91 vs 4.60±0.68)	-	-	$t_{27} = 9.00$	< 0.0001	***
lx at Older	-	$F(1.84, 16.5) = 24.1$	0.728	-	< 0.0001	***
	100 lx vs 300 lx (2.50±0.76 vs 3.20±1.01)	-	-	$t_{27} = 2.49$	0.0343	*
	300 lx vs 750 lx (3.20±1.01 vs 4.55±1.05)	-	-	$t_{27} = 5.71$	0.0009	***
	100 lx vs 750 lx (2.50±0.76 vs 4.55±1.05)	-	-	$t_{27} = 5.56$	0.0009	***

*: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$

S4 Table. Results of ANOVA on pupil size (A), post-hoc analysis in main effects (B) and in interaction of Age * lx (C).

(A)

Factor	*F*-value	Effect size(η_p^2)	*p*-value	
Age group (Age)	$F(2, 27) = 7.85$	0.368	0.0021	**
Correlated color temperature (CCT)	$F(1, 2) = 13.8$	0.34	0.0009	***
Illuminance (lx)	$F(1.86, 50.2) = 117.8$	0.81	< 0.0001	***
Age * CCT	$F(2, 27) = 0.12$	0.009	0.89	
Age * lx	$F(3.72, 50.22) = 2.91$	0.18	0.0338	*
CCT * lx	$F(1.73, 46.64) = 0.35$	0.0128	0.674	
Age * CCT * lx	$F(3.45, 46.64) = 0.173$	0.0126	0.890	

(B)

Factor	Comparison pair (Mean ± S.D.)	*t*-value	*p*-value	
Age	Children vs Middle-aged (13.4±4.91 vs 10.2±4.70)	$t_{27} = 3.92$	0.0215	*
	Middle-aged vs Older (10.2±4.70 vs 8.29±3.99)	$t_{27} = 1.48$	0.150	
	Children vs Older (13.4±4.91 vs 8.29±3.99)	$t_{27} = 3.92$	0.0016	**
lx	100 lx vs 300 lx (14.2±5.29 vs 10.4±4.14)	$t_{27} = 8.91$	< 0.0001	***
	300 lx vs 750 lx (10.4±4.14 vs 7.36±2.54)	$t_{27} = 7.92$	< 0.0001	***
	100 lx vs 750 lx (14.2±5.29 vs 7.36±2.54)	$t_{27} = 13.2$	< 0.0001	***

(C)

Factor	Comparison pair (Mean ± S.D.)	*F*-value	Effect size(η_p^2)	*t*-value	*p*-value	
Age * lx	-	$F(3.72, 50.22) = 2.91$	0.18	-	0.0338	*
Age at 100 lx	-	$F(2, 27) = 7.05$	0.343	-	0.0034	**
	Children vs Middle-aged (18.0±3.67 vs 13.8±5.27)	-	-	$t_{27} = 2.22$	0.0350	*
	Middle-aged vs Older (13.8±5.27 vs 11.0±4.44)	-	-	$t_{27} = 0.151$	0.142	
	Children vs Older (18.0±3.67 vs 11.0±4.44)	-	-	$t_{27} = 3.73$	0.0027	**
Age at 300 lx	-	$F(2, 27) = 6.52$	0.326	-	0.0049	**
	Children vs Middle-aged (13.2±3.92 vs 9.78±3.58)	-	-	$t_{27} = 2.36$	0.0255	*
	Middle-aged vs Older (9.78±3.58 vs 8.05±3.26)	-	-	$t_{27} = 1.18$	0.247	

	Children vs Older (13.2±3.92 vs 8.05±3.26)	-	-	$t_{27} = 3.55$	0.0043	**
Age at 750 lx	-	$F(2, 27) = 7.36$	0.353	-	0.0028	**
	Children vs Middle-aged (9.13±2.20 vs 7.12±2.06)	-	-	$t_{27} = 2.32$	0.0279	*
	Middle-aged vs Older (7.12±2.06 vs 5.84±2.27)	-	-	$t_{27} = 1.48$	0.150	
	Children vs Older (9.13±2.20 vs 5.84±2.27)	-	-	$t_{27} = 3.81$	0.0022	**
lx at Children	-	$F(2, 18) = 54.0$	0.857	-	< 0.0001	***
	100 lx vs 300 lx (18.0±3.67 vs 13.2±3.92)	-	-	$t_9 = 4.99$	0.0007	***
	300 lx vs 750 lx (13.2±3.92 vs 9.13±2.20)	-	-	$t_9 = 5.02$	0.0007	***
	100 lx vs 750 lx (18.0±3.67 vs 9.13±2.20)	-	-	$t_9 = 11.4$	< 0.0001	***
lx at Middle-aged	-	$F(1.53, 13.8) = 31.1$	0.776	-	< 0.0001	***
	100 lx vs 300 lx (13.8±5.27 vs 9.78±3.58)	-	-	$t_9 = 5.38$	0.0006	**
	300 lx vs 750 lx (9.78±3.58 vs 7.12±2.06)	-	-	$t_9 = 4.14$	0.0025	**
	100 lx vs 750 lx (13.8±5.27 vs 7.12±2.06)	-	-	$t_9 = 6.07$	0.0006	***
lx at Older	-	$F(1.39, 12.5) = 36.0$	0.800	-	< 0.0001	***
	100 lx vs 300 lx (11.0±4.44 vs 8.05±3.26)	-	-	$t_9 = 5.75$	0.0004	***
	300 lx vs 750 lx (8.05±3.26 vs 5.84±2.27)	-	-	$t_9 = 4.92$	0.0008	***
	100 lx vs 750 lx (11.0±4.44 vs 5.84±2.27)	-	-	$t_9 = 6.40$	0.0004	***

*: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$