Spatio-chromatic contrast sensitivity across the lifespan: interactions between age and light level in high dynamic range

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Abstract

We investigated spatio-chromatic contrast sensitivity in both younger and older color-normal observers. We tested how the adapting light level affected the contrast sensitivity and whether there was a differential age-related change in sensitivity. Contrast sensitivity was measured along three directions in colour space (achromatic, red-green, yellowish-violet), at background luminance levels from 0.02 to 2000 cd/m^2, and different stimuli sizes using 4AFC method on a high dynamic range display. 20 observers with a mean age of 33 y.o.a. and 20 older observers with mean age of 65 participated in the study. Within each session, observers were fully adapted to the fixed background luminance. Our main findings are: (1) Contrast sensitivity increases with background luminance up to around 200 cd/m^2, then either declines in case of achromatic contrast sensitivity, or remains constant in case of chromatic contrast sensitivity; (2) The sensitivity of the younger age group is higher than that for the older age group by 0.3 log units on average. Only for the achromatic contrast sensitivity, the old age group shows a relatively larger decline in sensitivity for medium to high spatial frequencies at high photopic light levels; (3) Peak frequency, peak sensitivity and cut-off frequency of contrast sensitivity functions show decreasing trends with age and the rate of this decrease is dependent on mean luminance. The data is being modeled to predict contrast sensitivity as a function of age, luminance level, spatial frequency, and stimulus size.

Introduction

The human visual system undergoes both optical and neural changes as we age. It is important to identify the causes and effects of these changes to better understand the needs of a large fraction of the population. Our work focuses on contrast sensitivity, i.e., the ability to detect small variations in intensity of colour across space. The key physiological factors that affect contrast sensitivity include changes in densities of lens and other ocular media [1, 2, 3] and the consequent changes in light scattering properties of the eye [4], macular degeneration [5] especially sensitivity losses in fovea [6, 7], and pupil size constriction [8, 9] also known as senile miosis. In addition to optical factors, neural changes in human visual system with age lead to changes in contrast sensitivity as well [10] especially in scotopic and mesopic range [11].

Previous studies have investigated age-related changes in both achromatic [9, 12, 10] and chromatic contrast sensitivity at low luminance levels [13, 14, 15, 16, 17, 18, 19, 20] and proposed models to characterize age-dependent contrast sensitivity functions [21, 22]. Changes in chromatic discrimination sensitivity across multiple mean luminance levels have also been reported [23]. However, the senescence of spatio-chromatic sensitivity at high light levels for both achromatic and chromatic stimuli has not been thoroughly investigated before. In this study, we are investigating the joint effects of luminance (ranging from 0.02 to 2000 cd/m^2) and age on spatio-chromatic sensitivity.

It is important to note here that aging is a fairly individualistic process and is considerably affected by an individual's lifestyle, genetics, environment, etc. And so, while contrast sensitivity across the lifespan decreases in general, the rate of said change is highly variable among individuals. This means that it is very difficult to generally characterize contrast sensitivity functions for older observers due to the unique circumstances of each individual which are amplified by age [21, 11].

A thorough characterization of normal age-related changes in human contrast vision can be applied for development of early clinical intervention protocols. A potential non-clinical application would be to use the knowledge from CSFs to customize and re-target images for observers based on their age and viewing conditions. Such applied research would help to understand difficulties faced by the older section of the population. For example, it could be used to simulate driving experiences of older drivers and develop interventions that maintain safe mobility. The framework developed can later be used to extend the research to other visual deficiencies.

Experiment

Stimuli

The stimuli were Gabor patches presented against a D65 neutral gray background and modulated along the three cardinal directions in Derrington-Krauskopf-Lennie (DKL) space: achromatic, red-green, and yellow-violet, designed to isolate the hy-

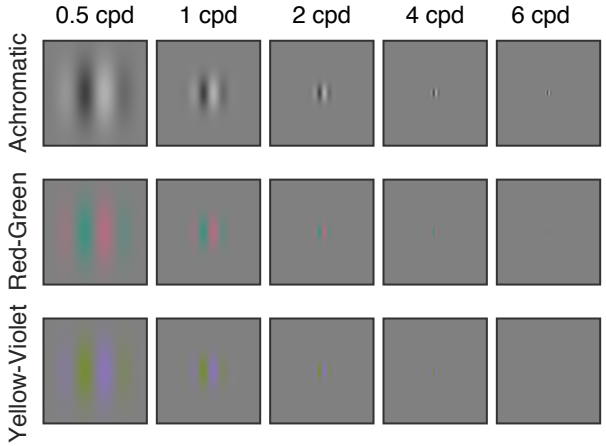

Figure 1: Fixed-cycles stimuli. Width of the Gaussian envelope was half of the wavelength, $\sigma = 0.5f^{-1}$ (deg).

pothetical post-receptoral mechanisms $(L+M)$, $(L-M)$, and $(S-(L+M))$. The width of the Gaussian envelopes enclosing the Gabor patch stimuli was set to be half of the spatial wavelength such that all stimuli had a fixed number of cycles for the five spatial frequencies (0.5, 1, 2, 4, and 6 cycles per degree (cpd)) used. Figure 1 shows the stimuli which were displayed at 6 different mean background luminance levels: 0.02, 0.2, 2, 2.0, 200, and 2000 cd/m^2. The stimuli were displayed on custom-built HDR display capable of handling such high contrasts [24].

Cone-contrast definition

Modulation along one of the three color directions in DKL space corresponds to incremental changes in L, M, and S cone responses. Thus the DKL stimuli contrast thresholds recorded from the experiments are transformed into their corresponding L, M, and S cone thresholds using the relationship derived in [25]. The resultant normalized cone contrast is defined in Eq. 1:

$$C_t = \frac{1}{\sqrt{3}}\sqrt{\left(\frac{\Delta L}{L_0}\right)^2+\left(\frac{\Delta M}{M_0}\right)^2+\left(\frac{\Delta S}{S_0}\right)^2} \quad (1)$$

C_t = Threshold cone contrast

$\Delta L, \Delta M, \Delta S$ = Incremental L,M,S cone absorptions

L_0, M_0, S_0 = L,M,S absorptions of the display background

Contrast sensitivity is the inverse of contrast threshold from Eq. 1. For achromatic modulations, Eq (1) is identical to Michelson contrast.

Observers

40 color-normal observers with no history of eye disease (based on self reports) participated in the study. All observers participated in six sessions, corresponding to mean background luminance levels: 0.02, 0.2, 2, 20, 200, 2000, and 7000 cd/m^2. The older group consisted of 20 observers (mean age = 65). The younger group consisted of 20 observers (mean age = 33). The procedure of the study was explained to the observers and written consent was obtained. The study was approved by Ethics committees in both University of Liverpool and University of Cambridge.

Procedure

The observers participated in one hour-long session per luminance level. The HDR display was set up in a dark room and the observers adapted to the respective mean luminance level prior to the start of the experiment. The observers were seated 91 cm from the display which subtended $12.5^\circ \times 9.4^\circ$. Within each session, stimuli were randomly interleaved across all three color directions and five spatial frequencies (Figure 1) presented at the same background luminance level.

Threshold measurements were made using a 4AFC procedure with the stimulus presented in one of the four quadrants; the other quadrants were kept at the respective mean luminance level of the grey background. The task of the observer was to identify the quadrant that contained the stimulus. The thresholds for each condition were estimated with 25 to 35 trials. The responses from each condition were fitted with a psychometric function and the threshold was estimated as the contrast level at which the probability of detection was 0.84.

Results and discussion

Results are presented in Figure 2. The data from the observers of both groups were averaged separately within each spatial frequency, each color direction and luminance level. On average, contrast sensitivities of older observers are roughly 3dB lower than those of younger observers (Figure 2).

Consistent with previous findings, the decrease in achromatic contrast sensitivity (Figure 2, first row) for older observers

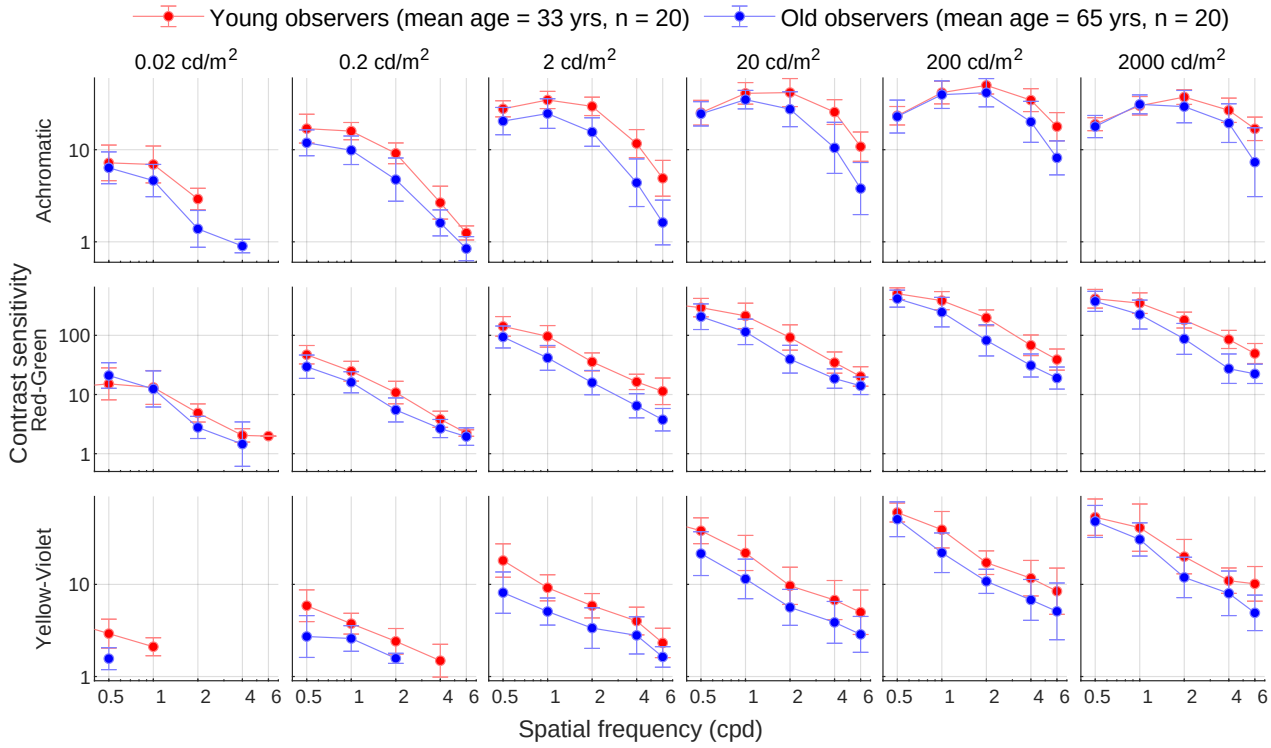

Figure 2: Comparison of contrast sensitivity measurements (error bars: standard deviation) from younger and older observers' age group. Each subplot contains the contrast sensitivity function for the corresponding color and luminance combination. Age-dependent decline in contrast sensitivity is larger with increasing spatial frequency for achromatic contrasts

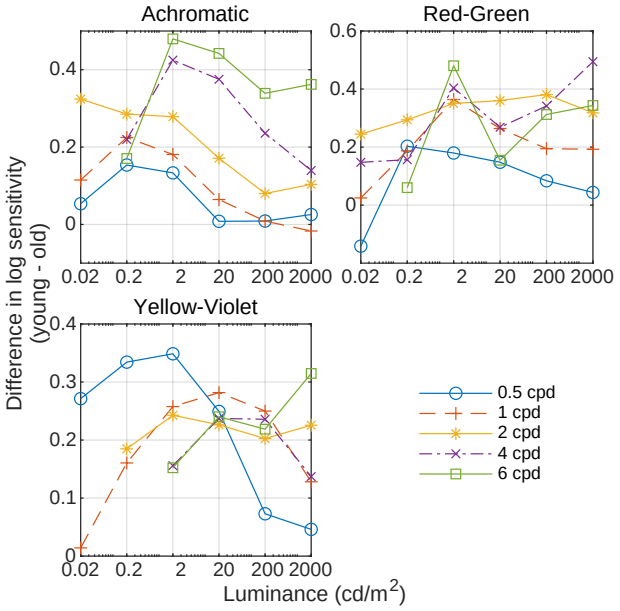

Figure 3: Differences in log sensitivity between younger and older age group across luminance levels for different spatial frequencies

is more pronounced at higher spatial frequencies [9, 12, 26, 21]. A similar pattern is found for the chromatic contrast sensitivity at medium to high luminance levels: at low spatial frequencies, the sensitivity is similar between the old and the young observer group.

We find a systematic decrease in both chromatic contrast sensitivities for luminance levels up to 20 cd/m^2 for all spatial frequencies [19, 16], which is more pronounced for the yellow-violet contrast sensitivities of the older observers. This differential age-related decrease in sensitivity for S-cone isolating stimuli is consistent with previous studies [27, 28]. The standard deviation of the estimated contrast thresholds is higher for older age group as individual variability becomes more pronounced with advancing age [29, 30, 21].

Another novel aspect of our study is the role of the background luminance (which controls the adaptational state of the observer) in determining the magnitude of differences in both chromatic and achromatic contrast sensitivity between age groups (Figure 3). The difference in log sensitivity is plotted against mean luminance level for each of the spatial frequencies. For achromatic contrasts, differences between the two age groups seem to peak at luminance levels 0.2 - 2 cd/m^2 which is consistent with the idea that mesopic vision is affected more severely in the older age group than both scotopic and photopic vision. The lower magnitude of the age-related scotopic sensitivity difference may reflect more significant changes in the cone pathway compared to the rod pathway, pointing to spatial vision at low luminances being more dependant on neural rather than optical factors. A similar trend is observed at all spatial frequencies but the magnitude of these differences increases with spatial frequency.

The age-related decline in red-green and yellow-violet sensitivity shows different trends. Yellow-violet mechanism contrasts input from S-cones against L and M cones, while the red-green mechanism contrasts input from L and M cones. For red-green stimuli, the larges difference between the young and the old age groups is observed at 2 cd/m^2 but there is no systematic change in sensitivity differences for higher light levels. For yellow-violet modulations, the age-related sensitivity difference is highest at a luminance level of 2 cd/m^2 for low spatial frequencies, but is reduced at higher light levels.

Modeling

We are incorporating age as a parameter in the model that we have proposed recently[1] [24]. The basis of the model is the assumption that CSFs can be specified as log-parabolas [21, 24].

$$\log_{10} S(f;S_{\max},f_{\max},b) = \log_{10} S_{\max} - \left(\frac{\log_{10} f - \log_{10} f_{\max}}{0.5\cdot 2^b}\right)^2 \tag{2a}$$

$$S'(f;S_{\max},f_{\max},b,t) = \begin{cases} \frac{S_{\max}}{t}, & \text{if } C_2,C_3 \text{ and } f < f_{\max} \text{ and} \\ & S(f;S_{\max},f_{\max},b) < \frac{S_{\max}}{t} \\ S(f) & \text{otherwise} \end{cases} \tag{2b}$$

CSFs from each observer are fitted as log-parabola functions using Eq. 2, where C_2, C_3 denote red-green and yellow-violet color directions. The parameters of interest are peak frequency $f_{\max}$, and peak sensitivity $S_{\max}$for each luminance and color channel. Cut-off frequency f_c is calculated as as the point where the contrast sensitivity predicted by the fitted CSF falls to zero. For each curve, the fitted values of peak frequency, peak sensitivity and cut-off frequency are obtained and are shown in Figure 4. Empty circles in the figure are optimized parameters; peak frequency, peak sensitivity, and the calculated cut-off frequency for each observer at multiple luminance levels plotted with respect to age. Solid lines are linear regression lines fitted to age versus the optimized values of the log parabola parameters with criteria $P < 0.1$ and show the approximate trend of change in parameter values with age.

For achromatic CSFs, peak frequencies of the functions are decreasing with age for all luminance levels, i.e., the peak of CSFs shift towards lower frequencies with age. This is also clearly shown in Figure 2 (first row). The relationship is highly statistically significant ($P < 0.001$) for luminance levels 20 and 200 cd/m^2. Peak sensitivities for achromatic contrast also show a decrease with age for luminance levels ranging from 0.2 to 20 cd/m^2. The cut-off frequency is calculated using the values of the optimized parameters for each individual. The values for cut-off frequency for achromatic stimuli appear to become more age-dependent with increasing luminance level, as indicated by the increasing slope parameters with increasing luminance. This shows the differential effect of age on contrast sensitivity at higher frequencies.

McGrath et al. (1981) also showed similar trends for senescence of achromatic CSFs at 2 cd/m^2 [31]. Similarly, Owsley et al. (1983) showed a large decrease in contrast sensitivity for higher spatial frequencies ($> 2cpd$) at 103 cd/m^2 [12]. Much of the age-dependent decrease in contrast sensitivity can be attributed to decreased retinal illuminance which largely results from changes in lens density and pupil constriction [1, 3, 8, 9]. From our data, we can see that achromatic CSFs are very much age-dependent for mid-range luminance levels (0.2 $\sim$ 200 cd/m^2). As the luminance level increases, the decrease in sensitivity is observed in higher spatial frequencies only. This could be explained by the greater rate of age-dependent change in pupil size for lower luminance levels [9, 8]. Because the reduction in retinal illuminance is much stronger in

[1]The code can be found at: `https://www.cl.cam.ac.uk/research/rainbow/projects/hdr-csf/`

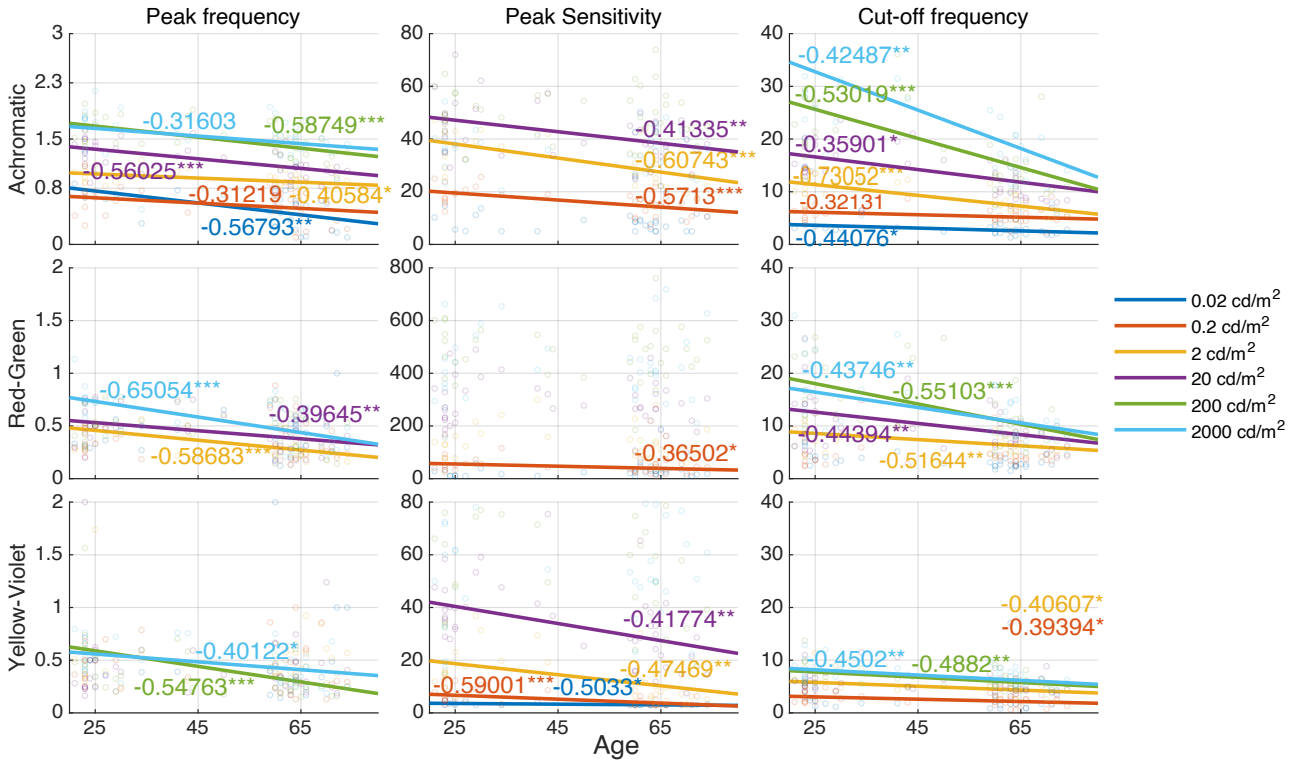

Figure 4: Change in log-parabola CSF parameters with age. Empty circles in the figure are optimized parameters: peak frequency, peak sensitivity, and cut-off frequency for each observer at multiple luminance levels plotted with respect to age. Solid lines are linear regression lines fitted to age vs. the optimized values of the three parameters. Peak sensitivity and cut-off frequency show decrease with age, and the slope of these lines appear to be luminance dependent. Peak frequency decreases with age for achromatic contrast as well as for chromatic contrasts. Only the correlations for which the value of p-test is below 0.1 are shown here. $*(P < 0.05), **(P < 0.01), ***(P < 0.001)$

low light, the sensitivity decreases with age almost uniformly across all spatial frequencies. Meanwhile, in high light level conditions this reduction in retinal illuminance impacts higher spatial frequencies only.

In terms of chromatic contrast, the decrease in peak frequency with age is predicted for luminance levels above 2 cd/m^2 and 200 cd/m^2 for red-green and yellow-violet color directions respectively. The peak frequencies predicted for chromatic channels are around 0.5 cpd which is consistent with other studies [15, 14, 13, 32]. However, this is also the lowest spatial frequency that we measured. The fits from our data suggest that this peak frequency may decrease further with observers' age. More data needs to be collected for isoluminant chromatic stimuli at lower spatial frequencies ($< 0.5cpd$) to verify this finding.

As shown in Fig. 2, peak sensitivity of yellow-violet color direction seems to be affected much more by age compared to red-green color direction. Fig. 4 shows a significant change to red-green peak sensitivity with age only at 0.2 cd/m^2. Meanwhile, yellow-violet peak sensitivity decreases with age for luminance levels up to 20 cd/m^2. This disparate effect among the two chromatic directions can be explained by changes in lens density with age. Studies investigating the spectral characteristics of human lens aging have shown that transmittance of the shorter end of the visible spectrum (blue/violet light) decreases much more rapidly with age compared to medium to long wavelengths [1]. Thus, while L and M cone responses are reduced with age, the ratio of these reductions is comparable in magnitude and so the age-dependent effect on red-green (L-M) contrast sensitivity is not very pronounced. On the other hand, S cone response is decreased much more with age compared to L and M cone responses, resulting in a much larger decrease in yellow-violet (S-(L+M)) contrast sensitivity. The study by Hardy et al. (2005) demonstrates that this large change in yellow-violet contrast sensitivity is in part due to the wavelength-dependent filtering happening in the ocular media and it can be accounted for when the stimuli are equated at the retina [16].

The values for cut-off frequency for red-green stimuli appear to become more age-dependent with increasing luminance level which shows that the sensitivity at higher frequencies decreases more rapidly with age. For yellow-violet stimuli, the correlation between cut-off frequency and age is statistically significant but the slopes are close to zero. Therefore, higher frequencies are not disproportionately affected by age in yellow-violet stimuli.

Conclusions

Our study investigates the joint effects of age and luminance level on achromatic and chromatic contrast sensitivity functions. Achromatic contrast sensitivity decreases with age across all spatial frequencies. However, for higher spatial frequencies this age-dependent sensitivity reduction becomes more prominent with increasing luminance levels. For chromatic contrast sensitivity, age-related contrast sensitivity changes are less dependent on spatial frequency, but contrast sensitivity in the yellow-violet color direction at low spatial frequency shows a significant decline with age.

These observations imply that for images shown on the newer generation of displays (e.g. HDR displays) that are capable of producing very high dynamic range light levels, the perceived image may vary considerably between observers be-

longing to different age groups. How these threshold measurements relate to supra-threshold appearance is still an open question since it is likely that higher-order neural mechanisms are in place that compensate for changes in age-related changes in pupil size and optical media.

Acknowledgments

This research was funded by EPSRC grants EP/P007503, EP/P007910, EP/P007902, and EP/P007600. This project has also received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No 725253–EyeCode).

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