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

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Abstract

We investigated the difference in spatio-chromatic contrast sensitivity between younger and older color-normal observers. We studied how the adapting light level affected the contrast sensitivity and whether there was a differential age-related change in sensitivity. Contrast sensitivity was measured for three chromatic directions, luminance levels from 0.02 to 2000 cd/m^2, and different stimuli sizes using 4AFC method on a high dynamic range display. 21 observers with mean age of 33 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 becomes constant in case of chromatic contrast sensitivity; (2) The sensitivity of the younger age group (<40 y.o.a.) 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 a lot of 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 image intensity and colour variations 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 has 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.

Moreover, there have been studies that translated the data collected as contrast sensitivity functions to image discrimination and image quality modeling [24, 25, 26, 27]. Similar methods can be used to simulate image appearance for observers of different ages, for a wider range of luminance levels using the data we collected for this study.

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. It is shown in previous studies as well that it is very difficult to generally characterize contrast sensitivity functions for older observers due to the unique circumstances of each individual which are enhanced 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 non-clinical applications is using the knowledge from CSFs to customize and re-target images for observers based on their age and viewing conditions. The research is helpful to understand difficulties faced by the older section of the population. It can be used to simulate driving experiences for older drivers and to design better road-safety equipment, for example. The framework developed can later be used to extend the research to other visual deficiencies as well.

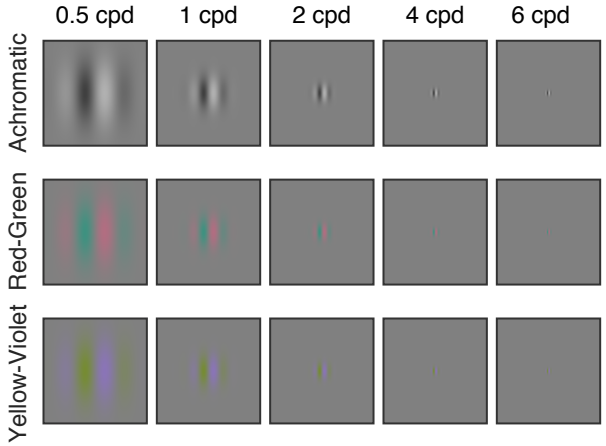

Figure 1: Fixed-cycles stimuli. Width of the Gaussian envelope was half of the wavelength, $\sigma = 0.5f^{-1}$ (deg).

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 corresponding to the hypothetical mechanisms $(L+M)$, $(L-M)$, and $(S-(L+M))$ respectively. 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 [28].

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 [29]. 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.

Observers

40 color-normal observers with no history of eye disease participated in the study. All observers participated in six sessions, corresponding to mean mean background luminance levels: 0.02, 0.2, 2, 20, 200, 2000, and 7000 cd/m^2. The old group consisted of 20 observers (mean age = 65). The young group consisted of 20 observers (mean age = 33).

Procedure

The observers participated in hour-long sessions for each luminance levels. The display was set up in a dark room and the observers were adapted to the room and the corresponding mean luminance level prior to 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 luminance level.

Threshold measurements were made using a 4AFC procedure with the stimulus presented on one of the four quadrants presented on the screen and the observers having to choose the quadrant which they perceive to be presenting 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 two groups was averaged separately across the spatial frequencies for each color direction and luminance level. We found that the contrast sensitivities of older observers are roughly 3dB lower than those of younger observers on average (Figure 2).

Our results are found to be consistent with other known findings. The decrease in achromatic contrast sensitivity (Fig-

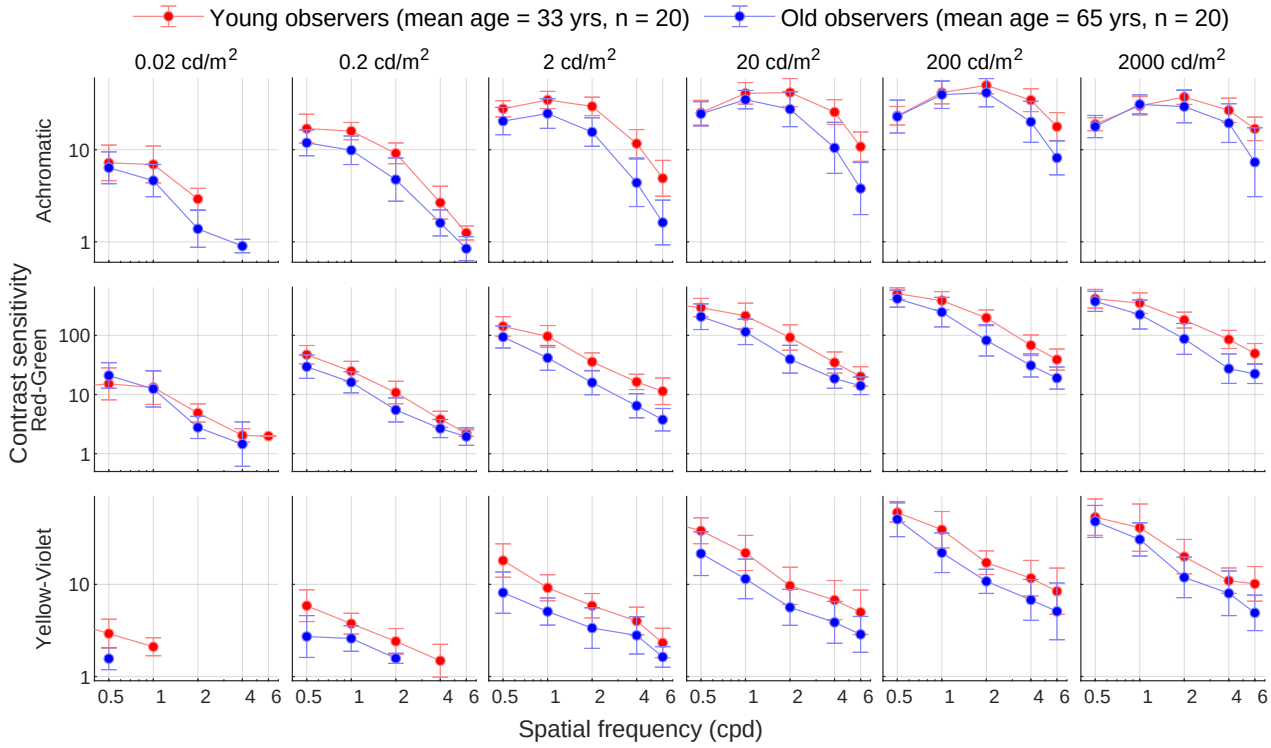

Figure 2: Comparison of contrast sensitivity measurements (error bars: standard deviation) from younger and older observers' age group. Each subplot contains the contrast sensitivity function for the corresponding color and luminance combination. Age-dependent decline in contrast sensitivity is larger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

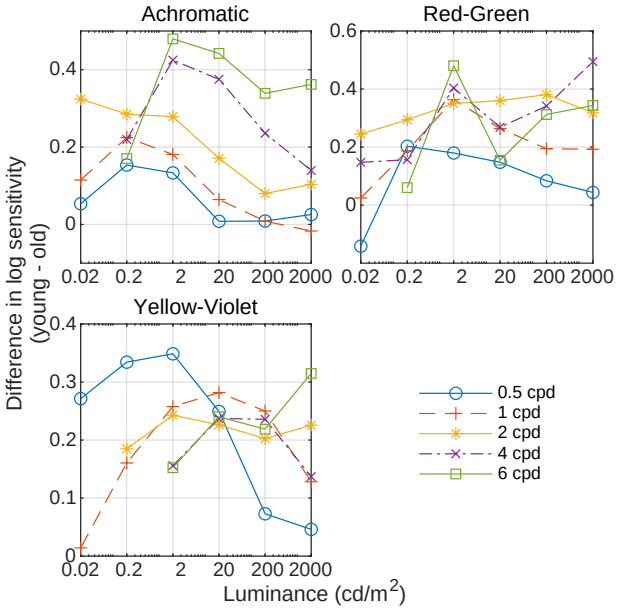

Figure 3: Differences in log sensitivity between younger and older age group across luminance levels for different spatial frequencies

ure 2, first row) for older observers becomes larger with increasing spatial frequency [9, 12, 30, 21]. The decrease in sensitivity for older observers is also amplified with decreasing luminances [9] to a certain extent. It is interesting to note that at 0.02 cd/m^2 the difference between the two age groups diminishes instead of increasing further. In literature review, we could not find precedence of this phenomenon as the lowest luminance level for a similar experiment found in literature review was 0.1 cd/m^2 [9].

The measures of variation (e.g., standard deviation) are higher for older age group as individual variability becomes more pronounced with advancing age [31, 32, 21]. Consistent decrease in both chromatic contrast sensitivities for luminance levels up to 20 cd/m^2 for all spatial frequencies [19, 16]. The yellow-violet contrast sensitivities of the older observers are particularly lower than those of younger observers for luminance levels up to 20 cd/m^2 [19]. Other studies have not specifically shown yellow-violet contrast sensitivities but have demonstrated that S-cone absorption and neural pathways are more affected with age [33, 34].

The novel finding of our study is the role of luminance in determining the magnitude of differences in both chromatic and achromatic contrast sensitivity between age groups (Figure 3). The differences are plotted against mean luminance levels to show the trend of change with respect to luminance. The difference is positive everywhere (except for red-green sensitivity at 0.02 cd/m^2 at 0.5 cpd, likely a measurement error) as the sensitivities from younger observers are always higher.

For achromatic contrasts, differences between the two age groups are the highest for luminance levels 0.2 - 2 cd/m^2 and then decrease when the luminance is either increased or decreased, which shows that mesopic vision is affected more severely with age than both scotopic and photopic vision. The lower magnitude of difference in scotopic range could mean that cone pathways are affected more than rods with age, pointing to neural factors predominantly dictating spatial vision at low luminances rather than optical factors. Similar trend is observed at all spatial frequencies but the magnitude of these differences increases with spatial frequencies.

The decrements in red-green and yellow-violet sensitivity show different trends. This is likely because S-cone pathway is affected differently than L, and M cones with age. For red-green stimuli, the highest difference between both groups is observed to be at 2 cd/m^2. The differences are observed to be the lowest for 0.5 cpd but then seem to be more or less frequency-invariant. The trend in yellow-violet stimuli is interesting, in that it shows the highest decrements at 0.5 cpd for luminance levels below 20 cd/m^2 and then the lowest decrements at 0.5 cpd for luminance levels above 20 cd/m^2.

Modeling

We are incorporating age as a parameter in the model that we have proposed in a recent publication[1] [28]. The basis of the model is the assumption that CSFs can be specified as log-parabolas [21, 28].

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

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

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. The bandwidth parameter was found to be neither age nor luminance-dependent and the bandwidth values were thus fixed for each color channel. 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 observed to be decreasing with age for all luminance levels, i.e., the peak of CSFs shift towards the left 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 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. This can be observed from the increasing slopes of the lines with increasing luminance. The observation further shows how age especially affects contrast sensitivity at higher frequencies.

McGrath et al. (1981) in their study have also shown similar trends for senescence of achromatic CSFs at 2 cd/m^2 [35]. The study by Owsley et al. (1983) have similarly shown large decrease in contrast sensitivity for higher spatial frequencies

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

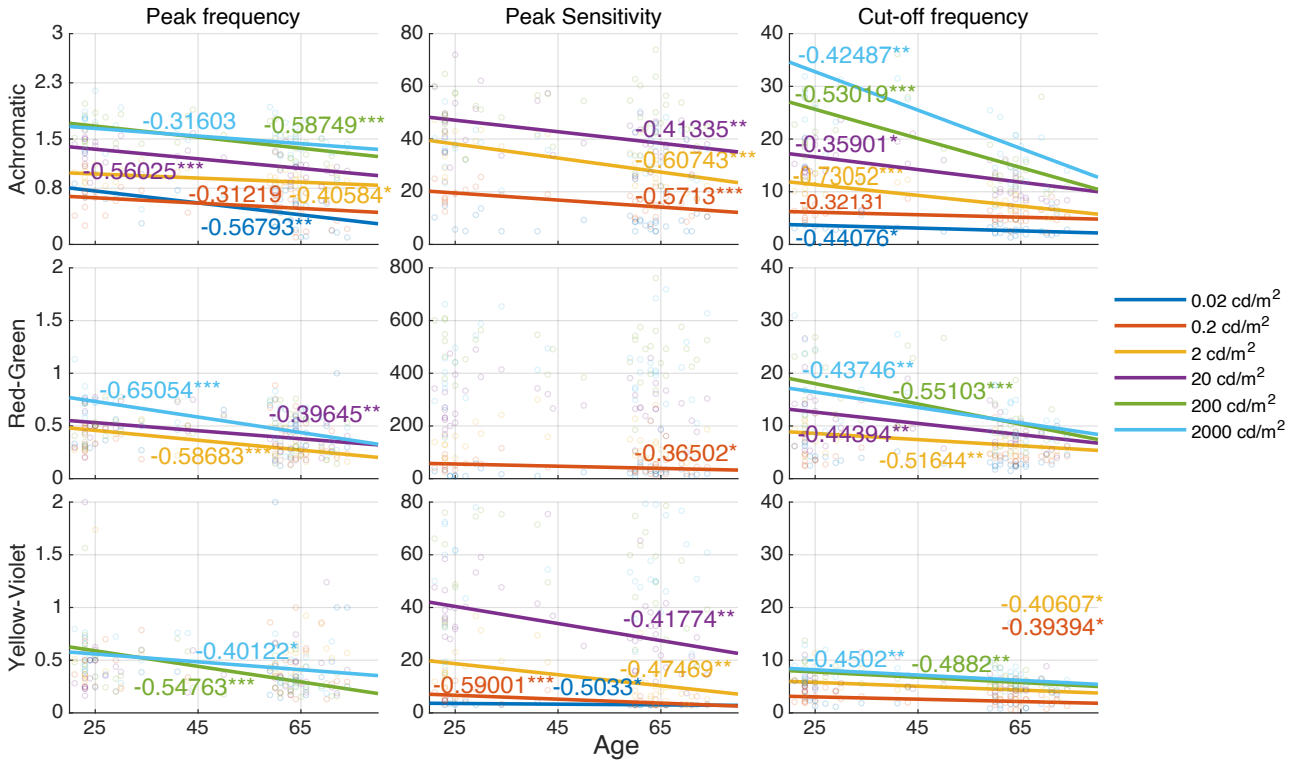

Figure 4: Change in log-parabola CSF parameters with age. Empty circles in the figure are optimized parameters: peak frequency, peak sensitivity, and cut-off frequency for each observer at multiple luminance levels plotted with respect to age. Solid lines are linear regression lines fitted to age vs. 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. $*(P < 0.05), **(P < 0.01), ***(P < 0.001)$

$(> 2cpd)$ 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 low light, the sensitivity is decreased with age almost uniformly across all spatial frequencies. While in high light level conditions, this reduction in retinal illuminance impacts higher spatial frequencies only.

In chromatic contrast directions, the decrease in peak frequency with age is predicted for luminance levels above 2, and 200 cd/m^2 for red-green and yellow-violet color directions respectively. However, it must be noted that the peak frequencies predicted for chromatic channels are around 0.5 cpd which is consistent with other studies [15, 14, 13, 36] but it is also the lowest spatial frequency that we measured. The fits from our data suggest that this peak frequency decreases even lower with observers' age. More data needs to be collected for isoluminant chromatic stimuli at lower spatial frequencies $(< 0.5cpd)$ to verify this result.

As shown in Fig. 2 as well, the peak sensitivity of yellow-violet color direction is observed to be affected much more with age compared to red-green color direction. In Fig. 4, a significant relationship between red-green peak sensitivity with age was only found at 0.2 cd/m^2. While, yellow-violet peak sensitivity decreased with age for luminance levels upto 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 the transmittance of the shorter end of the visible spectrum (blue/violet light), decrease much 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 are 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) demonstrate that this large change in yellow-violet contrast sensitivity is mostly due in part 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 decrease more rapidly with age . For yellow-violet stimuli, the correlation between cut-off frequency and age show significance, but the slopes are close to zero which shows that 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 sensitivities are decreased with age across spatial frequencies but with increasing luminance levels, the age-dependent sensitivity reduction is increased for higher spatial frequencies. For chromatic sensitivities the effects of age are predominantly frequency invariant, but contrasts in yellow-violet color direction are specially affected by age. These observations imply that for images shown on 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 belonging to different age groups.

The next-step in our work is to investigate whether there is a correlation between individual variations in psychophysical measurements and physiological measurements such as acuity, ocular media density, and pupil diameter measurements. We are also working on incorporating age as a factor in our general spatio-chromatic contrast sensitivity model. Moreover, our study so far deals with contrasts at threshold levels. It will be very interesting to investigate the effect of aging on supra-threshold levels and whether there are higher-order neural mechanisms in place that compensate for changes in pupil and optical media.

Acknowledgments

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