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Color and Contrast Sensitivity Threshold Norms Across Age Decades in Normal Subjects

Dolores de Fez [1,*], Ainhoa Molina-Martín [1], Mª José Luque [2] and David P. Piñero [1]

[1] Department of Optics, Pharmacology and Anatomy, University of Alicante, 03690 Alicante, Spain; ainhoa.molina@ua.es (A.M.-M.); david.pinyero@ua.es (D.P.P.)
[2] Department of Optics and Optometry and Vision Science, University of Valencia, 46100 Valencia, Spain; maria.j.luque@uv.es
* Correspondence: dolores.fez@ua.es

Abstract

The aim of the present study was to develop a reference database in a healthy population for a test measuring color discrimination thresholds and contrast sensitivity, with the purpose of establishing reference values that contribute to optimizing their use in vision research and clinical assessment. All measurements were performed using four portable electronic display devices (iPads), each of which underwent a specific colorimetric characterization. Experimental measurements were carried out using the Optopad test battery, which includes a test for the assessment of color discrimination thresholds and a test for measuring chromatic and achromatic contrast sensitivity functions. Mean color discrimination and contrast sensitivity threshold values and the reference region defined by the 2.5th and 97.5th percentiles for age decades in the [10, 80] age range were obtained for healthy subjects. These results allow us to define normative intervals with potential diagnostic applications, and information about the mean values of the contrast sensitivity functions for the different age ranges can be used, together with a spatio-chromatic model, to predict age-related changes in visual perception.

Keywords: color discrimination threshold; chromatic contrast threshold; achromatic contrast threshold

1. Introduction

Color vision and contrast sensitivity are essential for the proper performance of everyday visual activities and represent sensitive indicators of the functional integrity of the retina and central visual pathways [1,2].

In recent years, psychophysical methods aimed at the quantitative assessment of visual thresholds have gained increasing relevance in both basic research and clinical settings. Several studies have demonstrated that alterations in contrast sensitivity and color discrimination may appear in the early stages of ophthalmological and neurological diseases, even before significant changes in conventional visual acuity can be detected [3,4]. These measures have proven useful in conditions such as glaucoma, optic neuritis, diabetic retinopathy, and neurodegenerative diseases, where they allow for the identification of subtle functional deficits and the monitoring of disease progression [3–5].

The development of computerized systems and adaptive procedures has considerably improved the precision, reproducibility, and efficiency of perceptual threshold estimation [6]. In particular, computerized tests of contrast sensitivity and color discrimination

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provide more sensitive and objective quantitative measures than conventional visual assessments, facilitating their application in both experimental research and clinical practice. However, the proper interpretation of the results obtained through this type of testing requires the availability of normative databases derived from healthy populations.

The recent literature has highlighted the need to establish normative values specific to each evaluation methodology, taking into account the influence of variables such as age, sex, lighting conditions, stimulus characteristics, and display device properties [1,2,7]. Several studies have shown significant age-related changes in both contrast sensitivity and color discrimination, underscoring the importance of having appropriate population references for the clinical interpretation of results [1,7]. Likewise, the absence of standardized databases hinders comparisons across studies and limits the diagnostic applicability of these instruments in different clinical and experimental contexts.

In this context, the aim of the present study was to develop a reference database in a healthy population for a test measuring color contrast discrimination and contrast sensitivity thresholds, with the purpose of establishing reference values that contribute to optimizing its use in visual research and clinical assessment.

2. Materials and Methods

The Optopad test is a novel visual assessment tool, jointly designed and developed by the University of Alicante and the University of Valencia. Its design takes into account the specific color reproduction characteristics of each individual display, which were previously subjected to individual colorimetric characterization. The use of generic device characterizations or standard color profiles may introduce color reproduction errors that could compromise the diagnostic validity of visual assessments [8]. Our test was colorimetrically designed to reproduce the colors on each device based on its individual colorimetric characterization. This characterization must be performed as a preliminary step before calculating RGB values necessary to generate the desired color signals in the different plates of the test. In this way, the same test is reproduced across all devices, apart from the associated color reproduction errors. This procedure minimizes color reproduction errors, ensuring consistent color perception across the different devices used. All devices used in our studies showed color reproduction errors of no more than 1 CIEDE2000 color-difference unit, whereas the minimum color difference considered distinguishable by the visual system is approximately 2 units. Most devices showed errors below 0.5 units.

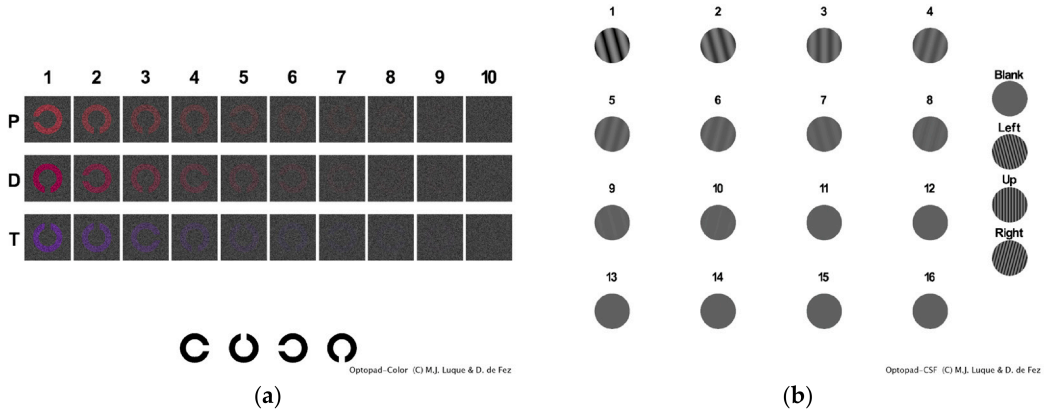
Optopad has demonstrated the feasibility of using portable tablet-based systems for the assessment of color discrimination (Optopad-Color) and spatial vision (Optopad-CSF) thresholds in both healthy and clinical populations, including young and adult individuals [9,10], patients with cataracts [10], subjects with color vision deficiencies [11], wearers of multifocal contact lenses [12], and individuals with other ocular pathologies [13].

Optopad-Color enables the assessment of chromatic discrimination thresholds along the confusion axes associated with congenital color vision deficiencies (PDT: protan, deutan, and tritan) and along the cardinal directions of the opponent-color space associated with acquired deficiencies (RGBY: red–green and blue–yellow). The test comprises three stimulus plates, designated PDT1, PDT2, and RGBY. Each PDT plate consists of three rows of ten Landolt C optotypes subtending 1.7°, presented at random orientations with a mean luminance of 60 cd/m^2 against an achromatic background set to the maximum luminance achievable by the device. Cone contrast values between test and the background are the same along the protan and deutan axes and vary in constant logarithmic steps. Tritan contrast values are the same in both PDT plates. The difference between PDT1 and PDT2 lies in the direction explored along the deutan confusion line: PDT1 evaluates the reddish direction ($\Delta M < 0$ in LMS cone space), whereas PDT2 evaluates the greenish

direction (ΔM > 0). The RGBY plate consists of four rows of ten Landolt Cs, with each row corresponding to a cardinal color direction (red, green, blue, or yellow). A detailed description of the test design and implementation can be found in de Fez et al., 2018 [11].

Optopad-CSF enables the measurement of both achromatic (CSF-A) and chromatic contrast sensitivity functions (CSF-T, red–green gratings; CSF-D, blue–yellow gratings). Contrast sensitivity is assessed using sinusoidal gratings presented on five plates, with each plate corresponding to a specific spatial frequency evaluated in the test. For the achromatic test, the spatial frequencies are 1.5, 3, 6, 12, and 24 cycles per degree (cpd), whereas for the chromatic tests the frequencies are 1, 2, 4, 8, and 12 cpd. Each plate contains a decreasing-contrast series of sinusoidal gratings with a mean luminance of 60 cd/m^2, displayed within 2° circular apertures at random orientations and arranged in a 4 × 4 matrix on an achromatic background with the maximum luminance available from the device. Further details regarding the methodology are provided in de Fez et al. 2024 [10].

Examples of the plates used in each test are shown in Figure 1. The maximum and minimum thresholds measurable with these devices can be seen in Tables S1–S3.



(**a**) (**b**)

Figure 1. As an example, (**a**) the PDT1 plate of Optopad-Color and (**b**) the 1.5 cpd plate of Optopad-CSF-A.

In the case of the Optopad-Color test, the parameter evaluated was the color contrast discrimination threshold in cone excitation space. For the Optopad-CSF test, contrast discrimination thresholds were obtained in the same space and transformed into sensitivity values by calculating their inverse.

The experimental data analyzed in this study were obtained from several independent investigations conducted by the authors at the Optometry Clinic of the University of Alicante (Alicante, Spain). All studies adhered to the tenets of the Declaration of Helsinki. Prior to participation, all subjects received a detailed explanation of the study procedures and provided written informed consent. Ethical approval was granted by the Ethics Committee of the University of Alicante (UA-2017-04-05).

All measurements were performed using four portable electronic display devices Apple iPads (Apple Inc., Cupertino, CA, USA). Three devices corresponded to iPad models released between 2013 and 2018 (2013-A1458, 2017-A1822, 2018-A1893), each equipped with a 9.7-inch Retina display emitting polarized light (resolution 1536 × 2048 pixels, pixel density 264 ppi). The fourth device was a 10.2-inch iPad model (2020-A2270) with similar Retina display (resolution 1620 × 2160 pixels, 264 ppi). The number of participants measured with each device can be seen in Table 1.

Table 1. Distribution of participants for each device and tests.

Test\iPad Model	Ipad1 2013-A1458	Ipad2 2017-A1822	Ipad3 2018-A1893	Ipad4 2020-A2270
Optopad-Color	51		74	
Optopad-CSF-A	45	24	160	96
Optopad-CSF-T/D	45	24	60	96

The repeatability of our visual test design has been assessed for both Optopad-Color [11] and Optopad-CSF, with similar results, although those for the latter have not yet been published. Inter-device agreement was not evaluated in the present study and should be addressed in future work to determine whether it represents a relevant limitation. If display-related color reproduction errors remain below the minimum difference distinguishable by the human eye, patients should not be able to differentiate the same stimulus presented on different displays.

Before the experimental procedures of the study, all patients underwent anamnesis and a comprehensive visual examination. The inclusion criteria were normal color vision with the Ishihara test, absence of ocular pathologies, the use of appropriate refractive correction with either spectacles or contact lenses, visual acuity (VA) greater than 0.8, and no history of intraocular lens (IOL) implantation. All measurements were performed monocularly (with the eye randomly selected) in a darkened room following a three-minute adaptation period, with the iPad connected to a power supply and placed 40 cm from the subject.

For the measurements performed using the Optopad-Color test, the plates were always presented in the same order: PDT1, PDT2, and RGBY, with no time limit. The duration of this part of the assessment ranged from 3 to 10 min.

For the measurements performed using the Optopad-CSF test, the plates were presented from the lowest to the highest spatial frequency, starting with achromatic stimuli, followed by red–green stimuli, and finally blue–yellow stimuli. A 2–5-min rest period was provided when switching between mechanisms, depending on the time required to complete each part. The total duration of this test ranged from 15 to 40 min.

Some participants underwent both the Optopad-Color and Optopad-CSF measurements, with a break of at least 15 min between the two tests. Optopad-Color was always administered first because of its simplicity. No session lasted longer than 1.5 h, including rest periods.

Statistical Analysis

Statistical analysis of the results was done using SPSS v.30.0.0 for Windows (SPSS Inc., Chicago, IL, USA). As indicated by the Kolmogorov–Smirnov test, most of the studied parameters were not normally distributed; therefore, non-parametric statistical tests were used. Participants were stratified into 10-year age groups, and the reference limits for each age group were defined by their 2.5th and 97.5th percentiles.

Comparisons among age decades were performed using the Kruskal–Wallis test. Pairwise comparisons were subsequently conducted using the Mann–Whitney U test, with Bonferroni correction applied to account for multiple comparisons. A p-value of 0.05 was considered statistically significant.

3. Results

A total of 125 participants, aged between 20 and 80 years, completed the Optopad-Color test. The achromatic CSF test was completed by 325 participants, whereas 225 participants completed the chromatic CSF-T and CSF-D assessments. Participants' ages ranged

from 10 to 70 years in these cases. Although participants in their 70s were initially included, this age group was excluded from the CSF analysis because many of them had intraocular lenses. The distribution of participants for age group and test is shown in Table 2.

Table 2. Distribution of participants for age groups and test.

Test\Age	10–19	20–29	30–39	40–49	50–59	60–69	70–79
Optopad-Color		61	18	17	16	8	5
Optopad-CSF-A	27	117	43	52	55	31	
Optopad CSF-T/D	11	86	32	30	37	29	

3.1. Optopad-Color

Color discrimination threshold values corresponding the mean (bars) and 2.5th and 97.5th percentiles (black lines) of a total of 125 patients, grouped by decades, for both the PDT1 and PDT2 plates are summarized in Figure 2a–f.

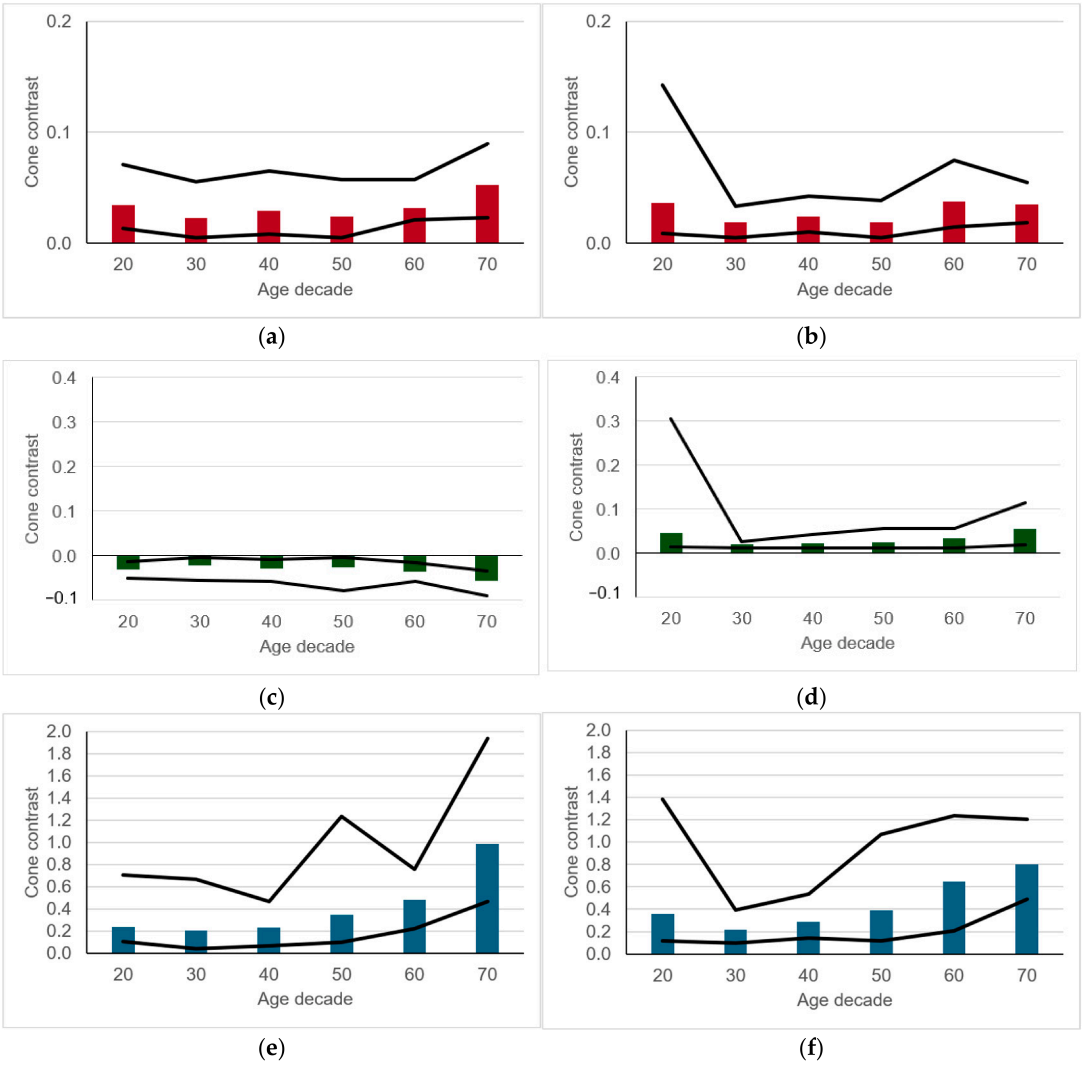


Figure 2. Mean color discrimination thresholds by decades (bars: red for P, green for D and blue for T) and reference range (region between the lines defining the 2.5th and 97.5th percentiles) along the cone-isolating directions: (**a**) line P1 of PDT1 plate, (**b**) line P2 of PDT2 plate, (**c**) line D1 of PDT1, (**d**) line D2 of PDT2, (**e**) line T1 of PDT1, (**f**) line T2 of PDT2.

Color discrimination threshold values corresponding to the mean (bars) and 2.5th and 97.5th percentiles (black lines) of a total of 125 patients grouped by decades for each line of the RGBY plate are summarized in Figure 3a–d.

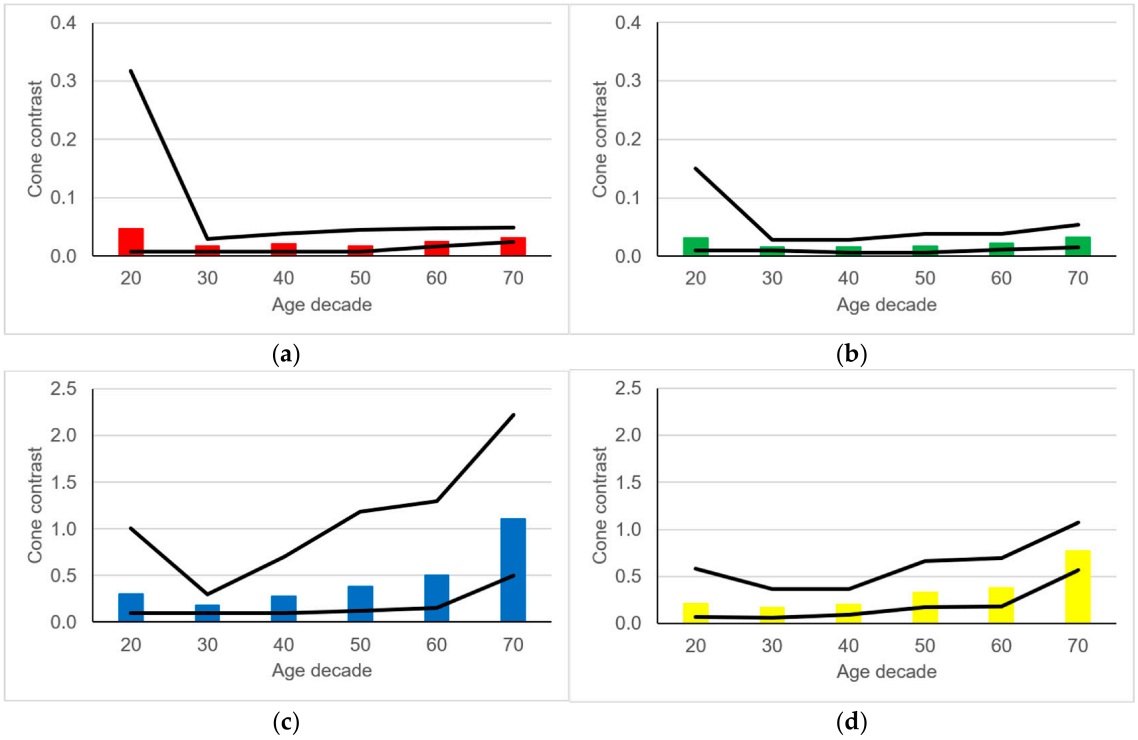


Figure 3. Mean color discrimination thresholds by decades (bars) and reference range (region between the lines defining the 2.5th and 97.5th percentiles) for each line of the RGBY plates: (**a**) cardinal color direction R (red bars), (**b**) cardinal color direction G (green bars), (**c**) cardinal color direction B (blue bars), (**d**) cardinal color direction Y (yellow bars).

When the discrimination thresholds of each decade were compared with those of the preceding decade, a decrease in thresholds was consistently observed up to the 30s decade, indicating an increase in chromatic sensitivity. Beyond this age, the overall trend shifted toward progressively higher threshold values, reflecting an age-related decline in sensitivity. An exception was observed during the 50s for the P1, P2, D1, and R lines, all corresponding to the red–green chromatic direction, where thresholds did not follow the general pattern of increase. Overall, decade-to-decade changes became more pronounced after 60 years of age, with the greatest deterioration occurring along the blue–yellow axis, particularly for the Tritan, B, and Y lines.

Table 3 presents the numerical results obtained from the experimental measurements: mean contrast threshold values in the cone excitation space and 2.5th and 95th percentiles for each decade.

The correlations between age and each line on each plate showed that significant age dependence was observed only for the P1, T1, P2, R, G, and Y lines. The results analyzed using the Kruskal–Wallis test revealed statistically significant differences, marked with an asterisk (*), among age groups for all rows of the PDT1 plate ($p < 0.001$), for the P2 row ($p = 0.004$) of the PDT2 plate, and for the R ($p < 0.001$) and G ($p = 0.002$) rows of the RGBY plate. In contrast, no significant differences were found among age groups for the D2, T2, B, and Y rows.

The Mann–Whitney analysis with Bonferroni correction for pairwise comparisons between age decades did not reveal consistent patterns across all mechanisms (confusion axes protan, deutan, and tritan and the cardinal directions of the opponent-color space).

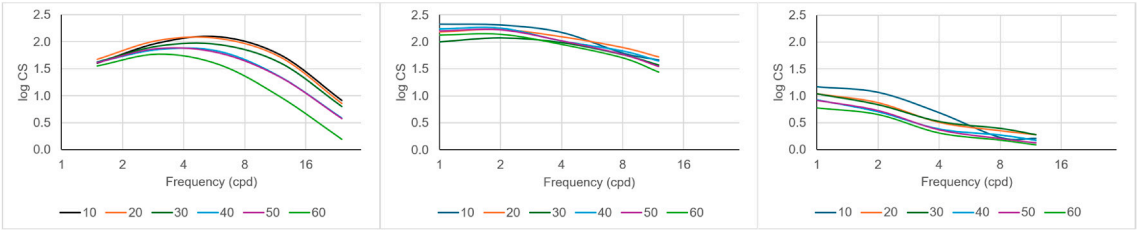
Statistically significant results can be found in Table S4. In general, significant differences between age decades were observed between the younger groups (20–50 years) and the older groups (60–80 years), although this pattern was not consistent across all mechanisms. The R line showed a statistically different pattern in the 20s age group compared with the other age groups, a finding that was not replicated for the G mechanism or for the P (protan) and D (deutan) confusion lines. The T1 (tritan) line showed the greatest number of significant differences in performance between younger and older participants.

Table 3. Mean contrast threshold values in the cone excitation space for each row of the three test plates, grouped by age decade. The limits of the normal range are reported as the 2.5th and 97.5th percentiles. An asterisk (*) indicates statistically significant differences between age groups with the Kruskal–Wallis test.

Age		P1 *	D1 *	T1 *	P2 *	D2	T2	R *	G *	B	Y
20s	mean	0.034	−0.031	0.236	0.036	0.045	0.358	0.047	0.031	0.299	0.210
	p2.5	0.013	−0.050	0.109	0.009	0.015	0.118	0.007	0.010	0.098	0.069
	p97.5	0.071	−0.013	0.703	0.143	0.305	1.385	0.317	0.151	1.007	0.586
30s	mean	0.022	−0.022	0.204	0.019	0.020	0.215	0.018	0.015	0.182	0.169
	p2.5	0.005	−0.056	0.041	0.005	0.012	0.100	0.007	0.010	0.099	0.060
	p97.5	0.056	−0.005	0.668	0.033	0.026	0.395	0.029	0.028	0.299	0.366
40s	mean	0.029	−0.029	0.232	0.024	0.022	0.286	0.021	0.016	0.279	0.202
	p2.5	0.008	−0.057	0.064	0.010	0.012	0.144	0.007	0.006	0.098	0.093
	p97.5	0.065	−0.008	0.465	0.043	0.043	0.532	0.039	0.028	0.700	0.369
50s	mean	0.024	−0.026	0.346	0.019	0.024	0.393	0.018	0.017	0.382	0.326
	p2.5	0.005	−0.080	0.100	0.005	0.012	0.115	0.007	0.006	0.123	0.173
	p97.5	0.057	−0.005	1.237	0.038	0.056	1.069	0.045	0.039	1.181	0.661
60s	mean	0.032	−0.034	0.485	0.038	0.034	0.646	0.025	0.023	0.505	0.376
	p2.5	0.021	−0.057	0.223	0.015	0.013	0.207	0.017	0.011	0.154	0.183
	p97.5	0.057	−0.015	0.758	0.074	0.056	1.237	0.048	0.039	1.293	0.697
70s	mean	0.053	−0.055	0.988	0.035	0.055	0.805	0.032	0.033	1.108	0.769
	p2.5	0.023	−0.089	0.465	0.019	0.019	0.487	0.024	0.015	0.499	0.565
	p97.5	0.089	−0.035	1.939	0.055	0.115	1.201	0.049	0.054	2.226	1.073

3.2. Optopad-CSF

The mean contrast sensitivity values for each age decade and for the three evaluated channels—achromatic (CSF-A, 325 patients), red–green (CSF-T, 225 patients), and blue–yellow (CSF-D, 225 patients)—are presented in Figure 4a–c.



(**a**) (**b**) (**c**)

Figure 4. Mean contrast sensitivity functions for each age group: (**a**) achromatic gratings (CSF-A), (**b**) chromatic red–green gratings (CSF-T) and (**c**) chromatic blue–yellow gratings (CSF-D).

As expected, in the achromatic sensitivity function (CSF-A), all age groups exhibited a band-pass-type curve, with a peak between 4 and 8 cpd that shifts towards lower frequencies with age. The highest sensitivities were observed in the first two decades (10 to 29 years), depending on spatial frequency, and progressively declined with age up to the 60s decade. When the average sensitivity of each decade was compared with that

of the preceding decade, the largest age-related declines were observed at medium and high spatial frequencies, with the most pronounced reductions occurring between the last two decades.

The chromatic sensitivity function also exhibited the expected low-pass–type curve for all age groups, with higher sensitivities in the first three decades. The red–green mechanism (T) showed minimal changes in mean sensitivity with age, exhibiting a slight decrease during the 30s while maintaining the overall trend of age-related decline across the remaining decades. Decade-to-decade variations in sensitivity were very small, occurring mainly at low spatial frequencies during the first two decades and at high spatial frequencies during the last two decades. For the blue–yellow mechanism (CSF-D), sensitivity generally decreased with age up to the sixth decade of life. The most pronounced decade-related sensitivity losses were observed at high spatial frequencies, beginning in the third decade.

Figure 5 shows the contrast sensitivity values corresponding to the mean value (black line) and the normal range limited by the 2.5th (orange line) and 97.5th (blue line) percentiles for each age group (rows) and for each of the three visual mechanisms evaluated: CSF-A, CSF-T and CSF-D (columns).

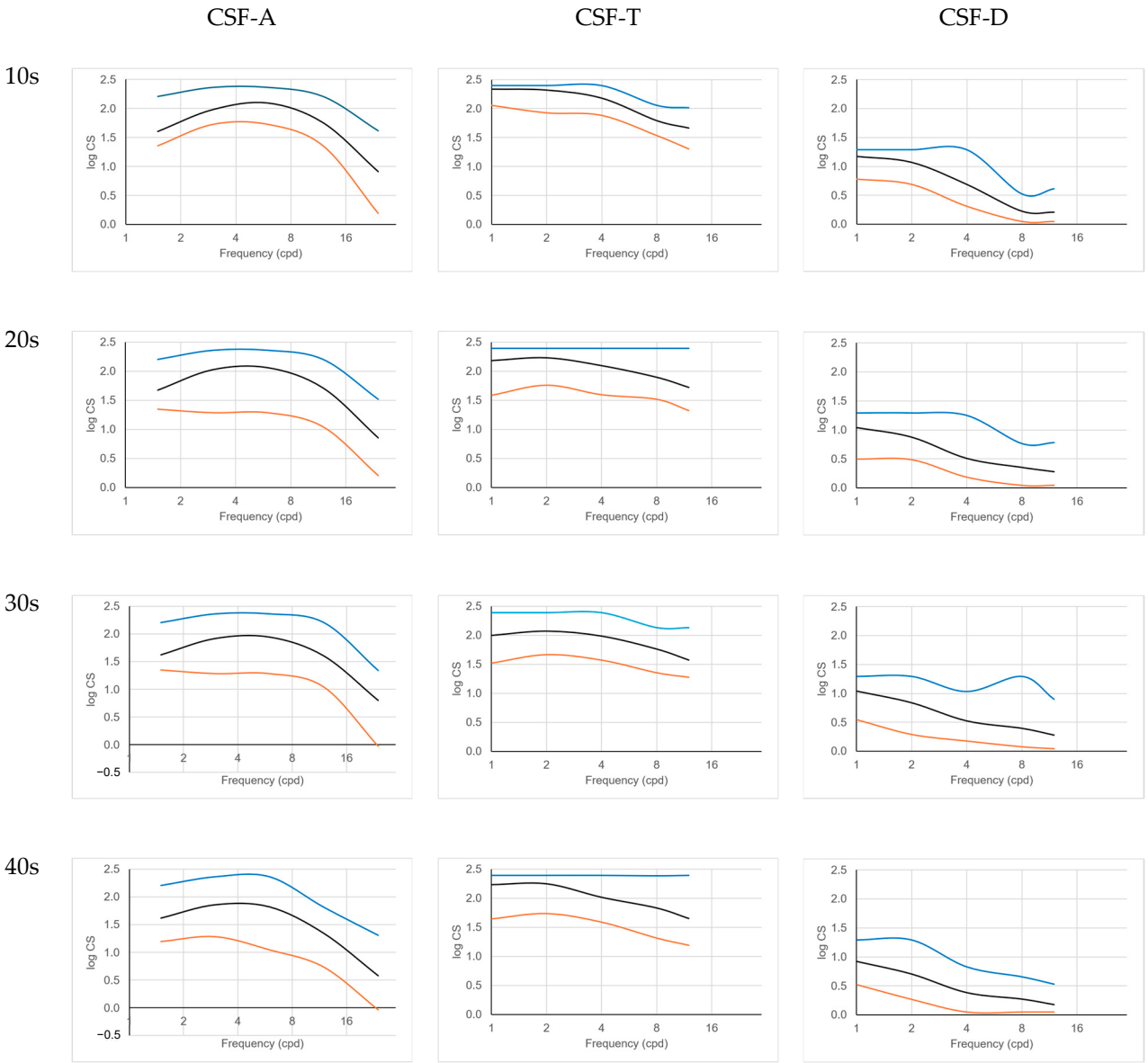


Figure 5. *Cont.*

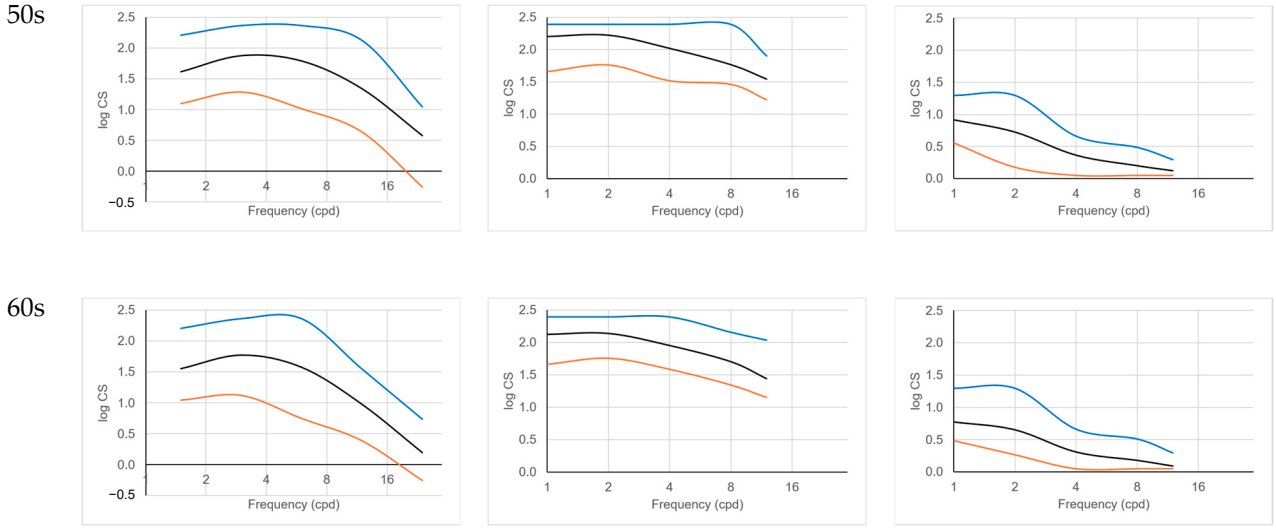


Figure 5. Mean contrast sensitivity functions (black line) for each age group (rows) and for achromatic (CSF-A), red–green (CSF-T), and blue–yellow (CSF-D) gratings (columns). The reference range is defined by the orange and blue lines, corresponding to the 2.5th and 97.5th percentiles, respectively.

Table 4 presents the numerical results obtained from the experimental measurements: mean contrast sensitivity (log) and 2.5th and 95th percentiles for each decade. The data are presented separately for each visual mechanism (A: achromatic; T: red–green; D: blue–yellow) and for each spatial frequency (A: 1.5, 3, 6, 12, and 24 cpd; T and D: 1, 2, 4, 8, and 12 cpd).

Table 4. Mean contrast sensitivity values (log) for each frequency of the three mechanisms (A, T and D), grouped by age decade. The limits of the normal range are reported as the 2.5th and 97.5th percentiles. An asterisk (*) indicates statistically significant differences between age groups with the Kruskal–Wallis test.

Age		A-1.5	A-3 *	A-6 *	A-12 *	A-24 *	T-1 *	T-2 *	T-4 *	T-8 *	T-12 *	D-1	D-2 *	D-4 *	D-8 *	D-12 *
10s	mean	1.605	1.982	2.096	1.756	0.912	2.332	2.316	2.178	1.790	1.661	1.169	1.066	0.686	0.224	0.206
	p2.5	1.353	1.723	1.723	1.353	0.190	2.055	1.926	1.883	1.536	1.305	0.783	0.691	0.311	0.047	0.047
	p97.5	2.207	2.364	2.364	2.207	1.615	2.393	2.393	2.393	2.055	2.012	1.292	1.292	1.292	0.528	0.617
20s	mean	1.674	2.025	2.058	1.711	0.856	2.183	2.231	2.096	1.897	1.723	1.042	0.876	0.508	0.352	0.277
	p2.5	1.348	1.287	1.287	1.045	0.208	1.586	1.759	1.596	1.518	1.325	0.496	0.486	0.187	0.047	0.047
	p97.5	2.207	2.364	2.364	2.207	1.523	2.393	2.393	2.393	2.393	2.393	1.292	1.292	1.250	0.768	0.783
30s	mean	1.622	1.917	1.943	1.603	0.800	1.998	2.072	1.985	1.761	1.571	1.040	0.838	0.525	0.397	0.280
	p2.5	1.353	1.287	1.287	1.045	−0.024	1.520	1.665	1.571	1.357	1.279	0.547	0.292	0.179	0.081	0.047
	p97.5	2.207	2.364	2.364	2.207	1.346	2.393	2.393	2.393	2.132	2.131	1.292	1.292	1.031	1.292	0.898
40s	mean	1.619	1.859	1.821	1.344	0.582	2.236	2.252	2.018	1.833	1.651	0.924	0.704	0.382	0.270	0.174
	p2.5	1.199	1.287	1.049	0.738	−0.032	1.643	1.734	1.587	1.316	1.192	0.525	0.268	0.047	0.047	0.047
	p97.5	2.207	2.364	2.364	1.815	1.311	2.393	2.393	2.393	2.392	2.393	1.292	1.292	0.830	0.660	0.534
50s	mean	1.614	1.875	1.789	1.340	0.580	2.200	2.221	2.017	1.766	1.544	0.914	0.724	0.364	0.201	0.122
	p2.5	1.099	1.287	1.016	0.638	−0.256	1.657	1.760	1.514	1.458	1.219	0.550	0.173	0.047	0.047	0.047
	p97.5	2.207	2.364	2.364	2.124	1.046	2.393	2.393	2.393	2.393	1.901	1.292	1.292	0.660	0.486	0.296
60s	mean	1.551	1.770	1.573	0.974	0.191	2.125	2.140	1.952	1.702	1.439	0.770	0.649	0.307	0.178	0.090
	p2.5	1.045	1.123	0.749	0.387	−0.256	1.665	1.760	1.587	1.342	1.149	0.486	0.266	0.047	0.047	0.047
	p97.5	2.207	2.364	2.364	1.550	0.738	2.393	2.393	2.393	2.158	2.036	1.292	1.292	0.660	0.510	0.295

The correlations with age showed significant dependence for all spatial frequencies except 1.5 cpd in the CSF-A, for the low spatial frequencies in the CSF-T (1, 2, and 4 cpd), and for the high spatial frequencies in the CSF-D (8 and 12 cpd). The results analyzed using the Kruskal–Wallis test revealed statistically significant differences, marked with an asterisk (*), among age groups for almost all evaluated parameters, including both spatial frequencies and channels, ($p < 0.04$), with only two exceptions. In the achromatic mechanism (CSF-A), the distributions across age groups did not differ significantly at the spatial frequency of 1.5 cpd ($p = 0.264$). For the chromatic mechanisms, no significant

differences among age-group distributions were observed only at the spatial frequency of 1 cpd (p = 0.628) in the blue–yellow channel (CSF-D).

The Mann–Whitney analysis with Bonferroni correction for pairwise comparisons between age decades, again, did not reveal consistent patterns across all mechanisms (achromatic, red–green, and blue–yellow). Statistically significant results can be found in Tables S5–S7. For the achromatic CSF, significant differences were observed at medium and high spatial frequencies between participants younger than 40 years and those older than 40 years. For CSF-T, significant differences at low spatial frequencies appeared to distinguish the 20–29-year age group from the other age groups. In contrast, for CSF-D, the most notable differences were observed at high spatial frequencies between participants younger than 40 years and those older than 40 years.

There is a weak but significant positive correlation between the sensitivities of the red–green and blue–yellow mechanisms (Table S8a,b) that cannot be accounted for just by the correlation between sensitivity and age (Table S10a,b). The sensitivity of the achromatic mechanism also shows a weak significant positive correlation with the two chromatic mechanisms (Tables S9 and S11).

4. Discussion

The stimuli in the PDT plates are defined along the cone-isolating directions in cone space, while in RGBY and CSF-A, CSF-T and CSF-D, we are exploring the cardinal directions of the Derrington–Krauskopf–Lennie colour space [14], which represent directions isolating generic achromatic, red–green and blue–yellow mechanisms in the lateral geniculate nucleus. To avoid intrusions of the achromatic mechanisms in the responses of the chromatic mechanisms, achromatic noise is used. This paper deals with the effect of age on these generic cardinal mechanisms. The age-related pattern of color discrimination thresholds measured with Optopad-Color revealed that participants in their twenties performed similarly to those aged 30–39 years, albeit with slightly higher thresholds and greater interindividual variability. Beyond the age of 40, color discrimination gradually deteriorated, with thresholds increasing progressively across successive age groups and being more pronounced along the blue–yellow axis. Several authors have similarly reported optimal performance in individuals in their twenties [15–19], although color discrimination appears to be worse at younger ages [15–17]. In contrast, other studies have reported more heterogeneous age-related trends, with optimal color discrimination observed between 20 and 50 years of age, whereas older adults exhibited a substantial increase in discrimination errors and a higher degree of interindividual variability [19–21]. Numerous studies have reported increasing Farnsworth–Munsell 100-Hue error scores with advancing age, particularly along the blue–yellow axis, a finding that is consistent with our results [15–18]. Also, the findings reported by Barbur and Rodríguez-Carmona (using CAD test [20]) and by Paramei and Oakley (using CCT [21]) consistently show that color discrimination declines with increasing age, again, with the strongest effects observed along the blue–yellow axis. However, the interpretation of the underlying mechanisms differs between the studies. Barbur and Rodríguez-Carmona argue that a substantial proportion of age-related color vision losses can be attributed to pre-receptoral optical changes, such as lens yellowing and reduced transmission of short-wavelength light, suggesting that neural color-processing pathways remain relatively resilient during healthy aging. In contrast, Paramei and Oakley propose a broader explanation, attributing the decline in chromatic discrimination to the combined effects of optical, retinal, and neural aging. While optical factors undoubtedly contribute to the deterioration of color vision in older adults, the increased variability observed among elderly participants suggests that neural and retinal changes may also

play a meaningful role. Therefore, age-related color vision decline is likely multifactorial rather than solely optical in origin.

Focusing on the blue–yellow mechanism from Optopad-Color plates, the absence of age-related differences in the T2 row is particularly noteworthy, given that the stimuli presented in both tritan rows (T1 and T2) are identical, unlike those in the protan and deutan rows. This finding may be attributable either to context effects when the plates are viewed as a whole, since the color of the D row just above is different in plates PDT1 and PDT2, or to a fatigue effect resulting from task repetition. Likewise, no significant age-related differences were found along the blue–yellow axis of the RGBY plate.

The age-related pattern of contrast discrimination thresholds measured with Optopad-CSF showed that participants in the first three decades of life displayed the highest sensitivity across spatial frequencies, followed by a gradual decline with age, extending into the 70s. In the literature, studies evaluating contrast sensitivity using achromatic stimuli (non-gratings) or the contrast sensitivity function (CSF) with achromatic sinusoidal gratings (see [22–24], for instance) can be found. In all cases, the observed behavior consistently shows an age-related decline in contrast sensitivity. The deterioration typically appears first at high spatial frequencies and subsequently affects a broader range of frequencies, which is consistent with our results.

Regarding the variation in chromatic contrast sensitivity with age, measurements with chromatic gratings are scarce, in part due to the difficulty of silencing the contributions of the achromatic mechanisms and avoiding chromatic aberration effects. The literature is often based on studies that do not evaluate chromatic sensitivity as a function of spatial frequency using chromatic gratings. It has been found that age-related declines in chromatic sensitivity are particularly pronounced in short-wavelength-sensitive (S-cone) pathways, along with a relative preservation of L–M mechanisms, which is consistent with our findings. Evidence from psychophysical studies indicates that these losses cannot be fully explained by age-related optical changes, suggesting additional neural deterioration within post-receptoral chromatic mechanisms [25–27]. Hardy et al. [28] found elevated chromatic contrast thresholds in older observers across all tested spatial frequencies (0.5–4 cpd) under conditions compensating for chromatic aberration and the influence of prereceptoral media, but similar results were found under normal viewing conditions, with individually determined equiluminance settings [29]. Although sensitivity decreased with increasing spatial frequency in both young and older participants, the age-related loss was largely independent of spatial frequency, suggesting a generalized decline in chromatic contrast sensitivity rather than a selective deficit at higher spatial frequencies. This behavior would be independent of the average luminance of the stimuli [30]. Page & Crognale [31], using 1 cpd stimuli, found that contrast thresholds for chromatic pathways increase with age and provided psychophysical and electrophysiological evidence that age-related losses in chromatic vision involve neural changes beyond the optics of the aging eye. The findings reported in these studies, despite being based on a very limited range of spatial frequencies, are consistent with our results within those same spatial frequencies. It should be noted that our study covers a much wider range, extending up to 12 cpd.

The red–green and blue–yellow mechanisms in the human visual system are supported by two separate neural pathways, the parvo and koniocellular pathways, which are assumed to be independent at threshold. However, evidence of some correlation between the responses of both mechanisms has been found. Kim and coworkers found a correlation between the parameters defining the curve fitting the CSF of normal subjects measured with the qCSF method [32]. Our data shows weak but statistically significant Spearman correlations between the sensitivities of both mechanisms, that cannot be accounted for by the dependence between sensitivity and age. However, if we linearly interpolate the

achromatic CSF to obtain sensitivity values for the frequencies measured in the chromatic CSFs and compute the Spearman correlation coefficients, the values obtained also reveal weak to moderate correlation between the sensitivities of the achromatic and chromatic mechanisms (although, again, not for the AUC), as can be seen in the tables below. Correlations are slightly stronger for lower frequencies. Kim and co-workers found a weak correlation between chromatic and achromatic mechanisms that could be traced to the presence of an outlier. This is not the case here.

This study provides clinicians with an evidentiary basis for the application of this innovative test in clinical practice. It should be noted that establishing a physiological reference range for any visual function test is essential, as such ranges are a prerequisite for its use in clinical decision-making. Previous preliminary studies using the evaluated color test have demonstrated its ability to detect changes in achromatic and chromatic contrast sensitivity, both when fitting multifocal contact lenses [13] and in cases of visual function deterioration associated with COVID-19 [12]. The definition of a reference range in this study facilitates clinicians' task of determining whether a specific change may be pathological, and even enables the identification of diagnostic patterns in specific visual or neurological conditions. Future studies should be conducted in pathological conditions confirming the clinical usefulness of the normality patterns obtained in the present series. The strengths of this study include the use of a large sample measured under standardized conditions, using digital devices that had been previously colorimetrically characterized. As with any plate test design, with a limited number of contrast steps, ceiling and flooring effects are possible and we still need more evidence with pathological subjects to prove the validity of the test. We consider the database presented in this paper to constitute a reference database derived from a healthy population. Its clinical utility and diagnostic performance remain to be established through prospective studies comparing the proposed reference limits with measurements obtained from well-characterized patient populations. In fact, a potential limitation is the absence of pathological groups, which would allow for confirmation of the validity of the reference ranges defined; however, this could be considered an objective for future studies. Additionally, pediatric populations and individuals over 70 or 80 years of age were not included. Addressing this gap will be necessary in future research in order to extend the normality ranges to these population groups.

Ultimately, the suitability of the Optopad test should be considered in relation to the specific objectives of the assessment, the characteristics of the population being tested, and the clinical or research setting in which it is used. The combination of its advantages and limitations may make it particularly useful in situations where portability, affordability, standardized color reproduction, and access to chromatic contrast sensitivity measurements are important considerations. At the same time, users should take into account the limitations inherent to display-based testing when interpreting the results, particularly when assessing pathological populations or when high precision and reproducibility are required. Thus, the applicability of the test should be evaluated according to the specific requirements of each clinical or research context.

5. Conclusions

The literature suggests that age is an important factor influencing color and contrast discrimination performance. Therefore, the availability of age-appropriate normative datasets is fundamental for separating healthy age-related changes from visual deficits associated with ocular or neurological disorders.

The results obtained with the Optopad test, including color discrimination thresholds and contrast sensitivity function measurements, in the normal population allow us to define

reference intervals with potential diagnostic applications, and information about the mean values of the contrast sensitivity functions for the different age ranges can be used, together with a spatio-chromatic model, to predict age-related changes in visual perception.

With the Optopad-Color test, the PDT1 plate provides the most robust basis for normal reference values. Combined with the RGBY plate, which complements PDT1 by assessing acquired color vision deficiencies, it may offer a more comprehensive evaluation of chromatic vision. For Optopad-CSF, the achromatic, red–green and blue–yellow mechanisms showed the expected age-related decline in contrast sensitivity from the 30s onward.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/technologies14100621/s1, Table S1: Maximum and minimum cone contrast thresholds in the different lines and plates in Optopad Color; Table S2: Maximum generable cone contrast and minimum log sensitivity in Optopad CSF; Table S3: Minimum cone contrast and maximum log sensitivity per frequency and mechanism in Optopad-CSF; Table S4: Mann-Whitney U test with Bonferroni correction for Optopad-Color; Table S5: Mann-Whitney U test with Bonferroni correction for Optopad-CSF-A; Table S6: Mann-Whitney U test with Bonferroni correction for Optopad-CSF-T; Table S7: Mann-Whitney U test with Bonferroni correction for Optopad-CSF-D; Table S8a: Spearman correlation coefficients between the red-green and blue-yellow mechanisms; Table S8b: *p*-values for the Spearman coefficients in Table S8a; Table S9a: Spearman correlation coefficients between the achromatic and the two chromatic mechanisms; Table S9b: *p*-values for the Spearman coefficients in Table S9a; Table S10a: Partial correlation Spearman coefficients between red-green and blue yellow mechanisms, correcting by age; Table S10b: *p*-values for Table S10a; Table S11a: Partial correlation Spearman coefficients between the achromatic and chromatic mechanisms, correcting by age; Table S11b: *p*-values for correlation coefficients in Table S11a.

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Abbreviations

The following abbreviations are used in this manuscript:

CSF	Contrast Sensitivity Function
CSF-A	Achromatic Contrast Sensitivity Function
CSF-T	Chromatic Contrast Sensitivity Function, for red–green stimuli
CSF-D	Chromatic Contrast Sensitivity Function for blue–yellow stimuli
PDT	Protan–Deutan–Tritan
RGBY	Cardinal direction: Red, Green, Blue, Yellow

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