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Evaluation of relationship between color discrimination ability, stereoscopic acuity and contrast sensitivity in healthy individuals

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Abstract

To evaluate color discrimination ability (CDA), stereoscopic acuity (SA), and contrast sensitivity (CS) by considering age factor and educational level in healthy individuals. This study was design as a prospective study.

The study included 43 binocular healthy individuals (31 males; mean age, 25.79±6.83 years) without a color vision deficiency who were aged between ≥18 years and ≤40 years and had an educational level of secondary education or higher. The following tests/system were used: the Farnsworth Munsell 100 (FM100) hue test for CDA; the TNO and Titmus tests for SA; the automatized ClearChart® 2 Digital Acuity System for CS. Total error score (TES), blue-yellow (b-y) local error score (LES) and red-green (r-g) LES of the FM100 hue test were 25.40±20.89, 14.26±12.09 and 10.53±10.13, respectively. Stereo test scores were 52.33±43.35 arcsec and 43.02±9.14 arcsec for the TNO and Titmus tests, respectively. The logCS score was 2.5±0 at low- and mid-spatial frequencies and 3.84±1.92 at high-spatial frequency. In the correlation analyses, TNO test score was positively correlated with TES, b-y LES, and r-g LES ($r=0.339$, $p=0.021$; $r=0.309$, $p=0.036$; and $r=0.308$, $p=0.037$, respectively). The Titmus test score was positively correlated with TES, b-y LES, and r-g LES ($r=0.575$, $p<0.001$; $r=0.539$, $p<0.001$; and $r=0.504$ $p<0.001$, respectively).

According to the study results, SA increased with increasing CDA and that b-y and r-g color zones contributed to this increment in the healthy adult group. Future large-scale studies would further illuminate both the topic and the underlying neurophysiological mechanisms.

Keywords: Color vision, stereoscopic vision, contrast sensitivity, Farnsworth Munsell 100 hue test, TNO test, Titmus test

Introduction

Color vision, which is provided by combined effects of neurological activities at various levels in the retina and cortex of the visual system, begins with comparisons of different photon absorptions of three different classes of cone photoreceptors with different spectral sensitivity in the retina (cones sensitive to long, middle or short wavelengths) (Trichromatic theory) and continues with comparisons of different spectral information received by the retinal ganglion cells from the cones in three different opponent systems (red-green [r-g], blue-yellow [b-y] and black-white receptor complexes) (Opponent process theory) [1-3]. The information from the opponent system is processed in the lateral geniculate nucleus of the thalamus and then transferred to the primary visual cortex (V1) [4,5]. Functional magnetic resonance imaging studies have reported that color brightness and color contrast are processed also in the V1 in addition to the extrastriate cortex [6].

Depth perception is an ability that results from stereopsis (or binocular parallax) produced by an interocular distance. In the development process of depth perception from stereopsis, stereoscopic neurons in the striate and prestriate cortexes match the features obtained from random point patterns in the left image with the corresponding features in the right image [7,8]. These stereoscopic neurons have been reported to perceive the link between matched retinal images, identify differences in binocular inequality, and compensate physiological inequalities [9]. The objects are perceived as a single three-dimensional (3D) visual image by evaluating information on color, shadow, relative movement and depth perception altogether in the visual cortex [10,11].

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It is thought that for the occurrence of depth perception, the brain can integrate all information, also including color and perspective viewpoint, for spreading better assumptions to higher cortical areas beginning from a low-level disparity draft [8]. In this regard, in our studies, we focused on the relationship between color discrimination ability (CDA) and stereoscopic acuity (SA). In our previous study, in which the relation of CDA with SA was investigated by comparing SA of individuals with red-green (r-g) congenital color vision deficiency (CCVD) with those of healthy individuals, the SA of CCVD patients was lower according to both Titmus and TNO stereo tests [12]. In the healthy group, SA determined by the TNO test showed a positive correlation with overall CDA and with CDA in the b-y zone, which were determined by the Farnsworth Munsell 100 (FM100) hue test. These outcomes observed in the healthy group were striking; thus, for further clarifying the issue, we planned to perform another study in healthy individuals consisting of new subjects also considering that the results of FM100 hue test and stereo tests are affected by age and educational level [13-16]. Accordingly, this study aimed to evaluate CDA, SA, and contrast sensitivity (CS) in a healthy group of males and females within an age range of ≥18 years to ≤40 years and having an educational level of secondary education or higher.

Materials and Methods

Subjects

This prospective study was conducted between November 2019 and March 2020 in the University of Health Sciences Antalya Training and Research Hospital and included healthy binocular male and female individuals aged between ≥18 years and ≤40 years who had an educational level of secondary education or higher and had a visual acuity of 20/20 (with or without correction) [17]. This healthy group were formed from hospital staff having secondary education, university students (from Biology Departments, Nutrition and Dietetics Departments, and Vocational School of Health Services) and healthcare professionals (mostly physicians) having university education. Individuals with CCVD, individuals without stereopsis, and individuals with an ocular disease (strabismus, amblyopia, nystagmus, history of ocular surgery, and retinal pathology) or a systemic disease (diabetes mellitus, hypertension) that is likely to influence vision tests, and pregnant women were excluded. All individuals participated were Caucasian. The study was approved by the Clinical Research Ethics Committee of the University of Health Sciences Antalya Training and Research Hospital (approval number: 23/5; date: 24/10/2019) and conducted based on the Helsinki Declaration. All individuals provided their informed consents.

Procedures

All participants underwent a detailed ophthalmologic examination including visual acuity test and slit lamp biomicroscopy. Presence of r/g CCVD was determined by the Ishihara pseudo-isochromatic plate test (IPPT) [18]. All tests were performed with both eyes open.

Assessment of Color Discrimination Ability

The FM100 hue test (Farnsworth 100 Hue Test, Richmond Products Inc. P/N 4436; Albuquerque, NM), which is based on the principle of arranging 84 caps in hue order to form color circle, was used to assess CDA. Total error scores (TES), r-g local error scores (LES), and b-y LES are calculated according to the arrangements [19]. A lower error score indicates a better CDA.

Assessment of Stereoscopic Acuity

Global stereopsis and local stereopsis were measured using the TNO stereo test (TNO test for stereoscopic vision; Schairer Frank Ophthal-Technik, Stuttgart, Germany) and the Titmus stereo test (Stereo Optical Company, Inc., Chicago, IL, USA), respectively. SA can be measured from 480 to 15 arcsec by the TNO stereo test and in a range of 800 to 40 arcsec by the Titmus stereo test [20,21]. For both tests, a decrease in the test scores indicate an increase in the SA.

Assessment of Contrast Sensitivity

Contrast sensitivity was tested using the automatized ClearChart® 2 Digital Acuity System (Reichert Technologies®, NY, USA). Logarithmic CS was measured at a standard light (80 cd/m²), standard distance (6 m), and low- (1.5 cycles per degree [cpd]), mid- (6 cpd), and high- (18 cpd) spatial frequencies. The results were recorded as the logarithm of CS (logCS).

Statistical analysis

Data were analysed using the IBM SPSS Statistics for Windows, Version 25.0 (IBM Corp, Armonk, NY, USA). Normality and variance homogeneity of the variables were tested using the Shapiro-Wilk and Levene tests. Variables were expressed as mean, standard deviation, percentage, and frequency. Groups were compared using the Student's t- test for parametric variables and using the Mann Whitney-U test for non-parametric variables. The relationship between two variables was analysed with the Pearson's and Spearman's correlation coefficients for continuous and nonparametric variables, respectively. A p value of <0.05 was considered statistically significant.

Results

Among 46 volunteers, two were excluded due to having deutan CCVD according to the IPPT and one was excluded due to being unable to perceive the depth according to the TNO and Titmus tests. Thus, 43 healthy and binocular individuals with a mean age of 25.79±6.83 years (median, 23 years; range, 19-40 years) were included. Of them, 31 (72.1%) were male (mean age, 27.74±7.09 years; median, 27 years [range, 19-40 years]) and 12 (27.9%) were female (mean age, 20.75±1.6 years, median, 20 years [range, 19-24 years]).

The FM100 hue test error scores (TES, b-y LES, and r-g LES), stereo test scores (TNO test and Titmus test scores), and logCS score in all subjects and according to sex are presented in Tables 1 and 2, respectively. No significant differences were determined between males and females regarding FM100 hue test scores, stereo test scores and logCS values ($p>0.05$ for all).

The correlation analysis (Table 3) revealed a positive correlation of the TNO test score with TES, b-y LES, and r-g LES of the FM100 hue test ($r=0.339$, $p=0.021$; $r=0.309$ $p=0.036$; and $r=0.308$, $p=0.037$, respectively). The Titmus test score was also significantly and positively correlated with TES, b-y LES, and r-g

LES of the FM100 hue test (r=0.575, p<0.001; r=0.539, p<0.001; and r=0.504, p<0.001, respectively). CS measurements of all study subjects were equal at the low- and mid-spatial frequencies (2,50±0.00); however, individual differences appeared at the high-spatial frequency (3.84±1.92). There was no correlation between the logCS values at high spatial frequency and scores of the stereo tests and the FM100 hue test (p >0.05).

Table 1. Farnsworth Munsell hue test error scores, stereo test (TNO and Titmus tests) scores, and contrast sensitivity in the study subjects

	N	Mean±SD	Minimum Maximum
FM100 hue test error scores			
TES	43	25.40±20.89	0.00-84.00
LES			
b-y LES	43	14.26±12.09	0.00-46.00
r-g LES	43	10.53±10.13	0.00-40.00
Stereo test scores, arcsec			
TNO test	43	52.33±43.35	15.00-240.00
Titmus test	43	43.02±9.14	40.00-80.00
Contrast sensitivity, logCS			
Low-spatial frequency (1.5 cpd)	34	2.50±0.00	2.50-2.50
Mid-spatial frequency (6 cpd)	34	2.50±0.00	2.50-2.50
High-spatial frequency (18 cpd)	37	3.84±1.92	2.50-12.50

SD, standard deviationFM100 hue test, Farnsworth Munsell 100 hue test; TES, total error score; LES, local error score; b-y, blue-yellow; r-g, red-green, logCS, logarithm of contrast sensitivity; cpd, cycles per degree

Table 2. Comparison of Farnsworth Munsell 100 hue test error scores, stereo test scores and (TNO and Titmus tests) scores and contrast sensitivity according to sex

	N	Males	N	Females	p*
FM 100 hue test error scores					
TES, Mean±SD	31	25.16±19.38	12	26±25.33	0.91
LES, Mean±SD					
b-y LES	31	14.45±12.42	12	13.75±11.7	0.87
r-g LES	31	10.23±8.7	12	11.33±13.58	0.80
Stereo test scores, arcsec					
TNO test, Mean±SD	31	52.26±45.97	12	52.5±37.57	0.99
Titmus test, Mean±SD	31	42.26±8.05	12	45±11.68	0.38
Contrast sensitivity, logCS					
Low-spatial frequency (1.5 cpd)	22	2.5±0.0	12	2.5±0.0	
Mid-spatial frequency (6 cpd)	22	2.5±0.0	12	2.5±0.0	
High-spatial frequency (18 cpd), Mean±SD	25	4.05±2.21	12	3.33±0.8	0.33

SD, standard deviation; FM100 hue test, Farnsworth Munsell 100 hue test; TES, total error score; LES, local error score; b-y, blue-yellow; r-g, red-green, logCS, logarithm of contrast sensitivity; cpd, cycles per degree
*Significance level was set at p<0.05

Table 3. Results of the correlation analyses performed for the relationship between color discrimination ability, stereoscopic acuity and contrast sensitivity

	TES	b-y LES	r-g LES	TNO test score	Titmus test score	Contrast Sensitivity (logCS)[1]
FM100 hue test scores						
TES						
r	-	0.922	0.899	0.339	0.575	-0.082
p	-	<0.001**	<0.001**	0.021*	<0.001**	0.632
b-y LES						
r	0.922	-	0.661	0.309	0.539	-0.088
p	<0.001**	-	<0.001**	0.036*	<0.001**	0.603
r-g LES						
r	0.899	0.661	-	0.308	0.504	-0.071
p	<0.001**	<0.001**	-	0.037*	<0.001**	0.674
Stereo test scores						
TNO						
r	0.339	0.309	0.308	-	0.656	0.132
p	0.021*	0.036*	0.037*	-	<0.001**	0.438
Titmus						
r	0.575	0.539	0.504	0.656	-	-0.0107
p	<0.001**	<0.001**	<0.001**	<0.001**	-	0.950
Contrast Sensitivity (logCS)[1]						
r	-0.082	-0.088	-0.071	0.132	-0.0107	-
p	0.632	0.603	0.674	0.438	0.950	-

* indicates significance at p<0.05 and ** indicates significance at p<0.01
1 at high-spatial frequency (18 cycles per degree [cpd])
TES, total error score; LES, local error score; b-y, blue-yellow; r-g, red-green, logCS, logarithm of contrast sensitivity; FM100 hue test, Farnsworth Munsell 100 hue test

Discussion

The results of this study, which was conducted in a healthy group of both sexes who were within an age range of 18-40 years and had an educational level of secondary education or higher to investigate CDA, SA and CS considering physiological and acquired differences (age, sex, educational level), revealed that SA increased with increasing CDA at both b-y and r-g color zones. CS function of the all subjects were highest level at low- and mid-spatial frequency.

In the studies on physiological mechanisms, it is important to pay attention to participant-related differences interacting with vision test results. In the present study, personal factors were optimized as much as possible and standard conditions were provided for the tests by means of excluding pathological, physiological and acquired factors known to interact with visual functions. In earlier studies, age and education have attracted attention as the factors affecting test scores in healthy subjects [14,22-25]. Studies

reporting FM100 hue test error scores according to age groups have suggested that TES yields a U-shaped curve according to age [16,26]. This graphic indicates that the TES of the FM100 hue test increases in children and in the advanced-age group and that the lowest error scores are seen in the 2nd and 3rd decades. With regard to the relationship between color vision and age according to color zones, more remarkable decreases have been reported in the b-y color zone with aging [27-32]. Based on these data, age factor was taken into account in the present study and thereby the study was conducted in individuals within an age range of ≥18 years to ≤40 years (mean age, 25.79±6.83 years).

Educational level was considered an acquired difference in the present study. Higher FM100 hue test error scores have been reported in individuals with low educational level [15]. Taking this information into account, individuals having a certain educational level (secondary education or higher) were included; that is, those with low education level were excluded. Accordingly, the observer was sure that the subjects understood the tests correctly.

The healthy group in our previous study was not inquired regarding their educational level and thus included subjects having different educational levels [12]. In the present study, however, we think that we further clarified the question whether CDA has an effect on SA in healthy subjects by eliminating increasing effects of advanced age and low educational level on test scores (by excluding individuals ≥40 years and with low educational level). Accordingly, the results of the present study suggested that SA increased with increasing CDA in healthy individuals and this correlation was determined both in the r-g and b-y color zones.

In the present study, the relationship between CS and CDA was investigated at low-, mid-, and high-spatial frequencies. To our knowledge, studies investigating the effects of contrast vision on the results of color vision tests and stereo tests in healthy individuals are limited in number. Using a computer modelling for low CS, Annadanam et al. investigated the effect of low CS on color vision tests (the IPPT, the Hardy-Rand-Ritter (HRR) test, and the Farnsworth D-15 test) in 11 subjects (mean age, 28.6±14.7 [range, 22-72 years]) [33]. They reported that the HRR test scores were significantly affected by the loss of CS but that the Farnsworth D-15 test scores showed no differences at any spatial frequency (high, middle, low) [33]. In a study performed by Lipsky et al. in 20 subjects (mean age, 33±7 years [range, 20-53 years]), almost all color vision tests (HRR test, IPPT, and Farnsworth D-15 test) yielded similar results in those with higher CS but error scores of the HRR test and Farnsworth D-15 test increased at lower CS [34]. Owsley et al. measured contrast thresholds for gratings of 0.5-22.8 cycles/degree and for real-world targets in individuals aged 20-77 years; based on the results of multiple regression techniques, they reported age and mid- and low-spatial frequencies as the threshold determinants for real-world targets and that spatial CS could be effective in predicting how well the targets in real life would be seen efficiently [35]. In the present study, all study subjects showed equal logCS values at the low- and mid-spatial frequencies; however, individual differences appeared at the high-spatial frequency. It was thought that the CS function being highest level at the low- and mid-spatial frequencies in all study subjects strengthened the relationship determined between CDA and SA. Nevertheless, further large-scale studies are required.

In the present study, the presence of a relationship between CS, CDA, and SA in healthy subjects was investigated by evaluating the relationship between the related test scores. On the other hand, presence of a functional hierarchy in the visual system has been investigating with different methodologies [36-40]. According to the results of the study by Peirce et al., there might be binocular neurons specifying the surface color and, at least, it is certain that cortical cells with maximum response to the isoluminant stimulus are frequently driven by both eyes [39]. Nasr et al. reported the presence of interdigitated selective columns of color and disparity in the V2 and V3 areas of the visual cortex using high-resolution functional magnetic resonance imaging [40].

Conclusion

To our knowledge, the present study is the first to investigate the relationship between CDA, SA, and CS in healthy individuals taking age and educational level into account. According to the study results, SA increased with increasing CDA and that both color zones (b-y and r-g color zones) contributed to this increment in the healthy adult group. Future large-scale studies with different and advanced methodology would further illuminate both the topic and the underlying neurophysiological mechanisms.

Conflict of interests
The authors declare that there is no conflict of interest in the study.

Financial Disclosure
The authors declare that they have received no financial support for the study.

Ethical approval
The study was approved by the Clinical Research Ethics Committee of the University of Health Sciences Antalya Training and Research Hospital (approval number: 23/5; date: 24/10/2019) and conducted based on the Helsinki Declaration.

References

1. Conway BR, Chatterjee S, Field GD, et al. Advances in color science: from retina to behavior. J Neurosci. 2010;30:14955–63.
2. Conway BR. Color vision, cones, and color-coding in the cortex. Neuroscientist. 2009;15:274–90.
3. Nathans J. The evolution and physiology of human color vision: insights from molecular genetic studies of visual pigments. Neuron. 1999;24:299–312.
4. Shapley R, Hawken MJ. Color in the cortex: single- and double opponent cells. Vision Res. 2011;13;51:701–17.
5. Mullen KT, Dumoulin SO, Hess RF. Color responses of the human lateral geniculate nucleus: selective amplification of S-cone signals between the lateral geniculate nucleno and primary visual cortex measured with high-field fMRI [published correction appears in Eur J Neurosci. 2008;28:2361]. Eur J Neurosci. 2008;28:1911–23.
6. Pasmanter N, Munakomi S. Physiology, Color Perception. [Updated 2019 Jun 15]. In: StatPearls [Internet], Treasure Island (FL): StatPearls Publishing; 2020. Available from: https://www.ncbi.nlm.nih.gov/books/NBK544355/
7. Read JCA, Cumming BG. Visual perception: neural networks for stereopsis. Curr Biol. 2017;27:R594–6.
8. Martins JA, Rodrigues JMF, du Buf H. Luminance, color, viewpoint and border enhanced disparity energy model. PLoS One. 2015;10:e0129908.
9. Poggio GE. Mechanisms of stereopsis in monkey visual cortex. Cereb Cortex. 1995;5:193–204.
10. Parker AJ, Smith JE, Krug K. Neural architectures for stereo vision. Philos Trans R Soc Lond B Biol Sci 2016;371:20150261.
11. Sung CH, Chuang JZ. The cell biology of vision. J Cell Biol. 2010;190:953–63.

12. Koctekin B, Coban DT, Ozen M, et al. Investigation of relationship between color discrimination ability and stereoscopic acuity using Farnsworth Munsell 100 hue test and stereo tests. Can J Ophthalmol. 2020;55:131–6.

13. Alavi MV. Aging and vision. Adv Exp Med Biol. 2016;854:393–9.

14. Garnham L, Sloper JJ. Effect of age on adult stereoacuity as measured by different types of stereotest. Br J Ophthalmol. 2006;90:91–5.

15. Koctekin B, Gundogan NU, Kocak Altintas AG, et al. Relation of eye dominancy with color vision discrimination performance ability in normal subjects. Int J Ophthalmol. 2013;6:733–8.

16. Kinnear PR, Sahraie A. New Farnsworth-Munsell 100 Hue test norms of normal observers for each year of age 5-22 and for age decades 30-70. Br J Ophthalmol. 2002;86:1408–11.

17. The Council of Higher Education. Study in Turkey. Turkish Higher Education System, http://www.studyinturkey.gov.tr/StudyinTurkey/ShowDetail?rID=Ec/rgHEN8Zg=&&cId=PE4Nr0mMoY4=;2019 access date 26 June 2020

18. Gündogan NÜ, Durmazlar N, Gümüş K, et al. Projected color slides as a method for mass screening test for color vision deficiency (a preliminary study). Int J Neurosci. 2005;115:1105–17.

19. Farnsworth D. The Farnsworth-Munsell 100-hue test for the examination of color discrimination. Revised ed. Baltimore: Munsell Color Company; 1957.

20. Nongpiur ME, Sharma P. Horizontal Lang two-pencil test as a screening test for stereopsis and binocularity. Indian J Ophthalmol. 2010;58:287–90.

21. Nabie R, Andalib D, Khojasteh H, et al. Comparison of the effect of different types of experimental anisometropia on stereopsis measured with titmus, randot and TNO stereotests. J Ophthalmic Vis Res. 2019;14:48–51.

22. Verriest C, Vandevyvere R., Vanderdonck R. Nouvelles recherches se rapportant à l'influence du sexe et de l'âge sur la discrimination chromatique, ainsi qu'à la signification pratique des résultats du test 100 hue de Famsworth-Munsell. Rev Opt Theor Instr. 1962;41:499–509.

23. Owsley C. Vision and aging. Annu Rev Vis Sci. 2016;2:255–71.

24. Plourde M, Corbeil ME, Faubert J. Effect of age and stereopsis on a multiple-object tracking task. PLoS One. 2017;12:e0188373.

25. Ginsburg AP. Contrast sensitivity and functional vision. Int Ophthalmol Clin. 2003;43:5–15.

26. Verriest G, Van Laethem J, Uvijls A. A new assessment of the normal ranges of the Farnsworth-Munsell 100-hue test scores. Am J Ophthalmol. 1982;93:635–42.

27. Shinomori K, Schefrin BE, Werner JS. Age-related changes in wavelength discrimination. J Opt Soc Am A Opt Image Sci Vis. 2001;18:310–8.

28. Knoblauch K, Vital-Durand F, Barbur JL. Variation of chromatic sensitivity across the life span. Vision Res. 2001; 41:23–36.

29. Barbur JL, Konstantakopoulou E. Changes in color vision with decreasing light level: separating the effects of normal aging from disease. J Opt Soc Am A Opt Image Sci Vis. 2012;29:A27–35.

30. Schefrin BE, Shinomori K, Werner JS. Contributions of neural pathways to age-related losses in chromatic discrimination. J Opt Soc Am A Opt Image Sci Vis. 1995;12:1233–41.

31. Werner JS. The verriest lecture: short-wave-sensitive cone pathways across the life span. J Opt Soc Am A Opt Image Sci Vis. 2016; 33:A104–22.

32. Ling BY, Dain SJ. Development of color vision discrimination during childhood: differences between Blue–Yellow, Red–Green, and achromatic thresholds. J Opt Soc Am A Opt Image Sci Vis. 2018;35:B35–42.

33. Annadanam A, Zhao J, Wang J, et al. Effects of contrast sensitivity on color vision testing. Neuroophthalmology 2017;41:182–6.

34. Lipsky L, Qureshi HM, Friling R, et al. The effect of reduced contrast sensitivity on color vision testing. Eye (Lond). 2019;33:1068–72.

35. Owsley C, Sloane ME. Contrast sensitivity, acuity, and the perception of 'real-world' targets. Br J Ophthalmol. 1987;71:791–6.

36. Mountcastle VB. The columnar organization of the neocortex. Brain. 120:701–22.

37. Ts'o DY, Roe AW, Gilbert CD. A hierarchy of the functional organization for color, form and disparity in primate visual area V2. Vision Res. 2001;41:1333–49.

38. den Ouden HE, van Ee R, de Haan EH. Color helps to solve the binocular matching problem. J Physiol. 2005;567:665–71.

39. Peirce JW, Solomon SG, Forte JD, et al. Cortical representation of color is binocular. J Vis 2008;8:1–10.

40. Nasr S, Polimeni JR, Tootell RBH. Interdigitated color- and disparity-selective columns within human visual cortical areas V2 and V3. J Neurosci. 2016;36:1841–57.