· Review Article ·

Factors affecting color vision: a systematic review

Faezeh Fayaz[1], Ebrahim Jafarzadehpur[2], Morad Amir Ahmad[3], Rasoul Amini Vishteh[1], Mohammad Reza Pishnamaz[1], Mohammad Saeid Hoseinzade[1], Leila Mirzaee Saba[4], Mohammad Kamali[5], Abbasali Yekta[6], Mehdi Khabazkhoob[7]

[1]Rehabilitation Research Center, Department of Optometry, School of Rehabilitation Sciences, Iran University of Medical Sciences, Tehran 1545913487, Iran
[2]Noor Ophthalmology Research Center, Noor Eye Hospital, Tehran 1983963113, Iran
[3]Department of Optometry & Physiotherapy, Erbil Technical & Medical Health Collage, Erbil Polytechnic University, Erbil, Kurdistan Region 44001, Iraq
[4]Noor Research Center for Ophthalmic Epidemiology, Noor Eye Hospital, Tehran 1968653111, Iran
[5]Department of Rehabilitation Management, Rehabilitation Research Center, School of Rehabilitation Sciences, Iran University of Medical Sciences, Tehran 1545913487, Iran
[6]Department of Optometry, School of Paramedical Sciences, Mashhad University of Medical Sciences, Mashhad 1394491388, Iran
[7]Department of Medical Surgical Nursing, School of Nursing and Midwifery, Shahid Beheshti University of Medical Sciences, Tehran 1983969411, Iran
Correspondence to: Ebrahim Jafarzadehpur. Noor Ophthalmology Research Center, Noor Eye Hospital, Tehran 1983963113, Iran. jafarzadehpour.e@iums.ac.ir
Received: 2025-05-05 Accepted: 2025-10-22

Abstract
● **AIM:** To summarize the influencing factors of color vision and their clinical implications, with an emphasis on the roles of genetic, environmental, demographic factors as well as ocular and systemic disorders.
● **METHODS:** Relevant literatures published from 2014 to 2024 were systematically retrieved from six databases including PubMed, Embase, Scopus, Web of Science, Cochrane Library, and Google Scholar. Search terms mainly covered color blindness, color vision deficiency (CVD), prevalence, incidence, protan, deutan, tritan, determinants, and risk factors. Eligible original English studies were screened according to predefined inclusion and exclusion criteria. Data extraction and quality evaluation were independently completed by two researchers. Qualitative systematic review was finally performed due to obvious inter-study heterogeneity.
● **RESULTS:** A total of 50 eligible studies were enrolled. The prevalence of CVD was markedly higher in males than in females. Age, gender, ethnicity, and occupation were closely correlated with CVD. Males and individuals aged over 60y were more vulnerable to red-green CVD. Occupational ultraviolet radiation exposure, systemic diseases including diabetes mellitus and hypertension, as well as optic nerve lesions were confirmed as vital risk factors for abnormal color vision.
● **CONCLUSION:** Apart from genetic and congenital factors, environmental exposure, aging, occupational characteristics, and various ocular and systemic diseases that impair retinal and optic nerve function can also affect color vision function. Clarifying these influencing factors helps ophthalmologists formulate targeted prevention schemes and individualized clinical interventions. Further well-designed longitudinal studies covering more diverse populations are still required in this field.
● **KEYWORDS:** color vision; influencing factors; genetics; environment; aging; ocular and systemic diseases
DOI:10.18240/ijo.2026.07.21

Citation: Fayaz F, Jafarzadehpur E, Ahmad MA, Amini Vishteh R, Pishnamaz MR, Hoseinzade MS, Mirzaee Saba L, Kamali M, Yekta A, Khabazkhoob M. Factors affecting color vision: a systematic review. *Int J Ophthalmol* 2026;19(7):1395-1405

INTRODUCTION

Color vision is a vital aspect of human visual perception, allowing us to distinguish and interpret a wide range of colors[1]. The main retinal neurons responsible for conscious vision consist of two broad types of cells: rods and cones[2]. In a normal retina, rods facilitate scotopic (nocturnal) vision, while cones are primarily used for photopic (daylight) vision[3]. The ability to perceive colors is mainly facilitated by cone cells in the retina, which are sensitive to different wavelengths of light[4]. The physiological basis of trichromatic color vision lies in the cone photoreceptors, which consist of three subtypes: cones sensitive to long (L-), medium (M-), and short (S-)

wavelengths. These have spectral sensitivity peaks around 558 nm (L-cone), 531 nm (M-cone), and 419 nm (S-cone)[5-7]. Signals from cones are transmitted *via* ganglion cells and lateral geniculate bodies to the visual cortex (V1), resulting in perception of the full color spectrum[8]. However, sometimes, due to genetic, congenital, or acquired factors, the cone cells may not function properly or may be insufficient in number, leading to issues with color vision, typically resulting in color vision deficiency (CVD). While researchers have significant knowledge about the genes causing color vision problems, these genes represent only a portion of the factors affecting color vision. Other factors such as demographic characteristics, environmental influences, and systemic and ocular diseases may also contribute to changes in color vision. Congenital CVD, usually involving red-green defects due to X-linked mutations, should be differentiated from acquired CVD, which often involves blue-yellow changes associated with ocular or systemic disease. As individuals age, various physiological, anatomical, neurological, and environmental changes occur in the eye that can affect its performance[8]. With aging, the crystalline lens becomes more yellow and dense, impacting light transmission, particularly in the blue spectrum[9]. The retina also undergoes changes, such as a reduction in the number of active photoreceptors[10]. Environmental factors, like exposure to certain chemicals or toxins and workplace hazards, can also lead to alterations in color vision[11-12]. Systemic and neurocognitive disorders, such as diabetes, Parkinson's disease, and ocular diseases like macular degeneration, may also impair color vision[13-15]. Sometimes, changes in color vision can be early indicators of these issues[16]. Importantly, in some cases, color vision changes may serve as an early clinical indicator of these conditions[17]. Some evidence suggests that prolonged exposure to digital devices and blue light may lead to color vision deficiencies[18].

This systematic review aims to provide an overview of the factors affecting color vision. Our objective is to identify and categorize the various factors that can impact color perception and offer insights that could lead to the development of better diagnostic tools, more effective treatment methods, and guidelines to mitigate the influence of external factors on color vision. The paper also identifies existing gaps in current literature and proposes recommendations for future research to advance our understanding of this crucial aspect of human visual function.

MATERIALS AND METHODS

Information Sources and Search Strategy This systematic review was conducted by searching six major databases: Google Scholar, PubMed, Scopus, Web of Science (WOS), Embase, and Cochrane Library. The last search was performed on December 31, 2024. The search included studies published between 2014 and 2024. The search strategy was based on a combination of keywords and search terms such as: "Color Blindness", "Prevalence", "Color Vision Deficiency", "Protan", "Deutan", "Tritan", "Determinant", "Incidence", "Risk Factor", and "Associated". ("Color Blindness" OR "Color Vision Deficiency" OR "Protan" OR "Deutan" OR "Tritan") AND ("Prevalence" OR "Incidence" OR "Determinant" OR "Risk Factor" OR "Associated" OR "Distribution"). In PubMed, the exact search string applied was: ("Color Blindness" OR "Color Vision Deficiency" OR "Protan" OR "Deutan" OR "Tritan") AND ("Prevalence" OR "Incidence" OR "Determinant" OR "Risk Factor" OR "Associated" OR "Distribution").

These terms were selected to ensure a comprehensive capture of studies related to color vision deficiencies and associated risk factors.

Inclusion and Exclusion Criteria Studies were selected based on the following inclusion criteria: 1) Articles focusing on the prevalence, incidence, and risk factors or determinants of CVD; 2) Studies addressing specific subtypes of color blindness such as Protan, Deutan, and Tritan; 3) Articles published between 2014 and 2024; 4) Articles published in English.

The exclusion criteria included: 1) As English-language inclusion inherently excludes other languages, non-English publications were not considered; 2) Studies unrelated to CVD; 3) Letters, and conference abstracts with incomplete or unavailable full-text; 4) Review articles were excluded to prevent double counting and potential bias.

Study Selection: The study selection process was conducted in three steps: 1) identification of records through database searches; 2) screening of titles and abstracts; 3) full-text assessment for eligibility. The number of records at each stage has been presented in a PRISMA flow diagram (Figure 1).

Data Analysis Due to the heterogeneity of the included studies, no statistical analysis (Meta-analysis) was performed. Instead, a descriptive synthesis was conducted. The findings of the studies were qualitatively reviewed and summarized to identify patterns in the prevalence and risk factors associated with CVD.

RESULTS

Totally 50 studies were included after applying the PRISMA selection process (Table 1) covering various populations from different geographic regions and age groups[11-15,17,19-62]. A total of 4624 records were identified across databases (PubMed 324, Scopus 950, Web of Science 800, Embase 700, Cochrane Library 150, Google Scholar 1700). After removal of duplicates and automated ineligible records (n=1100), 3524 records remained for title/abstract screening. Following screening, 474 full texts were sought, of which 20 could not be retrieved. A total of 454 articles underwent full-text assessment,

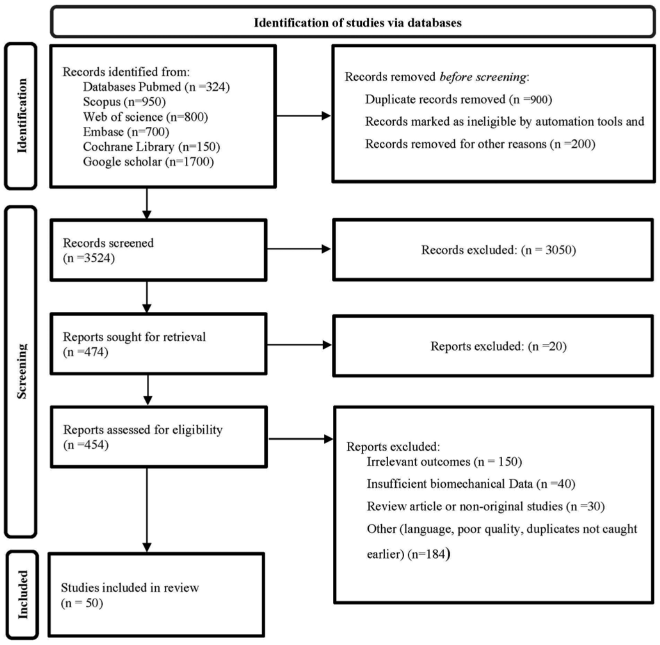

Figure 1 PRISMA flow chart Data extraction and quality assessment: Data extraction was carried out independently by two reviewers. Key information from the selected studies, including publication year, population characteristics, type of color vision deficiency, and associated factors, were collected. The quality of the included studies was assessed using a standardized checklist for observational studies, and studies were evaluated based on these quality criteria.

with 404 excluded (reasons: irrelevant outcomes, insufficient data, review articles, other). Finally, 50 studies were included in the qualitative synthesis (PRISMA flowchart, Figure 1). The prevalence of CVD varied significantly based on factors such as gender, age, ethnicity, and occupation. Review articles were excluded to prevent duplication and reduce risk of bias.

Prevalence and Demographic Factors Several studies reported a higher prevalence of CVD in men compared to women. For example, in Republic of Korea, Kim and Ng[19] observed a prevalence of 5.6% in men versus 1% in women. Similar gender disparities were found in studies conducted in Southern Taiwan, China (Kuo *et al*[20]) and Iran (Hashemi *et al*[22]), where men, especially older adults, exhibited a higher prevalence of red-green color blindness. Age also played a significant role, with older adults (60+) showing increased susceptibility, particularly in association with hypertension and glaucoma (Hashemi *et al*[22]). These findings suggest that ophthalmologists should consider routine color vision screening in older adults and high-risk male populations to support early diagnosis and management.

Geographic and Ethnic Variations Studies conducted in Ethiopia (Gudeta and Asrat[23]) and China (Gao[21]) highlighted the role of ethnic and education factors. In Ethiopia, CVD prevalence was reported among different ethnic groups, with the Amhara population showing the highest rate (7.45%), followed by the Oromo (5%) and Gurage (2.13%). Meanwhile, in China, individuals with higher education levels had lower rates of CVD, indicating a possible link between education and awareness of the condition.

Occupational and Environmental Influences Occupational factors were another significant determinant of CVD. For instance, welders in Iran exposed to ultraviolet light over long periods exhibited higher rates of color vision issues (Heydarian *et al*[32]). Additionally, truck drivers in Saudi Arabia and miners exposed to lead and zinc in Iran also showed an increased prevalence of CVD (Jafarzadehpur *et al*[40]; Fattahi *et al*[12]). Students and professionals in visual-demanding fields such as dentistry also demonstrated higher rates of CVD (Ngente *et al*[24]). Chronic exposure to digital devices and blue light was also identified as a potential environmental risk factor in some studies.

Health-Related Risk Factors Health conditions such as diabetes, hypertension, and optic neuropathy were identified as risk factors for CVD. Diabetic patients, particularly those with diabetic retinopathy, showed significant visual impairment, including color vision deficiencies (Chai *et al*[54]). In another study, chronic exposure to welding light and organic solvents was linked to higher rates of CVD in industrial workers (Krishnakumar *et al*[60]). These findings emphasize the importance of considering color vision changes as an early indicator of systemic diseases such as diabetes and hypertension.

Rare and Specific Findings Certain studies focused on rare conditions, such as schizophrenia, a neuropsychiatric disorder patient often exhibited various forms of CVD. For instance, 71.7% of schizophrenia patients in Nigeria showed some form of CVD (Balogun and Coker[17]). Similarly, patients with thalassemia were reported to develop CVD due to retinal pigment epithelium (RPE) degeneration and vascular changes, highlighting the need for specialized ophthalmic evaluation in such populations.

DISCUSSION

Demographic Factors Research has shown that with increasing age, physiological changes in the visual system occur, gradually leading to a decrease in color sensitivity[20-25,27,30,33,35,37-38,40,53,63]. These changes are primarily due to the clouding of the lens, where transparency of the lens and the refraction of light by lens fiber cells, which lack nuclei and other organelles, become impaired. This is a hallmark of aging, marked by the loss of protein homeostasis in an environment with limited metabolism[64]. Cataracts cause significant changes in the protan and tritan color vision vectors but do not significantly affect the deutan axis[65]. Based on electrophysiological measurements and psychophysical studies, researchers have confirmed that color discrimination declines mainly along the blue-yellow axis with aging[66]. Changes in the lens and the

Table 1 Summary of studies according color vision deficiency and determinants in worldwide

Author name	Year	Sample size	Age distribution	Location	Influential variable	Prevalence	Risk factor
Hyojin Kim[19]	2019	2686 people	19 to 49y	Republic of Korea	Gender: 5.6% prevalence in men and 1% in women	5.6% prevalence in men and 1% in women	Male gender
Hsi-Kung Kuo[20]	2023	-	-	Southern Taiwan, China	Gender: higher prevalence of red-green color blindness in men	Higher prevalence of red-green color blindness in men	Male gender
Jing-Ge Gao[21]	2023	381 people	17 to 38y	China	Gender and education level: higher education associated with lower prevalence of color vision deficiency	Higher education associated with lower prevalence of color vision deficiency	Low level education
Hassan Hashemi[22]	2023	3310 people	Above 60y	Iran	Age/gender: Higher prevalence of red-green color blindness in men and older adults (60+). Hypertension and glaucoma are also associated	Higher prevalence of red-green color blindness in men and older adults	Hypertension and glaucoma
Temesgen Bedassa Gudeta[23]	2024	846 people	9 to 12y	Ethiopia	Gender, race, and genetics: Prevalence among ethnic groups: Amhara (7.45%), Oromo (5.00%), Gurage (2.13%)	Gender, race, and genetics (ethics)	Male gender
Zodinliana Ngente[24]	2021	198 dentists	17 to 31y	Not reported (NR)	Age, gender, and occupation: higher color vision deficiency among students, particularly 17 to 21 years old	Age, gender, and occupation: higher color vision deficiency among students, particularly 17 to 21 years old	Male gender and be student between 17 to 21y
Satyasri B[25]	2023	371 people	10 to 30y	India	Gender	Higher prevalence in male	Male gender
Masoumeh Ahadi[26]	2021	2600 men	18 to 46y	Iran (Zanjan)	Age and refractive errors: myopes have higher prevalence of color vision deficiency compared to hyperopes	Myopes have higher prevalence of color vision	Myopia
AlShammari R[27]	2021	1115 people	Avg. age: 21.7±4.1y	Saudi Arabia	Gender and history of vision problems significantly linked to color vision deficiency; no correlation with current health issues	Higher prevalence in male	History of vision problems
Sruthi Sree Krishnamurthy[28]	2021	250052 people	6 to 17y	Southern India	Living location and public school	Higher prevalence in people who study in public schools and live in low level areas.	The lower level of the city and public schools
Hosseini SA[29]	2014	4400 students	7 to 12y	Mashhad, Iran	Refractive errors in school-age children with color vision deficiency (CVD) *vs* normal color vision (NCV)	-	Type of refractive error
Mohd Fareed[30]	2015	1028 people	6 to 15y	Northernmost state of India	Gender and distribution of color vision deficiency: Deutanomaly more prevalent than Deuteranopia. Parental education and awareness impact congenital red-green color blindness	Higher prevalence in male	Male gender
Sabbaghi H[31]	2015	2160 students	7 to 12y	Tehran, Iran	Although CVD was associated with lower visual acuity and amblyopia, no link with refractive errors, anisometropia, or strabismus was found	Higher prevalence in low visual acuity and amblyopes	Lower visual acuity and amblyopia
Samira Heydarian[32]	2017	50 welders	Age: 29.36±6.36y	Zahedan, Iran	Chronic exposure to welding light can cause color vision deficiency. Damage depends on exposure time and ultraviolet spectrum	Higher prevalence in welders	Chronic exposure to welding
Hassan Hashemi[33]	2017	3132 people	7 to 90y	Mashhad, Iran	Age and gender: higher prevalence of CVD in men and people over 46 years old	Higher prevalence of CVD in men and people over 46 years old	Male gender and over 46y
Gashaw Garedew Woldeamanuel[34]	2018	844 people	Age: 11.75±2.5y	Gorage region, South Ethiopia	Gender and religion: higher CVD prevalence among men and Muslims due to familial marriages	Higher prevalence of CVD in men and muslims	Male gender and being a muslim
Osama Abdulqadir Khairoalsindi[35]	2019	1126 people	Age: 18.7±0.7y	Mecca, Saudi Arabia	CVD linked to gender, CVD history, other eye problems, and use of visual aids. Tritan-type CVD interferes more with daily function	Higher prevalence in male and who has CVD history, other eye problems	Male gender and CVD history, other eye problems, and use of visual aids
Ayse Seda Ataol[36]	2022	710 people	Above 18y	Ankara, Türkiye	Significant differences in color blindness distribution based on educational institution and academic year	Higher prevalence of CVD in People who with a short duration of education and studied at low-level institutions.	Educational institution and academic year
Reena Kumari Jha[37]	2018	825 experts	17 to 25y	Nepal	Gender: higher prevalence of CVD in men	Higher prevalence in male	Male gender
Mengistu Zelalem Wale[38]	2018	850 people	8 to 18y	Northwest Ethiopia	Gender and vision impairment significantly linked to CVD	Higher prevalence in male and who has vision impairment	Vision impairment
Abbas Ali Yekta[39]	2022	30 with optic neuropathy	18 to 45y	Tehran, Iran	No significant link between color vision and retinal nerve fiber layer (RNFL) thickness	-	-
Farzaneh Fattahi[12]	2020	230 miners	Above 50y	Iran	Chronic exposure to lead and zinc in mining may cause color vision deficiency and reduced contrast sensitivity	Higher prevalence of CVD in people who work in mines	Chronic exposure to lead and zinc
Ebrahim Jafarzadehpur[40]	2014	6311 people	40 to 64y	Shahroud, Iran	Gender and age: CVD prevalence increases with age due to medical and ocular conditions, and racial/environmental factors	Higher prevalence in male and elderly people	Male gender and old age
Modupe Medina Balogun[17]	2024	118 people	18 to 70y	Lagos, Nigeria	71.7% of examined schizophrenia patients showed various types of color vision deficiency	Higher prevalence of CVD in schizophrenia patients	Schizophrenia disease
Ye Liu[41]	2024	NR	NR	NR	Endocrine hormones, including thyroid, affect cone cells and color vision *via* monocarboxylate transpoter 8 (MCT8)	Higher prevalence of CVD in people who with thyroid disorders	Deficiency in the secretion of thyroid hormones

Table 1 Summary of studies according color vision deficiency and determinants in worldwide (continued)

Author name	Year	Sample size	Age distribution	Location	Influential variable	Prevalence	Risk factor
Aliaa H Abdelhakim[42]	2024	24 people	NR	NR	Ocular manifestations in KIF1A-associated neurological disorder (KAND), causing color vision deficiency	Higher prevalence of CVD in people who with neurological disorders	Neurological disorders
Naveen K Challa[11]	2024	300 truck drivers	NR	Saudi Arabia	Road traffic accidents (RTA) affect visual function, including color vision and depth perception	Higher prevalence of CVD in drivers	Road traffic accidents
Zahra Nouri[43]	2024	3 people	Females aged 37, 40, 41y	Iran	All cases showed congenital non-syndromic hearing loss, reduced visual acuity, and poor color recognition	Higher prevalence of CVD in people who with congenital NSHL	Congenital NSHL
Shahrokh Ramin[44]	2024	37 people	Age: 61±9y	Tehran, Iran	Central retinal vein occlusion	Higher prevalence of CVD in people who with central retinal vein occlusion (CRVO)	CRVO
Rustum Karanjia[45]	2024	12 people	18 to 50y	Slovenia	Leber congenital disease	Higher prevalence of CVD in people who with leber congenital disease	Leber congenital disease
Harvey V Lankford[46]	2023	From climbers	NR	NR	High-altitude oxygen deficiency and high light intensity affect vision, including glare and contrast	Higher prevalence of CVD in people who live in mountainous areas and at high altitudes	High-altitude oxygen deficiency
Younes Sohrabi[47]	2024	From occupational exposure	NR	NR	Chemicals including benzene, toluene, ethylbenzene, and xylene (BTEX) affect vision	Higher prevalence of CVD in people who are more exposed to these material	Chemicals material
Aneesha Vyas[48]	2024	80 people	18 to 80y	NR	Ethambutol toxicity and optic neuropathy	Higher prevalence of CVD in patient with ethambutol toxicity and optic neuropathy	Ethambutol toxicity and optic neuropathy
Tatsuya Iizuka[49]	2023	NR	20 to 64y	NR	Cataracts due to aging	Higher prevalence of CVD in people who with cataracts	Cataracts
Jiahe Gan[50]	2022	2849	Age: 4.0±1.7y	China	There is an inverse relationship between the prevalence of color vision deficiency and the incidence of myopia	Higher prevalence of CVD in people who with myopia	Myopia
Nisar Sonam Poonam[51]	2022	26	Age: 10.98±46.96y	India	Thyroid optic neuropathy is associated with risk factors such as age, gender, and smoking (changes in color vision are the first signs of optic nerve pressure)	Higher prevalence of CVD in people who with thyroid disease	Thyroid disease and Optic neuropathy
Mengwei Li[52]	2022	7 rhesus monkeys	4 to 12y	Shanghai, China	There is a correlation between glaucoma and color vision deficiency	Higher prevalence of CVD in people who with glaucoma	Glaucoma
Neil M Schultz[15]	2021	37	Above 18y	USA, France, Germany, Italy, Spain, UK	Dry macular degeneration	Higher prevalence of CVD in people who with dry macular degeneration	Dry macular degeneration
Safaa Osman[53]	2021	1426	Above 18y	Egypt	Male gender and positive family history	Higher prevalence in male and who has positive family history	Male gender and positive family history
Sanbao Chai[54]	2022	1030	NR	NR	Significant visual impairment in visual functions, including color vision, was observed in patients with type 2 diabetes, with older age, lower education level, longer duration of diabetes, limited best-corrected visual acuity (BCVA), and the presence of diabetic retinopathy identified as risk factors	Higher prevalence of CVD in people who with type 2 diabetes, older age, lower education level, longer duration of diabetes	Type 2 diabetes, older age, lower education level, longer duration of diabetes
Renata Tavares de Souza Cabral[55]	2019	NR	NR	NR	Anti-malarial medication	Higher prevalence of CVD in people who take Anti-malarial medication	Anti-malarial medication
Laxmi Gella[56]	2017	958	44 to 86y	India	Type 2 diabetes	Higher prevalence of CVD in diabetics	Type 2 diabetes
Mohsen Bahmani Kashkouli[57]	2018	120	Above 5y	Iran	Traumatic optic neuropathy	Higher prevalence of CVD in people with traumatic optic neuropathy	Traumatic optic neuropathy
Murtaza S Khan[58]	2020	1	22y	NR	Central retinal vasculitis due to syphilis	Higher prevalence of CVD in people with syphilis	Central retinal vasculitis due to syphilis
Katarzyna Jończyk-Skórka[59]	2017	197	Age: 74.8±21.63y	NR	Diabetic retinopathy	Higher prevalence of CVD in diabetics	Diabetic neuropathy
Krishnakumar R[60]	2016	30 workers	Age: 39.7±7.6y	India	Organic solvents in petrochemical industries	Higher prevalence of CVD in people who are more exposed to organic solvents	Organic solvents in petrochemical industries
Goldis Espandar[61]	2016	59	16 to 83y	Semnan, Iran	Retinal toxicity from hydroxychloroquine	Higher prevalence of CVD in people who take hydroxychloroquine	Retinal toxicity from hydroxychloroquine
Srividya Neriyanuri[14]	2017	743	Age: 63.95±3.9y	India	Diabetic neuropathy	Higher prevalence of CVD in diabetics	Diabetic neuropathy
T H Lee[62]	2017	33	20 to 64y	Republic of Korea	Optic neuritis	Higher prevalence of CVD in people with optic neuritis	Optic neuritis
Joong-Seok Kim[13]	2017	12	42 to 83y	Republic of Korea	Parkinson's disease and accumulation of alpha-synuclein	Higher prevalence of CVD in people with Parkinson's	Parkinson's disease

reduction of S-cone cells cause a decrease in light absorption at shorter wavelengths (such as blue light), leading to a diminished ability to detect these colors[67]. Jafarzadehpur *et al*[40] found that with increasing age, due to changes in various eye tissues, some individuals may have difficulty distinguishing colors overall. Hashemi *et al*[22], as well as Bergholz *et al*[68], found that these issues could lead to reduced distinction in recognizing colors, including red and green. Gender differences in color vision are also notable. Women generally have better color discrimination and are less likely to suffer from color vision deficiencies, while about 8% of men experience red-green CVD[16,19-22,24-25,27,30,33-35,37-38,49,63]. Men are more affected as color blindness is an X-linked recessive trait[30]. These findings highlight the importance of routine color vision screening in older adults and men, which can help ophthalmologists detect and manage deficiencies early. In addition to age and gender, racial factors may also affect color vision, though these influences have been studied less extensively. One study showed that there are no pigmentary (*i.e.*, racial) differences in color vision as measured by two psychophysical methods[69]. However, other research suggests that differences in the prevalence of color blindness among races may be due to racial, genetic, and environmental factors[23,40].

Environmental Factors Prolonged exposure to sunlight can damage retinal cone cells, leading to a reduction in color sensitivity, especially in higher-altitude climates where oxygen levels are lower, and effects of intense light, such as glare and contrast reduction, are observed[46]. Certain chemicals can damage the retina, while others can cause changes in the lens or optic nerve[60]. The exact pathogenesis of vision loss caused by organic solvents is still unclear. Some of the most common hypotheses include: 1) degeneration of the visual pathway related to axonopathy; 2) direct effects of solvents on photoreceptor function; 3) cortical (and/or retinal) changes in neurotransmitter systems such as glutamate, dopamine, and acetylcholine[70]. The use of certain chemicals (such as ethambutol), toxins, and specific drugs can lead to optic neuropathy, causing color vision disorders[48]. Miners, due to chronic exposure to lead and zinc, may experience color vision defects and reduced contrast sensitivity. These color vision defects may be either red-green or blue-yellow. Lead can accumulate in the RPE, iris, and ciliary bodies. In rabbits, lead poisoning causes swelling of the RPE, leading to the loss of photoreceptors and, ultimately, color vision defects[12]. Several other studies have also established the link between chemical exposure and reduced color vision[47-48,71]. Some individuals in certain occupations, such as welders, may also develop color vision deficiencies; chronic exposure to welding light may cause a blue-yellow CVD[72]. Welding produces ultraviolet (UV), visible, and infrared (IR) radiation at harmful levels. These radiations and their secondary effects are responsible for eye hazards seen clinically. Moreover, truck drivers, due to a higher likelihood of road accidents and resulting brain and spinal injuries, may experience a reduction in the ability to distinguish various colors and depth perception[11]. Exposure to pollutants (including CO and CS_2), particularly in urban areas, may lead to eye inflammation, retinopathy, and changes in retinal vessels, ultimately contributing to cataracts and color vision problems as an environmental factor[73]. Certain religious rites and customs may indirectly affect eye health. Studies conducted in some Islamic countries suggest that a higher percentage of individuals in these societies suffer from color vision disorders due to the higher prevalence of consanguineous marriages[34]. Higher levels of education are usually associated with greater awareness of vision problems, while those with lower education may diagnose these disorders later or be less likely to seek treatment. Living in certain areas and attending public schools may be associated with reduced access to healthcare, vision screenings, and lower awareness of color vision disorders, which could lead to delays in diagnosis and treatment[21,30,36]. Refractive errors also impact CVD; for example, the lower prevalence of myopia among individuals with CVD supports the role of longitudinal chromatic aberration in creating refractive errors[26,28-29,50]. Additionally, prolonged use of digital displays may, due to blue light and the resulting reactive oxygen species (ROS) production, cause a reduction in photoreceptors, lipid peroxidation, cell apoptosis, and ultimately, color vision deficiencies[18]. These observations reinforce the need for environmental risk assessment and preventive strategies in occupational and daily-life settings.

Ocular and Systemic Factors Having a history of vision problems is strongly related to CVD, similar to other eye problems, the use of visual aids, and the presence of amblyopia. No link has been found between current health issues and CVD[27,35]. Cataracts are one of the most common eye problems affecting color vision. This disease causes clouding of the crystalline lens, preventing light from passing through the lens properly, resulting in reduced intensity and accuracy of color perception[22,74]. Sabbaghi *et al*[31] also found that neurological diseases can lead to CVD. In fact, CVD is associated with lower visual acuity and amblyopia, but no link exists between CVD and the type of amblyopia, refractive errors, anisometropia, or strabismus. Parkinson's disease (a neuro-cognitive disorder) patients also experience reduced color vision due to the accumulation of alpha-synuclein in the retina[13]. Other studies have also reported a link between CVD and neurological diseases[75-79]. Mental illnesses may also affect color vision, with 71.7% of examined schizophrenia patients (a mental disorder) exhibiting various types of CVD[17]. These findings highlight the potential utility of color vision testing in neurological and psychiatric assessments. The use of antipsychotic medications in treating psychotic disorders has been associated with various side effects, including the development of cataracts, one of the leading causes of blindness worldwide. It has been reported that about 10.2% of psychiatric patients taking antipsychotic medications have color vision deficiencies[17]. Other drugs may also temporarily or permanently affect color vision. For example, the use of antimalarial drugs or drugs used to treat cardiac arrhythmias may lead to color vision disorders[55,61]. Previous studies have shown that CVD, following retinal toxicity, results in damage to the outer retinal structures, retinal ganglion cells, the inner plexiform layer, and the retinal nerve fiber layers[80-83]. Endocrine diseases and hormonal disorders can also lead to color vision impairment. Endocrine hormones, including thyroid hormones, affect the diversity and regulation of cone cells and, subsequently, color vision by impacting monocarboxylate transporter 8 (MCT8), a membrane transporter in the pigmented epithelium. It can influence the gene expression of cone cells, leading to disruptions in electroretinogram responses[41]. Other studies have also demonstrated the influence of thyroid function on color vision[84-86]. Changes in color vision are an early sign in diseases where the optic nerve is under pressure, such as in optic neuropathy related to thyroid disease and optic neuritis[16,62]. Trauma to the optic nerve can also cause CVD due to axon damage and possible ischemia[57]. Ocular manifestations in neurological disorders associated with KIF1A (KAND) can also lead to CVD[42]. Other syndromes with neurological origins, such as congenital bilateral nonsyndromic hearing loss (autosomal recessive NSHL), show reduced visual acuity and poor color discrimination[87]. Cross-sectional studies indicate that individuals with cognitive impairments, such as Alzheimer's disease patients, have weaker visual function, including color vision, contrast sensitivity, and visual fields, compared to individuals with normal cognition. This is due to the accumulation of abnormal protein deposits (Lewy bodies) in the brain[75,88]. Schultz *et al*[15] found that retinal diseases, such as macular degeneration, can directly affect cone cells responsible for color detection, leading to CVD. Congenital diseases like Leber's congenital amaurosis and retinitis pigmentosa (RP) can also impair the optic nerve and retinal photoreceptors, resulting in CVD[45,52,89-90]. These diseases are usually associated with reduced sensitivity to medium- and long-wavelength colors, such as green and red. Increased intraocular pressure or glaucoma can damage the optic nerve and reduce sensitivity to colors. In advanced stages of the disease, recognizing colors, especially in peripheral visual fields, becomes more difficult. Studies have indicated that glaucoma and hypertension are significantly associated with red-green CVD[22], although another study suggested that glaucoma is related to blue-yellow CVD[52]. Central retinal vein occlusion or central retinal vasculitis caused by syphilis[44,58] and other retinal vascular diseases, such as diabetic retinopathy, a common complication of type 1 and type 2 diabetes, can lead to the loss of cone cells responsible for color detection, causing CVD. Neriyanuri *et al*[14] found that in addition to retinopathy, diabetic neuropathy can also lead to optic nerve damage and impair color processing along the retina-cortex pathway in the brain. This issue can cause diabetic patients to experience confusion and reduced accuracy in color recognition[14,44,54,56,59,91-93]. Studies have shown that diabetic patients often face greater difficulty in recognizing shorter wavelength colors, such as blue and yellow[56]. This impairment may be due to the long-term effects of high blood sugar on retinal and optic nerve function. Moreover, diabetes can also increase the risk of developing cataracts, which is recognized as a factor contributing to reduced color vision quality. The combination of these two issues (diabetes and cataracts) can severely diminish color recognition abilities in patients. Additionally, Heydarian *et al*[32], after reviewing the literature, concluded that iron toxicity in the body leads to night blindness, color vision defects, visual field defects, visual acuity disturbances, and RPE changes due to the deposition of ferritin in the retinal vessels and the retinal pigment layer, as well as in other organs like the pancreas. They also found that patients with thalassemia suffer from color vision defects, which are caused by retinal disorders in thalassemia patients, such as RPE degeneration, peripheral and central retinal thinning, venous twisting and occlusion, retinal hemorrhaging and edema, increased cup-to-disc ratio, and macular scarring[32].

Genetic Factors Color vision disorders often occur due to genetic defects in the genes related to retinal cone cells. These genes are mainly located on the X chromosome, which is why these disorders are more common in men[94]. Red-green color blindness is one of the most common genetic color vision disorders, caused by mutations in the *OPN1LW* and *OPN1MW* genes[95]. These genes are responsible for producing proteins that help cone cells detect red and green colors[95-96]. Blue-yellow color blindness, or tritanopia, is a rarer genetic disorder caused by a defect in the *OPN1SW* gene located on chromosome 7, and it is usually inherited in an autosomal dominant manner[97-98]. Additionally, research has shown that in some families, the inheritance pattern of color vision disorders is such that multiple generations may be affected by these conditions[99-100]. This indicates the significant role of genetic factors in this field. Achromatopsia (ACHM) and RP are hereditary disorders caused by mutations in the cone and rod photoreceptor genes, respectively. ACHM severely impairs daytime vision, while RP initially affects night vision and later impacts daytime vision. Currently, gene therapy treatments using recombinant adeno-associated viral vectors (rAAV) are being developed for various forms of ACHM and RP[101]. Research has shown that red contact lenses (RCL) can enhance performance on the Ishihara color vision test. The most effective lenses had reduced light transmission between 450–568 nm and allowed 90% of light to pass beyond 637 nm. Lenses that blocked more light in the 550–580 nm range were particularly helpful for individuals with more severe color vision deficiencies. Those with moderate to severe color blindness may benefit from red-tinted lenses, as the tint enhances luminance contrast, helping them make fewer mistakes on the Ishihara test. However, additional research is needed to determine if these lenses offer practical benefits in everyday settings[102]. This addition highlights potential clinical interventions and future research directions.

Conclusion and Limitations This systematic study provides an in-depth look at the factors affecting color vision. We reviewed numerous studies on genetic, demographic, environmental, physical, ocular, and systemic disease factors that play a role in color vision. The findings reveal that color vision is a complex process influenced by various factors such as hereditary color blindness and age-related ocular changes. We also found that certain diseases, medications, and occupational hazards can alter color vision by affecting the optic nerve and retina. Awareness of these factors helps us design better tests, provide personalized treatments, and establish regulations to protect color vision in different settings, and also prevent the progression of color vision defects in diseases such as RP. Despite being comprehensive, this review has limitations that should be considered. First, the studies we reviewed used various methods and had different sample sizes and populations, which makes it difficult to generalize the results and draw overall conclusions. We also encountered challenges in data synthesis due to the different methods used to assess and diagnose color vision issues. In addition, the possibility of publication bias and selective reporting may have influenced the available evidence, and some studies did not adequately control for confounding factors such as systemic comorbidities, medication history, and occupational exposures. Furthermore, many studies focused on specific groups or were conducted at a single point in time (cross-sectional), which may have overlooked long-term effects or causal relationships. To better understand the factors influencing color vision, future studies should aim to use more standardized methods and cover a wider range of individuals and factors. It is recommended that future research explore the long-term effects of various factors on color vision indices through longitudinal studies.

ACKNOWLEDGEMENTS

Foundation: Supported by Deputy of Research of Iran University of Medical Sciences, Tehran, Iran.

Conflicts of Interest: Fayaz F, None; **Jafarzadehpur E,** None; **Ahmad MA,** None; **Amini Vishteh R,** None; **Pishnamaz MR,** None; **Hoseinzade MS,** None; **Mirzaee Saba L,** None; **Kamali M,** None; **Yekta A,** None; **Khabazkhoob M,** None.

REFERENCES

1 Kernell D. Colours and colour vision: an introductory survey: Cambridge University Press; 2016.

2 Nilsson DE. The diversity of eyes and vision. *Annu Rev Vis Sci* 2021;7:19-41.

3 Ptito M, Bleau M, Bouskila J. The retina: a window into the brain. *Cells* 2021;10(12):3269.

4 Mustafi D, Engel AH, Palczewski K. Structure of cone photoreceptors. *Prog Retin Eye Res* 2009;28(4):289-302.

5 Dartnall HJA, Bowmaker JK, Mollon JD. Human visual pigments: microspectrophotometric results from the eyes of seven persons. *Proc R Soc Lond Ser B Biol Sci* 1983;220(1218):115-130.

6 Jolly JK, Simunovic MP, Dubis AM, *et al*. Structural and functional characteristics of color vision changes in choroideremia. *Front Neurosci* 2021;15:729807.

7 Roorda A, Williams DR. The arrangement of the three cone classes in the living human eye. *Nature* 1999;397(6719):520-522.

8 Swenor BK, Lee MJ, Varadaraj V, *et al*. Aging with vision loss: a framework for assessing the impact of visual impairment on older adults. *Gerontologist* 2020;60(6):989-995.

9 Zlatkova MB, Coulter EE, Anderson RS. The effect of simulated lens yellowing and opacification on blue-on-yellow acuity and contrast sensitivity. *Vis Res* 2006;46(15):2432-2442.

10 Stone J, Maslim J, Valter-Kocsi K, *et al*. Mechanisms of photoreceptor death and survival in mammalian retina. *Prog Retin Eye Res* 1999;18(6):689-735.

11 Challa NK, Alrasheed SH. Refractive error and abnormal stereopsis association with road traffic accidents in Saudi Arabian truck drivers. *Saudi J Ophthalmol* 2024;38(2):157-162.

12 Fattahi F, Khabazkhoob M, Jafarzadehpour E, *et al*. Evaluation of contrast sensitivity and color vision in lead and zinc mine workers. *Rom J Ophthalmol* 2020;64(1):43-49.

13 Kim JS, Park IS, Park HE, *et al*. α-Synuclein in the colon and premotor markers of Parkinson disease in neurologically normal subjects. *Neurol Sci* 2017;38(1):171-179.

14 Neriyanuri S, Pardhan S, Gella L, *et al*. Retinal sensitivity changes associated with diabetic neuropathy in the absence of diabetic retinopathy. *Br J Ophthalmol* 2017;101(9):1174-1178.

15 Schultz NM, Bhardwaj S, Barclay C, *et al*. Global burden of dry age-related macular degeneration: a targeted literature review. *Clin Ther* 2021;43(10):1792-1818.

16 Tagami M, Honda S, Azumi A. Insights into current management strategies for dysthyroid optic neuropathy: a review. *Clin Ophthalmol*

2022;16:841-850.

17 Balogun MM, Coker OA. Ocular toxicity of psychotropic medications in a tertiary hospital in Lagos, Nigeria. *Rom J Ophthalmol* 2024;68(2):99-107.

18 Cougnard-Gregoire A, Merle BMJ, Aslam T, *et al*. Blue light exposure: ocular hazards and prevention—a narrative review. *Ophthalmol Ther* 2023;12(2):755-788.

19 Kim H, Ng JS. Prevalence of color vision deficiency in an adult population in South Korea. *Optom Vis Sci* 2019;96(11):10.1097/OPX.0000000000001019.

20 Kuo HK, Tsao ST, Wu PC. Prevalence of congenital color vision deficiency in southern Taiwan and detection of female carriers by visual pigment gene analysis. *Int J Mol Sci* 2023;24(20):15247.

21 Gao JG. Prevalence of color vision deficiency among Chinese college students and their quality of life. *Int J Ophthalmol* 2023;16(9):1542-1548.

22 Hashemi H, Shahidi A, Hashemi A, *et al*. The prevalence of red-green color vision deficiency and its related factors in an elderly population above 60 years of age. *Int J Ophthalmol* 2023;16(9):1535-1541.

23 Gudeta TB, Asrat T. Prevalence and genotypic frequency of color vision defects among primary schoolchildren in Adama Town, Eastern Ethiopia. *BMC Pediatr* 2024;24(1):72.

24 Ngente Z, Jadav B, Aafaque S, *et al*. Prevalence of color vision anomalies among dental professionals. *Middle East Afr J Ophthalmol* 2021;28(3):169-173.

25 B S, K V PK. The prevalence of congenital color vision abnormality among patients attending a tertiary eye care center in Southern India. *Cureus* 2023;15(8):e43837.

26 Ahadi M, Ebrahimi A, Rahmani S, *et al*. Prevalence of refractive errors and color vision deficiency in a population of industry-workers in Abhar, Iran. *Medicine* 2021;100(46):e27758.

27 AlShammari R, Alamoudi N, AlOmar R, *et al*. Prevalence of color vision deficiency in medical students at a Saudi University. *J Fam Community Med* 2021;28(3):196.

28 Krishnamurthy SS, Rangavittal S, Chandrasekar A, *et al*. Prevalence of color vision deficiency among school-going boys in South India. *Indian J Ophthalmol* 2021;69(8):2021-2025.

29 Hosseini SA, Vatandoust S, Sharifi F, *et al*. Prevalence of refractive errors in students with and without color vision deficiency. *J Ophthalmic Vis Res* 2014;9(4):484.

30 Fareed M, Anwar MA, Afzal M. Prevalence and gene frequency of color vision impairments among children of six populations from North Indian region. *Genes Dis* 2015;2(2):211-218.

31 Sabbaghi H, Baghini A, Yaseri M, *et al*. Prevalence of color vision deficiency and its correlation with amblyopia and refractive errors among primary school children. *J Ophthalmic Vis Res* 2015;10(2):130.

32 Heydarian S, Jafari R, Dailami KN, *et al*. Ocular abnormalities in beta thalassemia patients: prevalence, impact, and management strategies. *Int Ophthalmol* 2020;40(2):511-527.

33 Hashemi H, Khabazkhoob M, Pakzad R, *et al*. The prevalence of color vision deficiency in the northeast of Iran. *J Curr Ophthalmol* 2019;31(1):80-85.

34 Woldeamanuel GG, Geta TG. Prevalence of color vision deficiency among school children in Wolkite, Southern Ethiopia. *BMC Res Notes* 2018;11(1):838.

35 Khairoalsindi O, Almasoudi B, Bamahfouz A, *et al*. Prevalence and determinants of color vision defects among preparatory university students at Makkah, Saudi Arabia. *Middle East Afr J Ophthalmol* 2019;26(3):133.

36 Ataol A, Ergün G. Prevalence and awareness levels of color blindness among students of faculty of dentistry and dental prosthesis technology program. *Eur Oral* 2022;56(3):149-157.

37 Jha RK, Khadka S, Gautam Y, *et al*. Prevalence of color blindness in undergraduates of kathmandu university. *JNMA J Nepal Med Assoc* 2018;56(214):900-903.

38 Wale MZ, Abebe Y, Adamu Y, *et al*. Prevalence of color blindness among school children in three primary schools of Gish–Abay town district, Amhara regional state, north-west Ethiopia. *BMC Ophthalmol* 2018;18(1):306.

39 Ali Yekta A, Sorouh S, Asharlous A, *et al*. Is retinal nerve fibre layer thickness correlated with visual function in individuals having optic neuritis *Clin Exp Optom* 2022;105(7):726-732.

40 Jafarzadehpur E, Hashemi H, Emamian MH, *et al*. Color vision deficiency in a middle-aged population: the Shahroud Eye Study. *Int Ophthalmol* 2014;34(5):1067-1074.

41 Liu Y, Ng L, Liu H, *et al*. Cone photoreceptor differentiation regulated by thyroid hormone transporter MCT8 in the retinal pigment epithelium. *Proc Natl Acad Sci U S A* 2024;121(30):e2402560121.

42 Abdelhakim AH, Brodie SE, Chung WK. Ophthalmic findings in the KIF1A-associated neurologic disorder (KAND). *Am J Ophthalmol* 2024;268:247-257.

43 Nouri Z, Sarmadi A, Narrei S, *et al*. Clinical characterizations and molecular genetic study of two co-segregating variants in PDZD7 and PDE6C genes leading simultaneously to non-syndromic hearing loss and Achromatopsia. *BMC Med Genom* 2024;17(1):173.

44 Ramin S, Rostami F, Ahmadieh H, *et al*. Vision-related quality of life in patients with retinal vein occlusion. *Int Ophthalmol* 2024;44(1):114.

45 Karanjia R, Sadun AA. Elamipretide topical ophthalmic solution for the treatment of subjects with leber hereditary optic neuropathy a randomized trial. *Ophthalmology* 2024;131(4):422-433.

46 Lankford HV, Hovis JK. Color vision in the mountains. *Wildern Environ Med* 2023;34(4):610-617.

47 Sohrabi Y, Rahimian F, Soleimani E, *et al*. Low-level occupational exposure to BTEX and Dyschromatopsia: a systematic review and meta-analysis. *Int J Occup Saf Ergon* 2024;30(1):9-19.

48 Vyas A, Subramanyam A, Phatak S, *et al*. Ethambutol and its ophthalmic effects; is screening and collaboration the new way forward *Indian J Tuberc* 2024;71(1):30-34.

49 Iizuka T, Kawamorita T, Handa T, *et al*. Cone contrast test-HD: sensitivity and specificity in red–green dichromacy and the impact of

age. *J Opt Soc Am A Opt Image Sci Vis* 2023;40(5):849-858.

50 Gan JH, Li SM, Atchison DA, *et al*. Association between color vision deficiency and myopia in Chinese children over a five-year period. *Invest Ophthalmol Vis Sci* 2022;63(2):2.

51 Poonam NS, Alam MS, Oberoi P, *et al*. Dysthyroid optic neuropathy: Demographics, risk factors, investigations, and management outcomes. *Indian J Ophthalmol* 2022;70(12):4419-4426.

52 Li MW, Chen XX, Yuan NN, *et al*. Effects of acute high intraocular pressure on red-green and blue-yellow cortical color responses in non-human Primates. *NeuroImage Clin* 2022;35:103092.

53 Osman S, Khalaf S, Mohammed H, *et al*. Prevalence and predictors of colour vision defects among Egyptian university students. *East Mediterr Health J* 2021;27(4):399-406.

54 Chai SB, Ge YM, Wan Y, *et al*. Visual functional defects in patients with type 2 diabetes mellitus: a questionnaire based cross-sectional study. *Int Ophthalmol* 2022;42(7):2205-2218.

55 Cabral RTS, Klumb EM, Couto MINN, *et al*. Evaluation of toxic retinopathy caused by antimalarial medications with spectral domain optical coherence tomography. *Arq Bras Oftalmol* 2019;82(1):12-17.

56 Gella L, Raman R, Kulothungan V, *et al*. Color vision abnormalities in type II diabetes: Sankara Nethralaya Diabetic Retinopathy Epidemiology and Molecular Genetics Study II report no 2. *Indian J Ophthalmol* 2017;65(10):989-994.

57 Kashkouli MB, Yousefi S, Nojomi M, *et al*. Traumatic optic neuropathy treatment trial (TONTT): open label, phase 3, multicenter, semi-experimental trial. *Graefes Arch Clin Exp Ophthalmol* 2018;256(1):209-218.

58 Khan MS, Kuruppu DK, Popli TA, *et al*. Unilateral optic neuritis and central retinal vasculitis due to ocular syphilis. *Retinal Cases Brief Rep* 2020;14(1):35-38.

59 Jończyk-Skórka K, Kowalski J. The evaluation of color vision and its diagnostic value in predicting the risk of diabetic retinopathy in patients with glucose metabolism disorders. *Pol Merkur Lekarski* 2017;43(253):15-21.

60 Krishnakumar R, Indhushree R, Monica R, *et al*. Visual functions of workers exposed to organic solvents in petrochemical industries. *Indian J Occup Environ Med* 2016;20(3):133.

61 Espandar G, Moghimi J, Ghorbani R, *et al*. Retinal toxicity in patients treated with hydroxychloroquine: a cross-sectional study. *Med Hypothesis Discov Innov Ophthalmol* 2016;5(2):41-46.

62 Lee TH, Ji YS, Park SW, *et al*. Retinal ganglion cell and axonal loss in optic neuritis: risk factors and visual functions. *Eye (Lond)* 2017;31(3):467-474.

63 Rezaei L, Hawasi E, Salari N, *et al*. Prevalence of color blindness in Iranian students: a meta-analysis. *J Ophthalmic Vis Res* 2022;17(3): 413-423.

64 Cvekl A, Vijg J. Aging of the eye: Lessons from cataracts and age-related macular degeneration. *Ageing Res Rev* 2024;99:102407.

65 Jolly JK, Pratt L, More AK, *et al*. The effect of cataract on color vision measurement with the low-vision Cambridge colour test providing an adjustment factor for clinical trials. *Ophthalmol Sci* 2022;2(2):100153.

66 Ao M, Li X, Qiu W, *et al*. The impact of age-related cataracts on colour perception, postoperative recovery and related spectra derived from test of hue perception. *BMC Ophthalmology* 2019;19:1-9.

67 Drum B, Verriest G. *Colour Vision Deficiencies IX: Proceedings of the ninth symposium of the International Research Group on Colour Vision Deficiencies, held at St. John's College, Annapolis, Maryland, U.S.A., 1–3 July 1987*. Dordrecht: Springer Netherlands; 1989.

68 Bergholz R, Dutescu RM, Steinhagen-Thiessen E, *et al*. Ophthalmologic health status of an aging population-data from the Berlin Aging Study II (BASE-II). *Graefes Arch Clin Exp Ophthalmol* 2019;257(9):1981-1988.

69 Dwyer WO, Stanton L. Racial differences in color vision; do they exist *Optom Vis Sci* 1975;52(3):224-229.

70 Costa TL, Barboni MTS, de Araújo Moura AL, *et al*. Long-term occupational exposure to organic solvents affects color vision, contrast sensitivity and visual fields. *PLoS One* 2012;7(8):e42961.

71 Triebig G, Stark T, Ihrig A, *et al*. Intervention study on acquired color vision deficiencies in styrene-exposed workers. *J Occup Environ Med* 2001;43(5):494-500.

72 Heydarian S, Mahjoob M, Gholami A, *et al*. Prevalence of color vision deficiency among arc welders. *J Optom* 2017;10(2):130-134.

73 Rozanova E, Heilig P, Godnić-Cvar J. The eye-a neglected organ in environmental and occupational medicine: an overview of known environmental and occupational non-traumatic effects on the eyes. *Arch Ind Hyg Toxicol* 2009;60(2):205-215.

74 Mehta U, Diep A, Nguyen K, *et al*. Quantifying color vision changes associated with cataracts using cone contrast thresholds. *Trans Vis Sci Tech* 2020;9(12):11.

75 Flanigan PM, Khosravi MA, Leverenz JB, *et al*. Color vision impairment differentiates Alzheimer dementia from dementia with lewy bodies. *J Geriatr Psychiatry Neurol* 2018;31(2):97-102.

76 Szeto JYY, Halliday GM, Naismith SL, *et al*. Exploring the phenotype in mild cognitive impairment to aid the prediction of those at risk of transitioning to Parkinson disease and dementia with lewy bodies. *J Geriatr Psychiatry Neurol* 2017;30(4):196-205.

77 Cabrera DeBuc D, Somfai GM, Arthur E, *et al*. Investigating multimodal diagnostic eye biomarkers of cognitive impairment by measuring vascular and neurogenic changes in the retina. *Front Physiol* 2018;9:1721.

78 Dick F, Semple S, Soutar A, *et al*. Is colour vision impairment associated with cognitive impairment in solvent exposed workers *Occup Environ Med* 2004;61(1):76-78.

79 Koh SB, Kim BJ, Lee J, *et al*. Stereopsis and color vision impairment in patients with right extrastriate cerebral lesions. *Eur Neurol* 2008;60(4):174-178.

80 Duncker G, Bredehorn T. Chloroquine-induced lipidosis in the rat retina: functional and morphological changes after withdrawal of the drug. *Graefes Arch Clin Exp Ophthalmol* 1996;234(6):378-381.

81 Pasadhika S, Fishman GA. Effects of chronic exposure to

hydroxychloroquine or chloroquine on inner retinal structures. *Eye* (*Lond*) 2010;24(2):340-346.

82 Hallberg A, Naeser P, Andersson A. Effects of long-term chloroquine exposure on the phospholipid metabolism in retina and pigment epithelium of the mouse. *Acta Ophthalmol* 1990;68(2):125-130.

83 Pasadhika S, Fishman GA, Choi D, *et al*. Selective thinning of the perifoveal inner retina as an early sign of hydroxychloroquine retinal toxicity. *Eye (Lond)* 2010;24(5):756-763.

84 Chen ZF, Lin ZC, Lu SQ, *et al*. Azole-induced color vision deficiency associated with thyroid hormone signaling: an integrated *in vivo*, *in vitro*, and *in silico* study. *Environ Sci Technol* 2022;56(18):13264-13273.

85 Sio SWC, Chan BKT, Aljufairi FMAA, *et al*. Diagnostic methods for dysthyroid optic neuropathy: a systematic review and analysis. *Surv Ophthalmol* 2024;69(3):403-410.

86 Potvin ARGG, Pakdel F, Saeed P. Dysthyroid optic neuropathy. *Ophthalmic Plast Reconstr Surg* 2023;39(6S):S65-S80.

87 Zahari KM, Rosland SF, Hannie C, *et al*. Streff-like syndrome in an adult: a case report. *Cureus* 2024;16(5):e61289.

88 Xu Y, Aung HL, Hesam-Shariati N, *et al*. Contrast sensitivity, visual field, color vision, motion perception, and cognitive impairment: a systematic review. *J Am Med Dir Assoc* 2024;25(8):105098.

89 Petrović Pajić S, Suštar Habjan M, Brecelj J, *et al*. Leber hereditary optic neuropathy in a family of carriers of MT-ND5 m.13042G>T (A236S) novel variant. *J Neuroophthalmol* 2023;43(3):341-347.

90 Toda S. Retinitis pigmentosa and color vision deficiency in Kamigoto island, Nagasaki Prefecture. *Nippon Ganka Gakkai Zasshi* 1997;101(8):669-676.

91 Piro A, Tagarelli A, Lagonia P, *et al*. Color vision study to assess the impaired retina-brain cortex pathway in type 2 diabetes: a pilot study in Calabria (Southern Italy). *Neurol Sci* 2019;40(9):1939-1942.

92 Mrugacz M, Bryl A, Zorena K. Retinal vascular endothelial cell dysfunction and neuroretinal degeneration in diabetic patients. *J Clin Med* 2021;10(3):458.

93 Trento M, Charrier L, Cavallo F, *et al*. Vision-related quality of life and locus of control in type 1 diabetes: a multicenter observational study. *Acta Diabetol* 2019;56(11):1209-1216.

94 Nguyen-Rodriguez ST, Unger JB, Spruijt-Metz D. Psychological determinants of emotional eating in adolescence. *Eat Disord* 2009;17(3):211-224.

95 Neitz M, Neitz J. Intermixing the OPN1LW and OPN1MW genes disrupts the exonic splicing code causing an array of vision disorders. *Genes* 2021;12(8):1180.

96 El Moussawi Z, Boueiri M, Al-Haddad C. Gene therapy in color vision deficiency: a review. *Int Ophthalmol* 2021;41(5):1917-1927.

97 Taylor D. Causes of Color Blindness: Function and Failure of the Genes that Detect Color. Liberty University 2020.

98 Neitz M, Krekling ED, Hagen LA, *et al*. Tritan color vision deficiency may be associated with an OPN1SW splicing defect and haploinsufficiency. *J Opt Soc Am A Opt Image Sci Vis* 2020;37(4):A26-A34.

99 Davidoff C, Neitz M, Neitz J. Genetic testing as a new standard for clinical diagnosis of color vision deficiencies. *Trans Vis Sci Tech* 2016;5(5):2.

100 Drummond-Borg M, Deeb S, Motulsky AG. Molecular basis of abnormal red-green color vision: a family with three types of color vision defects. *Am J Hum Genet* 1988;43(5):675-683.

101 Schön C, Becirovic E, Biel M, *et al*. Design and development of AAV-based gene supplementation therapies for Achromatopsia and retinitis pigmentosa. *Retinal Gene Therapy*. New York, NY: Springer New York, 2017:33-46.

102 Mutalib HA, Sharanjeet-kaur S, Lin OY, *et al*. Red tinted contact lenses on Ishihara test error scores in color deficient subjects: a pilot study. *Int J Ophthalmol* 2025;18(3):462-468.