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Meta-Analysis of Body-Related Factors of Color Sensitivity Variability

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Abstract

Introduction. Color sensitivity (the ability to distinguish individual colors and to perceive differences in the spectral composition of visible radiation and object colors) in individuals with normal color vision (healthy normal trichromats) can vary significantly under the influence of various factors, both internal and external. The most significant group of factors are physiological (or body-related). This paper is the first effort to systematize the results of empirical studies similar in methodology, in which the possible influence of body-related factors on color sensitivity was assessed using the Farnsworth-Munsell 100-Hue test. **Methods.** The study was conducted using systematic review and meta-analysis. The sources were selected in accordance with PRISMA recommendations via scientometric archives (PubMed, Scopus) and web platforms (Web of Science, Semantic Scholar). The database included the results of 35 studies conducted in the period from 1963 to 2024 in 17 countries with the participation of 4,024 subjects. **Results.** Thematic clustering of the identified works enabled us to divide the body-related factors of color sensitivity into three enlarged groups. The first group includes factors related to gender differences and endocrine specificity. The second group includes the main anthropological features of the eye, primarily the color of the iris, the density of macular pigment, and the size of the pupil. The third group includes various effects of age–related changes in the process of natural aging of the body. **Discussion.** A comparison of the total error score (TES) and partial error score (PES) of the Farnsworth-Munsell 100-Hue test obtained in each of the thematic clusters showed that color sensitivity has quite significant differences in the population, which correlate with gender, age, ethnic, and racial characteristics of the eye structure. One of the main limitations of the measurements is the involvement of participants from Europe and the United States in the studies. This is especially relevant for age-related norms. Research in this field needs to be continued and further developed.

Keywords

color sensitivity; color vision; variability of color perception; color cognition; Farnsworth-Munsell test; FM 100-Hue test; meta-analysis; systematic review; physiological factors; body-related factors

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Introduction

Variability of color sensitivity

The description and measurement of the variability of human color sensitivity is one of the relevant fields of modern interdisciplinary research into cognitive processes (see the research overview in: Bosten, 2022; Maule et al., 2023). In this case, color sensitivity is understood as the ability of the visual system to distinguish individual colors and perceive differences in the spectral composition of visible radiation and the color of objects (Izmailov et al., 1989), and its variability is understood as measurable individual differences in these sensations arising under the influence of various factors (Muraya et al., 2023).

The starting point for the beginning of a scientific discussion on individual differences in color sensitivity is considered to be the report of J. Dalton, delivered by him in 1794 and published four years later in the Proceedings of the Manchester Literary and Philosophical Society (Dalton, 1798). While studying botany, J. Dalton observed that he had considerable difficulties identifying plants by color. He found similar features of color vision in his brother, while most other people he knew saw colors differently.

Until then, the fact that color sensitivity can vary considerably from person to person has not been given much importance in science. Possible discrepancies in color recognition were mainly discussed in the context of philosophy, and there they were considered only as interesting curiosity (see: Osborn, 2012). Almost the same is the case today in the study of taste. Few people care whether all people are equally good at distinguishing the salinity or sweetness of the same product, and how these individual sensations correspond to the established standard (see for example: Spence, 2022).

The catalyst for studying color sensitivity was the development of rail transport and commercial shipping. In these new areas of activity, color began to be used as a sign of movement regulation, and an erroneous perception of color led to several major disasters, with many victims (the most famous occurred in Sweden in 1875) (Osborn, 2012, p. 324). As a result, interest in the state of color vision increased, however, greatly influenced by the practical needs of the time, the dichotomy paradigm became the main paradigm in the study of color sensitivity. From the point of view of color sensitivity, all people were simply divided into two groups – those with normal color sensitivity and those with impaired ability to distinguish between all or some shades (people with abnormal color sensitivity, or colorblind people) (see: Osborn, 2012, p. 325).

Farnsworth-Munsell 100-Hue Test

An important role in the development of a modern paradigm for studying the variation of color sensitivity has been played by the development of simple and easy to use measurement tools, especially the Farnsworth–Munsell panel tests (Farnsworth-Munsell 100-Hue, FM 100-Hue, FM-100). Developed in 1943 by D. Farnsworth based on the idea of W.O.D. Pierce (Pierce, 1934; see Pokorny & Smith, 1986) and the Munsell color system (Farnsworth, 1943, 1957), the test has been actively used since the mid-20th century to evaluate color vision and is currently one of the most widespread worldwide.

The widespread popularity of the test is related to several circumstances at once. The test is mass-produced and has a reasonable price; it is portable and convenient to transport; it has no cultural specificities and does not require any prior training from both the observer and the operator. The recognition of the test by the scientific community is also explained by the fact that it allows to quantify the color discrimination of an observer (Farnsworth, 1957; Smith et al., 1985) and compare the indicators obtained with those obtained in longitudinal studies or perform a comparative analysis of generalized groups. The test is quite resistant to refractive errors (Thyagarajan et al., 2007), has a high (up to 100%) sensitivity and specificity (83%) (Seshadri et al., 2005; Fanlo Zarazaga et al., 2019).

In the early years of the scientific application of the test, largely under pressure from the established dichotomic paradigm of color sensitivity description, individual differences, often recorded in psychophysical data within the normal range, have not become the subject of detailed discussion, much less independent research (Boston, 2022). The existence of even larger discrepancies in the data sets of people with normal color vision (normal trichromates) was seen more as an error; this was a sign that something was wrong with the study, and even a reason to distrust the averages presented, which were generally used in the analysis.

However, over time, the empirical data obtained have led to a rethink of the structure of differences in color sensitivity (see notes: Muraya et al., 2023). Researchers have come to understand that the boundaries of the norm are arbitrary, and people with normal color vision also see colors fundamentally differently. Individual differences in the processing of color-related information at different levels of the visual system affect all aspects of color perception, from color discrimination to constancy of color perception, color naming, and subjective color experience (Boston, 2022). The scientific interest thus focuses on variability, diversity in color sensitivity, research on factors that can affect it and the sociocultural consequences that this may lead to.

Throughout the long history of the Farnsworth-Munsell test, discussions of the possible influence on color sensitivity of factors that are not related to the functional capabilities of the visual system, both internal and external, have been the basis for a number of scientific publications that require systematic reflection and comprehensive analysis. Since all these papers are similar in methodology, the empirical data presented in them are suitable for comparison. Systematization and meta-analysis of the accumulated material will enable us to draw important conclusions for further research into color sensitivity and mechanisms of formation of color vision variability.

This paper **aims** to identify the physiological (body-related) factors most important for the formation of individual differences, based on a systematic review of the published results of empirical studies of the color vision of normal trichromats with the Farnsworth-Munsell test and a meta-analysis of quantitative indicators essential to the variability of color sensitivity.

Methods

Research methodology

The study uses systematic review and meta-analysis (see Littell et al., 2008), aimed at identifying, analyzing and synthesizing large amounts of quantitative empirical data from published studies using the Farnsworth-Munsell color sensitivity test.

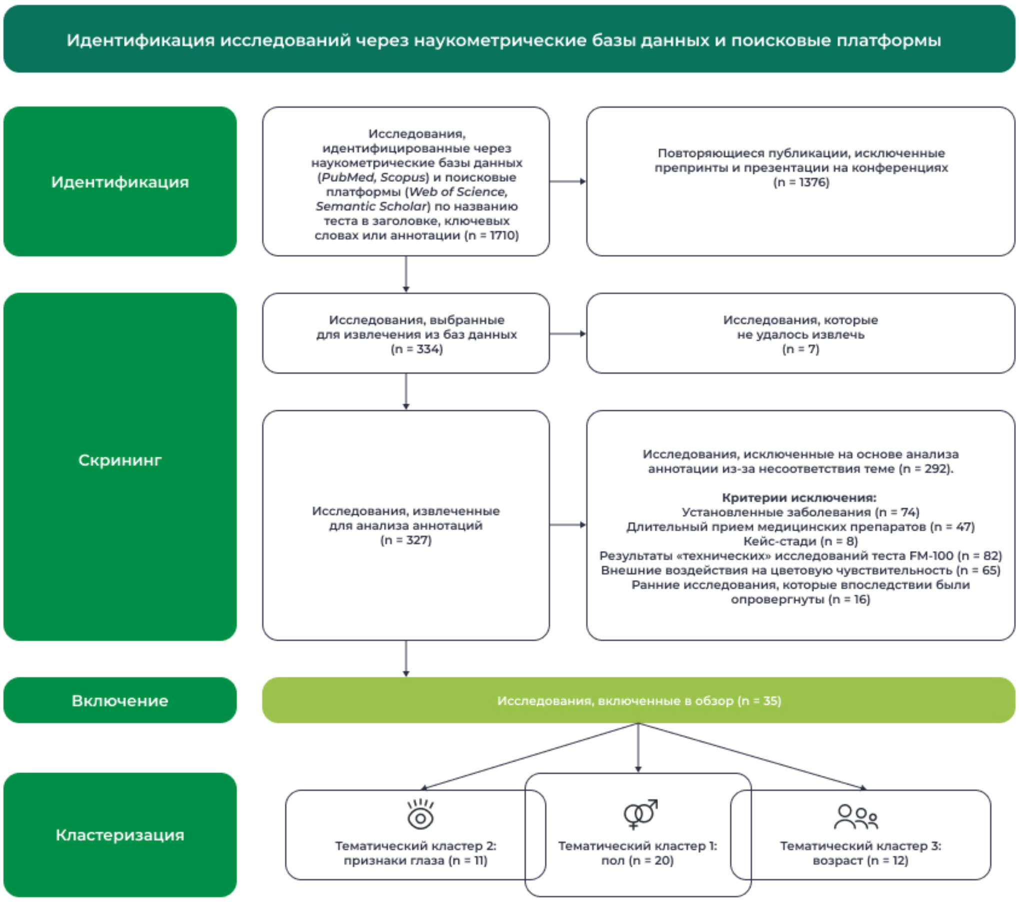
To our knowledge, this is the first systematic review of color sensitivity studies.

Source selection and formation of the research database

The selection of sources and formation of the research database were carried out in accordance with the recommendations of PRISMA (*Preferred Reporting Items for Systematic Reviews and Meta-Analyses*) (Page et al., 2021) and included 4 stages (Figure 1).

Figure 1

Stages of selecting sources and forming a research database



In the first stage, studies were identified using scientific databases (*PubMed, Scopus*) and search platforms (*Web of Science, Semantic Scholar*). Various variants of the test name accepted in scientific publications were used as a keyword (*Farnsworth–Munsell 100 Hue Color Vision test, Farnsworth–Munsell 100-Hue test, FM 100-Hue test, FM-100 test*). A search by titles, keywords, and abstracts revealed 1,710 relevant scientific publications.

During the screening, **in the second stage** of selecting sources, 1,376 repetitive publications, preprints, and conference presentations were excluded from the list. The remaining 334 articles, which could potentially be relevant to the issue under study, were prepared for extraction from the relevant databases and 327 of them were successfully extracted.

The subsequent analysis of the full texts of the abstracts in the **third stage** of source selection enabled us to form a final list of sources for a systematic review of physiological factors and a meta-analysis of the variability of color sensitivity. When forming the list, sources containing the results of measurements of color vision in individuals with established diseases (eye diseases, diabetes, dementia, Parkinson's disease, bipolar disorder, coronavirus, etc.) or long-term users of medications (antiepileptic, antidiabetic, anti-tuberculosis, and many others) were excluded. The analysis of individual cases (case studies) presented in it, the results of "instrumental" studies of the FM-100 test (for example, its comparison with others), as well as the analysis of various external influences on color sensitivity, including economic (food quality, medical care), geographical (altitude above sea level, air composition, habitual illumination), socio-cultural (field of activity, ethnic traditions, hobbies and organization of daily life), and psychological ones (alcohol and drug addiction), were also considered as reasons for excluding the study from the database.

When selecting early studies, the main criterion for inclusion in the database was their importance for the development of modern ideas about the factors of color vision variability. We did not include in the review the results of the studies that were subsequently rechecked and refuted.

Thus, the database for a systematic review and meta-analysis of the factors of color sensitivity variability, which we conditionally called body-related, includes the published results of 35 studies conducted between 1963 and 2024 in 17 countries located on all continents. These results include data obtained from the Farnsworth-Munsell test on color vision of 4,024 people aged 5 to 81.

In the **final stage** of the database formation, all the documents selected for the study were divided into three thematic clusters. The first cluster consisted of studies of gender differences and endocrine specificity of color sensitivity (n = 20). The second cluster included papers that discussed the possible impact of the main anthropological features of the eye on color sensitivity variability, including the color of the iris, the density of macular pigment, and pupil size (n = 11). The third cluster included papers on age-related changes in color sensitivity during the natural aging of the body (n = 12). The studies analyzing factors from two clusters simultaneously were included in the two corresponding groups (n = 8).

The texts of all articles selected for the review were thoroughly examined and analyzed.

Results

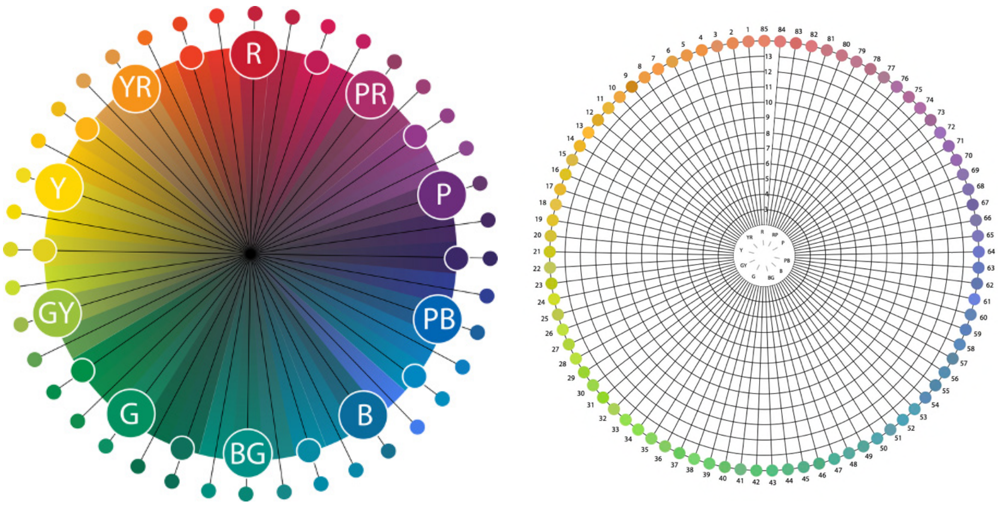
Quantitative indicators of color sensitivity variability

Test structure

The FM 100 Hue test (X-Rite, Grand Rapids, Michigan, USA) contains 85 caps, the shades of which together form a complete color wheel (Figure 2 on the left). The shades are divided into approximately equal steps of perception. In the conventions of the Munsell system (see: Griber, 2018), all shades have the same lightness and saturation values (Value = Chroma = 6) and differ only in tone (Figure 2 on the right).

Figure 2

Munsell color wheel (left) and template for presenting the results of the Farnsworth-Munsell 100 Hue test (right)



The caps are arranged in 4 trays, which are often indicated by the Latin letters A, B, C, and D. Tray A contains 22 caps, while the other three contain 21 caps. In each of the four trays, the caps represent a specific sector of the color wheel – from red to red-orange (tray A, caps 85–21), from yellow to yellow-green (tray B, caps 22–42), from green to green-violet (tray C, caps 43–63), and from indigo to magenta (tray D, caps 64–84).

The outermost caps in each tray are fixed, while the others are movable. To measure color sensitivity, the caps are mixed up and the observer is asked to rearrange the sequence in each tray so that the transition from one color to another is as smooth as possible.

Despite this seemingly simple task, only 1–2% of people with normal color vision can correctly place all caps (Pokorny & Smith, 1986). The average color difference (delta E) between the shades is only about 2.2 units, which allows for the detection of the smallest differences in color sensitivity. However, the values of this indicator vary among different color trays. Tray A is the least challenging, while tray C is the most challenging (Lakowski, 1966). The shades of the caps from 85 to 8 and from 35 to 65 are the most similar. As a result, placing these caps in the correct order is more difficult for the observer (Dain et al., 1991).

Total Error Score (TES)

The traditional analysis method first includes the calculation of the Total Error Score, TES. This indicator reflects the chromatic sensitivity in general and is calculated as the sum of the scores for the caps in the four trays. The score for a single cap is calculated as the sum of the absolute difference between the number of errors for a particular color and the number of errors for the caps adjacent to it minus 2 (Farnsworth, 1957):

$$Total\ Error\ Score\ (TES) = \sum_{i=1}^{4} iES = \sum_{i=1}^{4}\left(\left(\sum_{j=1}^{n+2} CE_j\right) - ((n+2)*2)\right) \quad (1)$$

where $CEj = |Cj\text{-}Cj\text{-}1| + |Cj\text{-}Cj+1|$; i – tray (i=1 indicates tray A, 2 – B, 3 – C, 4 – D); Cj – cap number j; CEj – cap error j; n is the number of movable caps in the tray corresponding to i (n = 22 for tray A, and n = 21 for trays B–D). For the formula to work correctly, the terms |Cj-Cj+1| and |Cj-Cj-1| must be equal to 1 when the caps are placed correctly. Since the first free cap in tray A is cap 85, not 1, a dummy array is required to calculate the value of the cap, which assigns the value 1 to cap 85, the value 2 to cap 1, and so on. The cap error (CE) is calculated for the outermost caps of the tray, otherwise the scoring would be incorrect; this requires (n + 2) terms in formula (1), where 2 accounts for the outermost caps (Esposito, 2019).

The errors made in each of the trays are denoted by AES, BES, CES, and DES, respectively (Esposito, 2019). If all the caps are placed in the correct order, the total error value, TES, is 0; the more caps are misplaced, the higher the TES value. Since TES has an asymmetric distribution, modern calculations often use the square root of the total error (√TES) to obtain a distribution that is closer to normal (Kinnear, 1970).

A special computer program (X-Rite, V.3.0, USA) is commonly used for quick estimation of the total error under laboratory and field conditions.

Depending on the magnitude of the total error score (TES), observers are traditionally divided into three groups: those with superior color discrimination (TES between 0 and 16), those with average discrimination (TES between 20 and 100), and those with low discrimination (TES>100). Most normal trichromats in the population (approximately 68%) have average discrimination, while approximately one-sixth have low discrimination and one-sixth have superior sensitivity (16% each) (Farnsworth, 1957).

Partial error scores (PES)

To determine the color sensitivity variability, partial error scores are used, which are calculated (1) separately for each cap (*IES, Individual Error Score*) (Verriest, 1963) or (2) for individual ranges of colors (*PES, Partial Error Score*).

For individual color categories (*HPES, Hue Partial Error Score*), the Total Error Score is usually divided into 10 segments (Griber & Paramei, 2024; Trukša et al., 2024):

(1) from red to yellow-red (R-YR), caps 1–9; from the long-wave region of the color spectrum to 590 nm;

(2) from yellow-red to yellow (YR-Y), caps 10–17; 590-580 nm;

(3) from yellow to green-yellow (Y-GY), caps 18–26; 580-560 nm;

(4) from green-yellow to green (GY-G), caps 27–35; 560-500 nm;

(5) from green to blue-green (G-BG), caps 36–45; 500-490 nm;

(6) from blue-green to blue (BG-B), caps 46–53; 490-470 nm;

(7) from blue to purple-blue (B-PB), caps 54–60; 470-450 nm;

(8) from purple-blue to purple (PB-P), caps 61–70; 450 nm to the short-wave end;

(9) from purple to red-purple (P-RP), caps 71–77; 560*–500* nm;

(10) from red-purple to red (RP-R), caps 78–85 (complementary to shades from green-yellow to green).

To assess the number of errors along the main axes of the perceptual color space – blue-yellow and red-green – the total error score is divided into two parts: the B-Y axis (*BY-PES, Blue-Yellow Partial Error Score*) (caps 1–12, 34–54, and 76–85) and the R-G axis (*RG-PES, Red-Green Partial Error Score*) (caps 13–33 and 55–75 (Smith et al., 1985).

As with the Total Error Score (TES), square roots of all the scores required for discussion are usually used in the analysis to obtain a distribution that is close-to-normal.

Index of change dynamics

To assess the dynamics of color sensitivity in longitudinal studies, the index of change is used, which is calculated by the formula (2):

$$\sqrt{TES_1} - 0{,}25 - \sqrt{TES_2} \quad (2)$$

where TES_1 is the total error score at the first survey, TES_2 is the total error score at the second survey.

The use of this formula allows the learning effect to be taken into account in calculations when repeating FM 100-Hue test (Verriest et al., 1982).

Age standardization of test results

Age standardization (AS) of test results can be performed based on the normative values for the age group according to the formula (3):

the individual TES – average score in the age group

the standard deviation (SD) from the average score in the age group.

The score obtained in this case shows by how many magnitudes of the standard deviation (SD) the individual TES differs from the normal average score corresponding to age (Mäntyjärvi, 2001).

Calculations using Vingrys and King-Smith method

In some studies, additional calculations are performed using the Vingrys and King-Smith method (Vingrys & King-Smith, 1988). This analysis method is based on D. Farnsworth's idea that the measurements of color sensitivity obtained using the FM 100-Hue test can be "transferred" to the color space and the difference in chroma for caps located nearby can be calculated (Farnsworth, 1943). The calculations proposed by the authors transform the cap scores from CIE 1931 into a single chromaticity space CIELUV 1976 to determine the vectors of color differences between adjacent caps in the analyzed sequence. The direction of the vectors obtained shows the type of violation of the observer's color perception, and its length shows the degree of displacement of adjacent caps.

Calculations using Vingrys and King-Smith method traditionally include the determination of five main indicators, including the confusion angle, the minor radius, the major radius, the scatter index (S-index = major radius / minor radius) and the confusion index, C-index (see Griber & Paramei, 2024). In modern research, Vingrys and King-Smith analysis is usually performed using specialized WEB-based programs (see for example: http://www.torok.info/fm100/).

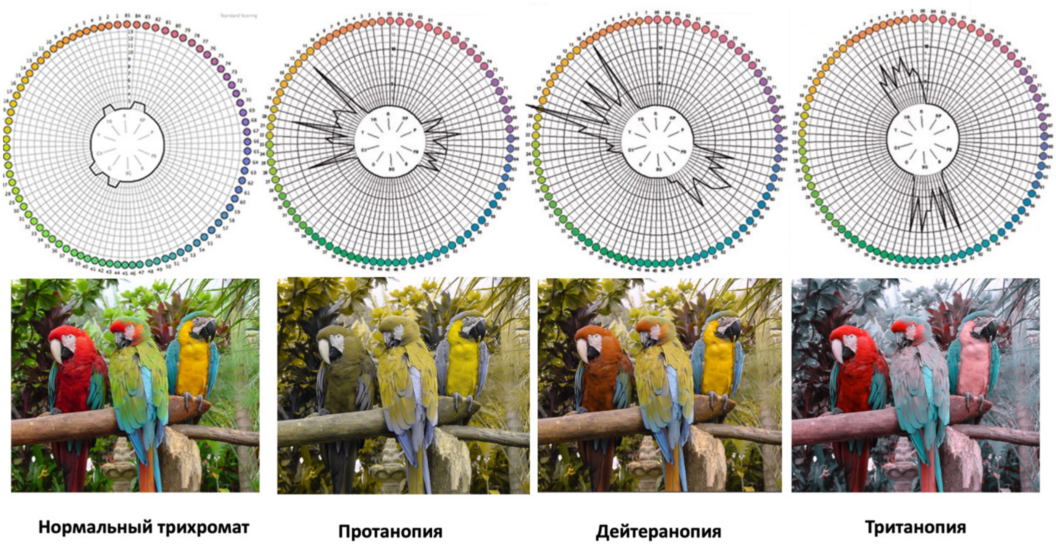
Interpretation of color sensitivity variability indicators

To interpret the variability of color sensitivity, the terminology of congenital color vision abnormalities is usually used, although congenital disorders of color sensitivity and its variability within the normal range most often have a fundamentally different nature and different scale. In the case of color sensitivity variability, we are not talking about pronounced defects, but only about weakness of color vision. However, in both cases, errors made during the test on the color wheel contribute to a characteristic pattern (see, for example, Birch, 1989).

Deutane defects is caused by pigment changes in the M-type cones, and protane defects – in the L-type cones. People with both types of color disorders do not distinguish well between the same colors (for example, orange, yellow and green; dark green, brown and red), therefore such disorders are also called red-green color vision deficiency. The two main differences between these two types of disorders are that people with deutane defects retain normal brightness sensitivity to red light, while people with protane defects have decreased brightness sensitivity, resulting in poor discrimination between red and gray. People with tritan defects usually confuse purple, gray and yellow-green; blue and blue-green; blue-green and bluish-white; dark blue and black. As a result, this disorder is also called blue-yellow color vision deficiency (Lankford & Hovis, 2023). By analogy with color vision anomalies, color vision variability is also described depending on the predominant axis (as blue-yellow or red-green changes) or compared with a specific type of color anomaly (deutane-, protane-, or tritane-like deficiency) (Figure 3).

Figure 3

The characteristic location of error zones for various color vision abnormalities in the results of the Farnsworth-Munsell test (above) (reconstruction based on diagrams in the sources (Lakowski, 1969; Kinnear, 1970; Knoblauch, 1987)) and modeling the color perception of a complex scene with each type of violation (below) using a simulator (Coblis, 2025)



Meta-analysis of body-related factors of color sensitivity variability

The thematic clustering of factors that can be conventionally referred to as body-related allows us to combine them into three extended groups: (1) gender and endocrine specificity, (2) the main anthropological characteristics of the eye (iris color, macular pigment density, pupil size), and (3) age-related changes in the process of natural aging of the body. Each of these groups is considered separately in the following review.

Gender and endocrine specificity

A comparative analysis using the Farnsworth-Munsell test on color sensitivity in men and women has not yet yielded clear results (Table 1). In most of the studies conducted, no statistically significant differences between men and women were found (Verriest, 1963; Knoblauch et al., 1987; Rigby et al., 1991; Mäntyjärvi, 2001; Karaca et al., 2005; McCusker et al., 2012; Koçtekin et al., 2013; Oji et al. al., 2014; Simionato et al., 2021). A number of studies have found that young women are better able to distinguish shades than men of the same age (Fine, 1973; Fine & Kobrick, 1980 vs. Fine, 1983; Panchal et al., 2013; Imbery et al., 2018, 2020, 2022; Gupta et al., 2020), and this advantage persists until about 25 years of age (Verriest, 1963). However, the opposite result was also recorded – fewer errors were recorded among young men compared to their peers (Dain et al., 2004).

The rhetoric of the publications included in the review indicates that, in general, possible differences in color sensitivity between men and women are generally expected for researchers due to gender dimorphism, pronounced hormonal, ontogenetic and environmental inconsistencies between the genders, as well as significant gender differences in the cognitive processing of color information at all levels, from color perception to color metacognition, which may be related to a wide range of social and behavioral reasons (see: Grieber, 2025).

Traditionally, women are believed to have a more developed color sensitivity than men. In many respects, this view is stereotypical, because men are statistically ten times more likely than women to have hereditary color vision disorders; 8% of men and only 0.4% of women have various color vision abnormalities worldwide (see, for example, Moreira et al., 2024). However, this factor could actually influence the result obtained: since color abnormalities screening was not carried out in most studies, men were more likely than women to have an unidentified observer with severe color vision impairments among the average results, if excluded, the gender difference would lose statistical significance.

Researchers attribute higher color sensitivity rates in men to gender differences in pupil diameter. Because men have a larger pupil diameter than women, more light enters the retina, which has a positive effect on color discrimination (Dain et al., 2004).

The differences in the obtained results may be explained by the fact that participants in some studies may have simply been motivated and more attentive to the task than participants in others (Murray et al., 2012).

Another possible cause may be unaccounted for endocrine changes, which are discussed separately in a number of published papers (Giuffre et al., 2007; Orbán & Dastur, 2012). Studies have shown that women's color vision experiences subtle but statistically significant fluctuations at different stages of the menstrual cycle under the influence of changes in estradiol levels. As a result, women are better able to distinguish color during ovulation compared to the beginning and end of the menstrual cycle (Giuffre et al., 2007).

Significant improvements in color discrimination (lower total error scores (TES) compared to non-pregnant women) are also noted in the background of pronounced hormone dynamics in pregnant women during the first trimester of pregnancy. Researchers believe that changes in color discrimination can be part of a network of perceptual and physiological defense mechanisms (including changes in the sense of smell and taste, nausea and vomiting) that perform adaptive functions. They increase the likelihood of visual signals associated with food toxicity, thereby reducing the risk of eating foods containing teratogens that can cause abnormal fetal development (Orbán & Dastur, 2012).

Table 1

Mean score and standard deviation of the total errors scores (TES) for healthy normal trichromats of different genders, presented in (Verriest, 1963, Table 2), (Dain et al., 2004, Table 2), (Panchal et al., 2013, Table 1), (Gupta et al., 2020, Tables 2 and 3)

Gender	Healthy normal trichromats of different genders													
	Verriest (1963)				Dain et al. (2004)		Panchal et al. (2013)		Imbery et al. (2018)		Gupta et al. (2020)			
	N	Mean TES ± SD 15–19	N	Mean TES ± SD 20–24	N	Mean TES ± SD 18–24	N	Mean TES ± SD 18–22	N	Mean TES 21–44	N	Mean. TES ± SD 18–25	Right eye Mean TES ± SD 18–25	Left eye Mean TES ± SD 18–25
M	25	60.1 ± 29.4	60	42.3 ± 34.9	30	21.4 ± 19.1	50	43.80 ± 28.52	59	29.2	101	76.00 ± 10.61	89.56 ± 18.92	95.92 ± 22.27
F	31	44.5 ± 25.5	34	25.5 ± 20.6	32	30.6 ± 19.4	50	28.38 ± 22.62	36	18.6	69	48.85 ± 13.02	58.81 ± 16.70	64.35 ± 16.52

Note. Binocular measurements are indicated in dark grey, monocular indicators of the right eye are light grey. The table contains only data from studies in which the differences between the indicators for men and women were statistically significant.

Anthropological characteristics of the eye

According to the published data, color sensitivity has quite noticeable differences that correlate with the anthropological characteristics of the eye – the color of the iris, the density of macular pigment, pupil size, and lens color. Moreover, the results of the measurements indicate that all these qualities seem to be interrelated (see the review of research in Garakani & Ng, 2019).

In particular, if we reduce the entire variety of existing iris color options to three main types, which correspond to the classes of the Bunak scale (Bunak, 1941) (this is exactly what some researchers did to test their hypotheses) – (1) dark type (the iris is black, dark brown, light brown, or yellow); (2) light type (the iris consists of gray, blue, light blue and gray-blue color elements) and (3) mixed type (the iris contains areas of dark and light color and it has a green, gray-green, brown-green, brown-gray shade or is colored gray or blue with a brown aureole) – then all other marked indicators will correlate with this division.

A dark eye color usually means a smaller pupil size and a denser macular layer (Hammond et al., 1996; Hammond & Caruso-Avery, 2000; Dain et al., 2004). Macular pigments, which are located in front of photoreceptors, most actively absorb waves in the blue part of the spectrum, with a length of approximately 460 nm. Thus, they are a kind of optical yellow filter for photoreceptors (Budzinskaya, 2018). Simulating an increase in the density of the macular layer using artificial filters significantly reduces color sensitivity. This leads to an increase in the total error index and causes a pronounced tritan-like polarity along the blue-yellow axis (Moreland & Dain, 1995). A natural increase in the density of the macular layer also leads to an increase in the overall error rate (Woo & Lee, 2002; Dain et al., 2004) and partial errors in the blue (caps 50-68) and blue-green (caps 36-54) parts of the color spectrum, which, however, does not reach the level of statistical significance (Davison et al., 2011; Garakani & Ng, 2019).

On the contrary, a light eye color, as a rule, correlates with a larger pupil size and a less dense macular layer (Woo & Lee, 2002; Dain et al., 2004). As a result, fair-skinned people with light iris colors (blue or green), according to the FM 100-Hue test, have higher color sensitivity than observers with dark (brown) eye color (Zlatkova et al., 2014; Garakani & Ng, 2019).

The analysis of eye anthropological characteristics also correlates with ethnicity and race (Woo & Lee, 2002; Dain et al., 2004; Garakani & Ng, 2019). In particular, pigmentation, including eye color, is crucial in racial classification, is a racial diagnosis feature and is used to characterize populations (see Loskutova, 2013).

In general, studies indicate the existence of a certain pattern. A higher rate of total error and especially so-called tritan errors (errors along the blue-yellow axis of perceptual space) is typical for people with dark skin and dark iris colors – Africans (Kaimbo Wa Kaimbo et al., 1994), Asians (Woo & Lee, 2002; Garakani & Ng, 2019), Indian reservation populations (Burdick & Chebib, 1982). The light-skinned observers with light eye color surveyed in Europe and the USA had the least number of errors. The difference between groups increases with age and is less evident among younger participants.

Table 2

Mean score and standard deviation of the square root of the total error score (√TES) for healthy normal trichromats of different ages, presented in (Verriest et al., 1982, Table 1), (Roy et al. 1991, Table 1), (Mäntyjärvi, 2001, Table 1) and (Kinnear & Sahraie, 2002, Table 1)

Age group	Healthy normal trichromats of different age													
	Verriest et al. (1982)				Roy et al. (1991)				Mäntyjärvi (2001)				Kinnear & Sahraie (2002)	
	N	Mean √TES ± SD	Right eye Mean √TES ± SD	Left eye Mean √TES ± SD	N	Right eye Mean √TES ± SD	N	Left eye Mean √TES ± SD	N	Right eye Mean √TES ± SD	N	Left eye Mean √TES ± SD	N	Mean √TES
5–9					7	15.6 ± 6.3	7	14.1 ± 5.5					72	15.7
10–14	27	9.13 ± 1.85	9.71 ± 2.54	9.51 ± 2.29	13	7.2 ± 3.0	13	6.3 ± 2.9	24	8.66 ± 2.29	24	8.76 ± 2.56	153	9,7
15–19	32	6.63 ± 1.91	7.62 ±2.04	7.07 ± 2.15									68	7.2
20–29	29	5.69 ± 2.07	6.47 ± 2.42	6.35 ± 2.39	25	6.0 ± 2.2	25	6.0 ± 2.5	30	7.44 ± 2.46	30	7.56 ± 2.36	35	6.7
30–39	29	6.71 ± 2.90	7.50 ± 2.68	7.45 ± 2.60	16	6.7 ± 1.9	17	5.8 ± 2.7	23	7.80 ± 3.09	23	8.13 ± 2.54	10	7.3
40–49	30	8.23 ± 2.44	9.28 ± 2.33	8.66 ± 2.34	13	5.8 ± 1.1	12	5.3 ± 2.0	31	9.34 ± 2.22	34	9.22 ± 2.38	10	8.1
50–59	30	8.68 ± 2.64	10.36 ± 2.43	10.22 ± 1.99	10	8.2 ± 2.0	10	8.0 ± 2.7	27	9.62 ± 1.59	23	9.28 ± 2.01	10	9.5
60–69	28	9.57 ± 2.44	10.93 ± 2.59	11.11 ± 2.76	20	10.1 ± 3.0	18	9.6 ± 3.0	21	10.07 ± 2.03	20	10.16 ± 2.68	10	10.7
70–80	27	11.46 ± 2.01	13.45 ± 2.04	13.30 ± 2.18	9	11.9 ± 2.1	9	12.3 ± 1.4					10	12.3

Note. Binocular measurements are indicated in dark gray, monocular scores of the right eye are light gray.

Age

A large number of studies focus on age-related differences in color sensitivity in normal trichromats. All these studies can be roughly divided into two groups. The first group is devoted to the development of age-related limits of the norm. The second one is the study of factors explaining the age-related dynamics of color vision.

The specificity of studies aimed at determining the age-related limits of the norm of color sensitivity lies in a sufficiently large number of observers, who are grouped into five- or ten-year-old age cohorts to calculate generalized indicators. The first work of this kind was published in 1963 (Verriest, 1963). In subsequent years, updated normative scores were presented for healthy normal trichromats of mature age groups (Pinckers, 1980; Verriest et al., 1982; Roy et al., 1991; Trukša et al., 2024) from different ethnic groups (Mäntyjärvi, 2001; Karaca et al., 2005) and more detailed data on younger cohorts (Kinnear & Sahraie, 2002).

The measurements were performed monocularly or binocularly (Table 3), in various light conditions, which varies from 100 to 1000 lux, and in different populations – Belgians (Verriest, 1963; Verriest et al., 1982), British (Aspinall, 1974; Kinnear & Sahraie, 2002), Dutch (Pinckers, 1980), Americans (Roy et al., 1991), Turks (Karaca et al., 2005), and Finns (Mäntyjärvi, 2001). Nevertheless, all these studies on the age-related dynamics of color vision indicate the same trend. Chromatic sensitivity usually increases before the age of 20-30, remains relatively stable during the following years of life, and decreases after 40. The most noticeable statistically significant differences in the total error score are observed between the age groups 19-29 ($M = 23.96$, $SD = 12.98$) and the groups 40-49 ($M = 39.97$, $SD = 25.12$), 50-59 ($M = 55.40$, $SD = 12.98$) (Trukša et al., 2024). At the same time, the values of the partial error along the red-green axis practically do not change throughout life. The changes mainly affect the blue-yellow B-Y axis, especially the BG-B, B-PB, G-BG and RP-R categories (Maule et al., 2023).

The mean error score in monocular and binocular testing is comparable and does not differ statistically. The normative differences between the monocular indices ($\sqrt{R} - \sqrt{L}$) for different age groups coincide and reach 0 ± 1.16 (Aspinall, 1974).

Studies of the age-related variability of color sensitivity of the second type are intended to test hypotheses on the influence of specific factors of different types on age-related changes in color vision. In this case, scientists develop the design of experiments to “isolate” any single factor and draw conclusions as a result of the study on its role in the processes of reducing color vision or excluding its influence.

In younger cohorts, decreased color vision is usually associated with the late completion of the formation of the blue-yellow system (Dain, 2004). Until recently, the negative dynamics of color vision recorded in the older groups were associated with age-related changes in the lens, which increase the adsorption capacity of short wavelengths of the visible spectrum, such as an increase in the density of the lens, changes in its color and transparency.

To simulate the yellowing of the lens in young observers, the researchers used special yellow filters. In early studies (Verriest, 1963), this caused a marked increase in the number of errors when performing the FM 100 Hue test. However, scientists later concluded that filters probably did not accurately reproduce age-related changes that occur in the ability of the lens to transmit light waves in reality. More recent studies have shown that the yellowing of the lens can hardly be regarded as a decisive factor in age-related changes in color vision (see the review of studies in Griber et al., 2020). The researchers also found no significant relationship between psychophysical estimates of lens density and the FM 100 Hue test results in a group of normal subjects with a limited age range (50-70 years) (Sample et al., 1988).

Today, it is considered a more reasonable strategy to take into account age-related changes in color sensitivity as a result of a complex combination of physiological changes that must be taken into account in combination (Beirne et al., 2008). The most significant are age-related decreases in pupil size and the associated decrease in retinal illumination (Knoblauch et al., 1987; Dain et al., 2004), blurred vision (Thyagarajan et al., 2007), and changes in the thickness of the macular layer (Moreland & Dain, 1995; Woo & Lee, 2002; Dain et al., 2004).

Color vision changes that are more pronounced than age-related norms occur in various diseases, including diabetes mellitus, glaucoma, cataracts and a number of others (see the review of studies in: Trukša et al., 2024).

Table 3

A list of papers presenting the results of empirical studies using the FM 100 Hue test of the effects of various body-related factors on color sensitivity

Authors	Year	Country	N	F	Age	Factor		Method	Time limit	Light control	Indicators
Verriest	1963	Belgium	480	233	10–64			bino	no	yes	TES, IES, HPES
Fine	1973	USA	56	0	n/s (soldiers)			bino	2 min	no	TES
Aspinall	1974	UK	113	n/s	n/s			mono	no	yes	TES
Fine & Kobrick	1980	USA	36	9	n/s (soldiers)			bino	2 min	yes	TES
Pinckers	1980	Nether-lands	410	n/s	0–69			bino	no	yes	TES
Burdick & Chebib	1982	USA, Canada	92	0	24–49			bino	no	no	TES, IES
Verriest et al.	1982	Belgium	232	123	10–80			bino, mono	no	yes	TES, AES, BES, CES, DES

Authors	Year	Country	N	F	Age	Factor	Method	Time limit	Light control	Indicators
Fine	1983	USA	30	30	17–62 (32.6 ± 13.5)		bino	2 min	yes	TES, AES, BES, CES, DES
Knoblauch et al.	1987	France	75	39	20–78	 	bino, mono	no	yes	TES, IES
Rigby et al.	1991	UK	30	7	20–45+		bino	no	yes	TES
Roy et al.	1991	USA	115	63	5–81		mono	no	yes	TES
Kaimbo Wa Kaimbo et al.	1994	Zaire	132	n/s	20–49		bino	no	no	TES
Moreland & Dain	1995	UK, Australia	10	n/s	n/s		mono	no	yes	TES, IES
Mäntyjärvi	2001	Finland	160	106	10–69	 	mono	no	yes	TES, AES, BES, CES, DES AS
Kinnear & Sahraie	2002	UK	382	193	5–79		bino	2 min	no	TES, BY-PES, RG-PES
Woo & Lee	2002	Hong Kong	100	49	30–59 (43.48 ± 7.66)		bino	no	yes	TES, IES, BY-PES, RG-PES

Authors	Year	Country	N	F	Age	Factor	Method	Time limit	Light control	Indicators
Dain et al.	2004	Australia	63	32	18–24 (21.4)		bino	no	yes	TES, V&K-S
Karaca et al.	2005	Türkiye	180	90	10–69		mono	no	yes	TES, AES, BES, CES, DES, BY-PES, RG-PES
Giuffrè et al.	2007	Italy	15	15	21–34 (25 ± 4)		mono	no	yes	TES, AES, BES, CES, DES
Thyaga-rajan et al.	2007	United Kingdom	15	7	21–34		mono	no	yes	TES, IES, BY-PES, RG-PES
Beirne et al.	2008	United Kingdom	20	10	(22.2 ± 2.65) (54.5 ± 2.64)		mono	no	yes	TES, BY-PES, RG-PES
Davison et al.	2011	United Kingdom, South Africa	102		18–40 (29 ± 6)		mono	no	yes	TES, IES, HPES (blue, cyan)
McCusker et al.	2012	United Kingdom	30	18	20–61		mono	no	yes	TES

Authors	Year	Country	N	F	Age	Factor	Method	Time limit	Light control	Indicators
Orbán & Dastur	2012	Canada	13	13	20–29 (28.35)	⚤	bino	no	yes	TES
Koçtekin et al.	2013	Türkiye	50	19	(21.18 ± 2.52)	⚤	mono	no	no	TES, BY-PES, RG-PES
Panchal et al.	2013	India	100	50	(19.51 ± 1.46)	⚤	bino	no	no	TES
Oji et al.	2014	Japan	68	20	27–69 (44.3 ± 9.1)	⚤	bino	no	yes	TES, PES 64–78 (tongue color region)
Zlatkova et al.	2014	United Kingdom	28	15	20–30	👁	bino	no	yes	TES, BY-PES, RG-PES
Imbery et al.	2018	United States	95	36	21–44 (25)	⚤ 👁	bino	no	yes	TES
Garakani & Ng	2019	United States	30	17	18–40 (25.1 ± 2.5)	👁	mono	no	yes	TES, BY-PES, RG-PES

Authors	Year	Country	N	F	Age	Factor	Method	Time limit	Light control	Indicators
Gupta et al.	2020	India	170	69	18–25 (18.6 ± 0.91)	⚤	bino, mono	2.5 min	no	TES
Imbery et al.	2020	United States	291	147	(24.9 ± 3.9)	⚤ 👁	bino	no	yes	TES
Simionato et al.	2020	Brazil	120	67	20–29 (22.7)	⚤	bino	2 min	yes	TES
Imbery et al.	2022	United States	98	59	22–26 (25.5 ± 4.1)	⚤ 👁	bino	no	yes	TES
Trukša et al.	2024	Latvia	146		19–70	👥	bino	no	yes	TES, HPES, BY-PES, RG-PES

Note: The articles are listed in chronological order, with each year listed in alphabetical order. The age description includes a range, with minimum/maximum values, the mean score ± standard deviation in parentheses. The following symbols are used in the table: N – total number of observers; M – males; F – females; bino – binocular measurement; mono – monocular measurement; n/s – not specified; TES – total error score; AES – tray A error score; BES – tray B error score; CES – tray C error score; DES – tray D error score; IES – individual error (for each cap); HPES – partial error score for individual hues; BY-PES – partial error score along the blue-yellow axis, RG-PES – partial error score along the red-green axis; AS – age standardization of test results; V&K-S – Vingrys and King-Smith calculations. Thematic groups of body-related factors are indicated graphically: ⚤ – factors related to gender differences and endocrine specificity; 👁 – the main anthropological characteristics of the eye; 👥 – factors of age-related changes in the process of natural aging of the body.

Discussion

The systematic review presented in this paper contains a critical analysis of the literature in the subject area, which enables us to compare the available data, identify trends and locate gaps in the study of body-related factors of color sensitivity. The review covers empirical studies over the past 60 years conducted in various countries of the world on all continents (Table 3).

The systematization of quantitative indicators and traditions of interpretation of test results shows that most studies use standard indicators for the analysis of collected data – total error score (TES) and (less often) partial error score (PES). In earlier studies partial error scores are most often calculated for individual trays (see, for example: Verriest et al., 1982; Fine, 1983; Mäntyjärvi, 2001; Karaca et al., 2005; Giuffrè et al., 2007); in later studies – along the main axes of the perceptual color space – blue-yellow and red-green (see, e.g., Kinnear & Sahraie, 2002; Woo & Lee, 2002; Karaca et al., 2005; Thyagarajan et al., 2007; Beirne et al., 2008; Koçtekin et al., 2013; Zlatkova et al., 2014; Garakani & Ng, 2019; Trukša et al., 2024). More complex calculations (for example, the calculation of partial error scores separately for each hue or by zones corresponding to the type of color vision impairment (see, for example: Verriest, 1963; Davison et al., 2011; Trukša et al., 2024), as well as the use of Vingrys and King-Smith coefficients and the interpretation of data in three-dimensional color space) (see, for example, Dain et al., 2004) are still rare.

In some cases, refusing to use certain methods is really justified. In particular, the Vingrys and King-Smith method provides the most significant results when analyzing significant color anomalies. On the contrary, in studies of color sensitivity variability that does not exceed normal limits, color vectors may have very variable angles, which makes the application of the method problematic (see, for example, Dain et al., 2004).

In the case of testing the same hypothesis, there are quite obvious differences between the indicators in different studies in some cases (Tables 1 and 2), which, however, usually indicate the presence of the same or similar trends. Researchers explain the differences between the indicators in different ways, most often by differences in the level of motivation of observers (see, for example, Murray et al., 2012), low or uncontrolled illumination (see, for example, Verriest et al., 1982; Knoblauch et al., 1987) or the possible presence in databases of unaccounted-for patients with minor color sensitivity disorders under the influence of any unaccounted-for factors, for example, endocrine ones (cf.: Giuffre et al., 2007; Orbán & Dastur, 2012).

The thematic clustering of studies confirming the possible effect on color sensitivity of internal physiological mechanisms and anthropological characteristics allows us to identify three groups of factors that can be conditionally referred to as body-related, including (1) gender and endocrine specificity, (2) the main anthropological characteristics of the eye, and (3) age-related changes in the process of natural aging of the body. A comparison of the indicators obtained in each of the thematic clusters indicates that the detected violations are moderate or even mild and, in general, manifest within the age-appropriate norm (see, for example, Pinckers, 1980; Verriest et al., 1982; Roy et al., 1991; Mäntyjärvi, 2001; Kinnear & Sahraie, 2002; Karaca et al., 2005; Trukša et al., 2024). However, at the population level, such dynamics allow us to draw important conclusions on physiological factors that influence color perception. In particular, according to published data, color sensitivity has quite noticeable differences that correlate with ethnic and racial features of the eye structure – the color of the iris, the density of macular pigment, pupil size (see, for example: Burdick & Chebib, 1982; Kaimbo Wa Kaimbo et al., 1994; Moreland & Dain, 1995; Woo & Lee, 2002; Dain et al., 2004; Davison et al., 2011; Zlatkova et al., 2014; Garakani & Ng, 2019); with gender differences (Fine, 1973; Fine & Kobrick, 1980 vs. Fine, 1983; Dain et al., 2004; Panchal et al., 2013; Imbery et al., 2018, 2020, 2022; Gupta et al., 2020) and endocrine specificity (Giuffrè et al., 2007; Orbán & Dastur, 2012).

Conclusion

One of the main limitations of the measurements was that European and American participants were mainly involved in the research. This is especially relevant for age-specific norms. Attempts to test the stability of age-specific norms in other ethnic and racial conditions, especially in Zaire black population, Asians and the population of American Indian reservations, are still sporadic and are usually conducted in a small sample. Research in this field needs to be continued and further developed.

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Conflict of Interest Information

The authors have no conflicts of interest to declare.