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UDC (Universal Decimal Classification) 001 Science and knowledge in general, 004 Computer science and technology, 159.91 Psychophysiology, 612.8 Neurophysiology and Sensory perception.
The title of the book reflect traditional integration between sensory physiology and communication technology. Neurotechnology as a part of information technology was based on sensory physiology, decision making and planning the movements for goal achievement. Neurotechnology is a part of the creation of the artificial intelligence systems, the convergence of man and autonomous intelligent artificial devices with targeted activities. This book reflects a wide range of investigations from biological and artificial neural networks to rehabilitation neurotechnologies for neurological patients, with sensory and cognitive dysfunctions. The most part of this book has been discussed by the authors at the IEEE International Conference «Video and Audio Signal Processing in the Context of Neurotechnologies» November 7–11, 2022 at I. P. Pavlov's Institute of physiology RAS.

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Chapter 9. Assessment of color discrimination thresholds by the strict substitution method: a pilot study

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Abstract

Introduction. Color discrimination of human visual system has particular thresholds, which are usually described by color discrimination ellipses (MacAdam, 1942). Shape of the ellipses may depend on a number of experimental method parameters. Although the "strict substitution" method is considered to be the most accurate (Wyszecki, Stiles, 2000), the ellipses are usually obtained by comparison of two adjacent stimuli.

The goal: To estimate color discrimination thresholds with strict substitution method for five CIE-recommended color centers and to validate a new device for color threshold assessment.

Methods. After adaptation (1 min), the participant observes a 2° self-luminous stimulus. The initial color of the stimulus was set in xyY coordinates and corresponded to one of the five color centers (Robertson, 1978). The reference stimulus was replaced by a test one at a frequency of 0.33 Hz. The subject had to change the chromaticity coordinates of a test stimulus until the flicker became distinguishable. Test stimulus chromaticity was changed along eight directions (separated by 45°) on the xy plane. The resulting thresholds were compared with the predictions of the CIEDE2000 color difference formula.

Results. STRESS metric results are (color center, STRESS value): red, 0.337; yellow, 0.119; green, 0.170; blue, 0.199; gray, 0.158.

Conclusion. The new device tested allowed us to obtain color vision thresholds by strict substitution method. The data obtained for all color centers except for the red one agree well with the CIEDE2000 formula and with other researchers' data.

Introduction

Human vision has an ability to discriminate colors, and that ability is based on several types of photoreceptors in our retina. For a long time, it was mainly accepted that color vision is based on three cone receptors only. Even though there is some evidence that both rods and intrinsically photosensitive retinal ganglion cells may contribute to the perceived colors (Graham, 2014; Graham et al., 2007; Zele et al., 2018), nevertheless most research and application for color vision still work with the three cones paradigm. Three cone based color vision models are also fully acceptable for central vision, since in the central part of the retina (foveola) humans do not have neither rods, nor ganglion cells.

Three types of cones usually discussed for color vision research are S-, M- and L-cones, differing in the position of their spectrum sensitivity peaks. Short wavelength sensitive cones (S-cones) have peaks at about 420–440 nm, middle wavelength sensitive ones have peaks at 534–545 nm, and long wavelength sensitive cones have peaks at about 564–580 nm. Example of sensitivity spectra is presented in Figure 1.

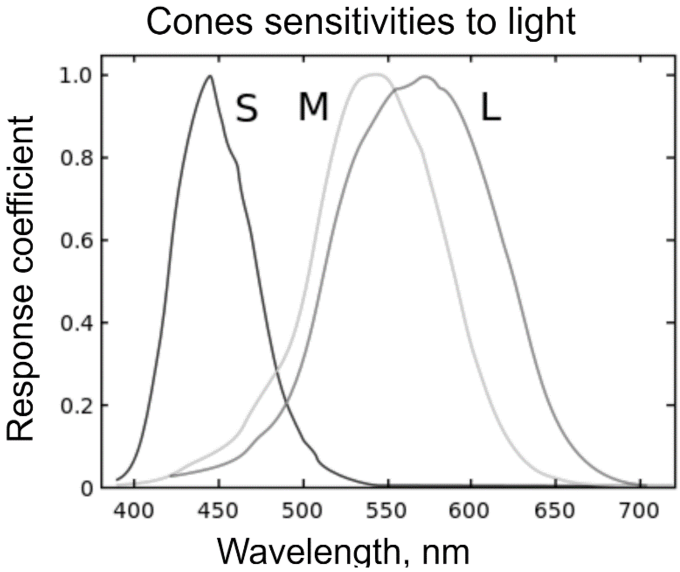


Figure 1. *Cone sensitivity spectra. S, M and L are referring to the S-, M-, and L-cones, respectively. Image source: https://en.wikipedia.org/wiki/Spectral_sensitivity#/media/File: Cones_SMJ2_E.svg, CC BY3.0*

To operate colors in practical needs many attempts were made to create color vision space and color vision models, and most of them are based on data for central color vision and three cones types. One of the most popular spaces are CIE1931, CIE1964, CIELUV, CIE Lab, and many others. An example of the entire range of possible chromaticities in CIE1931 color space is presented in Figure 2 by a horseshoe shaped outer curve.

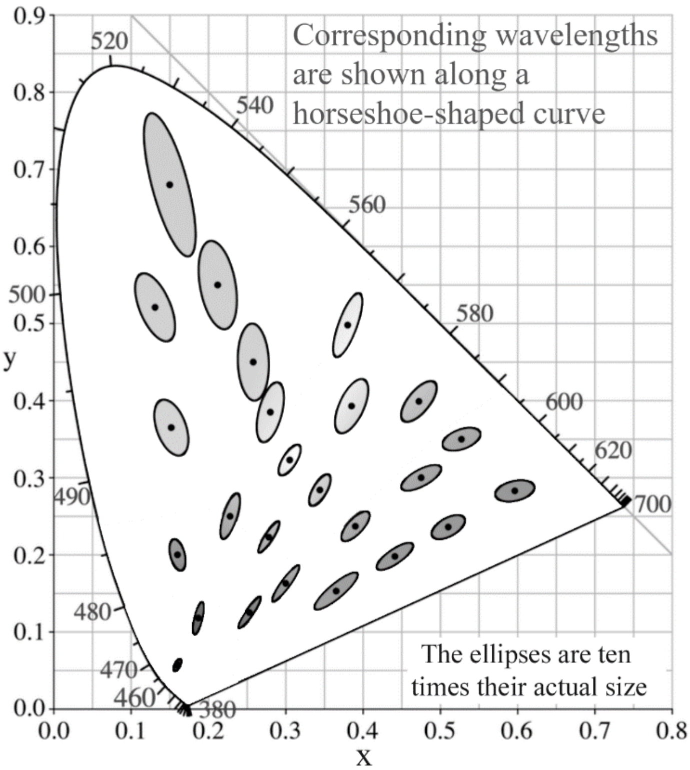


Figure 2. *Entire range of possible chromaticities in CIE1931 xy chromaticity diagram and MacAdam ellipses of indistinguishable colors. The ellipses are ten times their actual size, as depicted in MacAdam's paper. Along a horseshoe-shaped outline of all possible colors, referring wavelengths are marked.*

Intuitively easy to understand, that human color vision has some color resolution thresholds. If a person with normal trichromatic color vision looks at two colors, for example, yellow and violet, he/she could easily see the difference. If different colors are chosen, for example, violet and slightly more purplish violet, the difference between colors is not so obvious. At some point, such colors may be chosen, that even though they have different coordinates in color space, human participants are unable to see the difference.

In 1942 it was shown that in the CIE1931 xy chromaticity diagram the areas of indistinguishable colors have the form of ellipses of different size, axes angles and ratios (see Figure 2). The work was conducted by David MacAdam (MacAdam, 1942), and the color threshold ellipses are often called after him as MacAdam ellipses. For people with normal (trichromatic) color vision those differences in ellipse forms do not reflect any properties of human color vision. The ellipse's different shapes only reflect that the color space is not perfect, or rather it is not uniform in color contrast.

Since the famous MacAdam paper in 1942, a lot of work has been devoted to assessment of color thresholds and perceived color differences. There are several most famous papers on threshold assessment (Silberstein, MacAdam, 1945; Brown, Macadam, 1949; Brown, 1957; Wyszecki, Fielder, 1971; etc.), a concise and nicely written summary of which could be found in (Wyszecki, Stiles, 2000, ch. 5). Another type of research is devoted to assessment of suprathreshold differences: in that case a participant could clearly see the difference between two colors and have to assess the amplitude of such difference. One of the most common experimental designs for such assessments includes comparison with gray scale (see Figure 3 for an example). Some recent examples of suprathreshold studies may be found in (Xu et al., 2021; Zhao et al., 2020; Mirjalili et al., 2019; Xu et al., 2019). Both types of those studies, threshold and suprathreshold, are essential for further progress of color science.

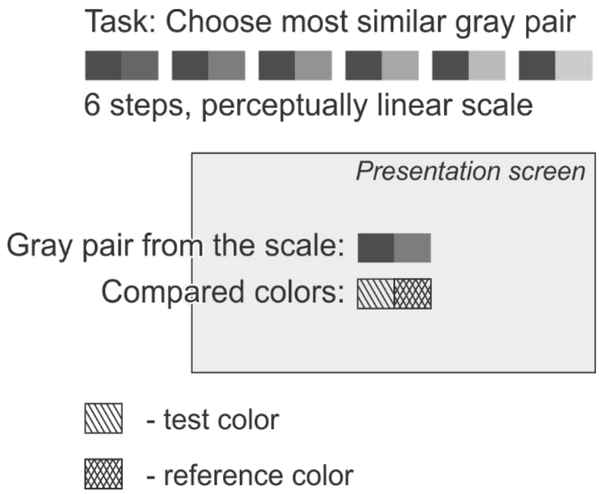


Figure 3. *An example of experimental design for small color differences assessment (suprathreshold differences). A pair of colored samples are presented (test color and reference color) on a presentation screen or a presentation surface. A set of gray pairs are presented as a scale. Each pair may be chosen and positioned near the colored samples. A participant's task is to choose a gray pair that is the most similar in difference to the colored pair.*

After CIE1931, many attempts were made to develop uniform color space. In such a uniform space all MacAdam ellipses should look like circles of equal sizes. In Figure 4, MacAdam ellipses are presented in CIELUV 1976 chromaticity space. It is obvious that ellipses in Figure 4 are more similar to each other than in Figure 2 that presents them in CIE xyY1931.

Nevertheless, even in CIELUV there are some strong disparities in size, angle and axis ratios of ellipses.

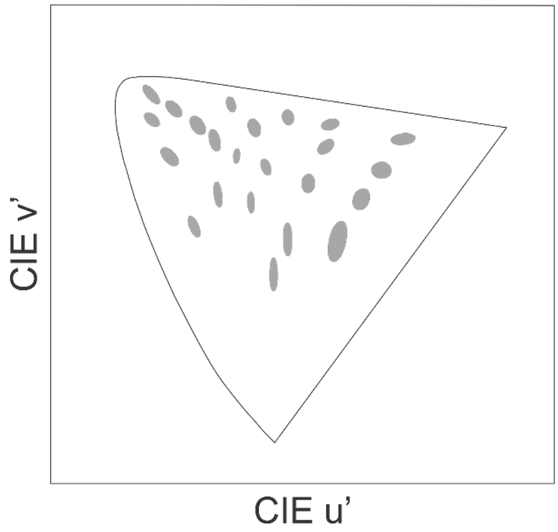


Figure 4. MacAdam ellipses plotted in CIELUV 1976 chromaticity space. Comparing those ellipses to the ones in CIE xyY1931 (Figure 2) one could easily see that in CIELUV ellipses are much more similar to each other. Nevertheless, there are still some strong disparities in size, angle and axis ratios of ellipses, meaning the space is not purely uniform.

Understanding color differences have quite clear significance for industry and practice: to operate with colors (which is essential in polygraphy, textile industry, design, in image processing, etc.) one has to understand what colors and their combinations would be perceived by a real human observer. That is why a field of uniform color spaces is still blossoming with new color models, new color spaces and new color difference formulas.

Verification of results of all these scientific developments requires a big amount of data obtained in real human participants. There are some datasets available, for example (Luo, Rigg, 1986; Alman et al., 1989; Berns et al., 1991; Witt, 1995; Witt, 1999; etc.). Most of the existing datasets have limited coverage in color space. Nowadays, with industry progress and with the emergence of a new generation of displays, new datasets are required. New experiments have to cover a wide color gamut and a high dynamic range of luminance.

In this paper, we present pilot experimental results of color threshold assessment by a new developed device with a wide color gamut. The device itself is described in another chapter of this book.

The aims of the research:

- To estimate color discrimination thresholds with strict substitution method for five CIE-recommended color centers.
- To validate the developed device.
- To validate the experimental protocol.

Materials and Methods

The device

The device is developed in IITP RAS and is fully described in another chapter of this book by Alexander V. Belokopytov.

The device consists of a control box and a stimulus box (Figure 5, a). The control box has an auxiliary screen to display color coordinates of presented colors and rotating knobs (encoders) to change the stimuli. The stimulus box has a display and adjustable apertures to regulate the size of the stimulus. For this study, we used an aperture that provided 2° stimulus from 60 cm viewing distance.

The stimuli presentation was made according to a strict substitution method (Wyszecki, Stiles, 2000, pp. 278–293). In strict substitution procedure, test and reference colors are positioned in the same location (in contrast to bipartite procedures) and interchange in time (Figure 5, b). In our experiment, the colors change with 0.33 Hz frequency. The strict substitution method is sometimes considered as the best method for color comparison, since in such a procedure the same retinal area is stimulated by both stimuli.

a

b

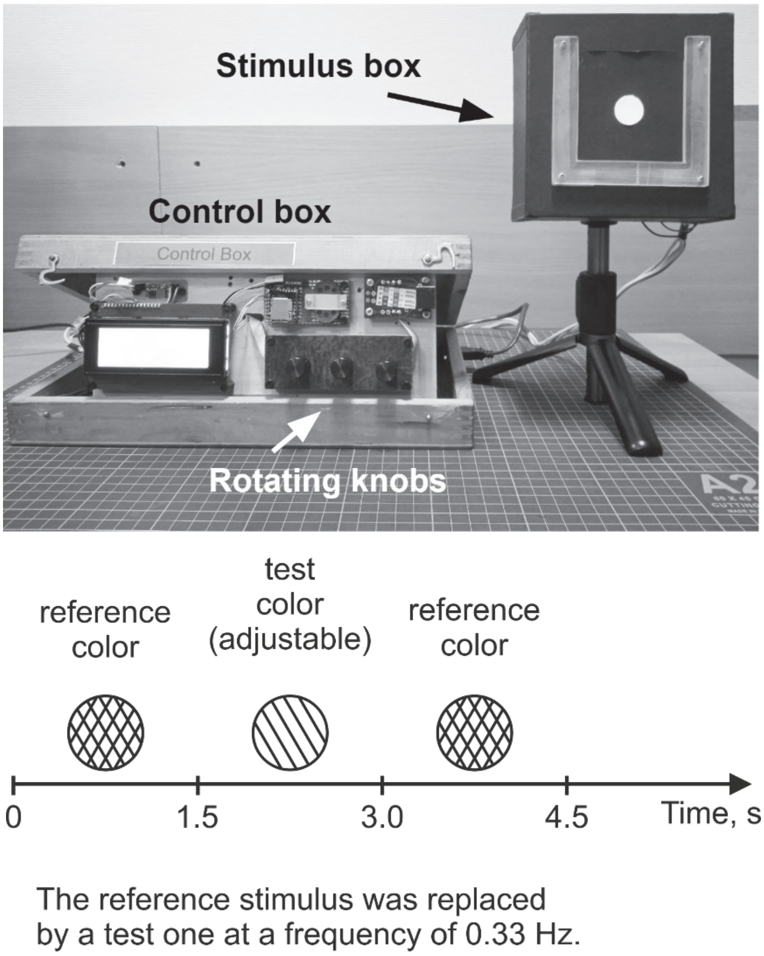


Figure 5. *The apparatus used and its description.*

a) *The device was developed in IITP by Alexander V. Belokopytov. The device consists of two main parts: control box and stimulus box. Control box has a screen to output the color coordinates (in CIE1931 xyY color coordinate system) and rotating knobs to change the color. Additionally, a separate part with rotating knobs may be added for better participant experience. Stimulus box consists of a LED matrix, cooling fan, temperature sensor and a changeable aperture.*

b) *The scheme of a stimulus presentation in a strict substitution method. The test and reference stimuli are interchangeable in time; the change frequency is 0.33 Hz. After 1.5 s of reference stimulus, the test stimulus is presented for 1.5 sec, and so on.*

The main benefit of the device is its wide color gamut, providing opportunity to collect the data in a wide color range. Figure 6 presents several datasets and distribution of the samples in color range, standard sRGB gamut (dashed gray line), and color gamut of the device used in this study (solid black line) in a CIE1931 chromaticity diagram. All color datasets presented do not cover the full range of possible colors. New device covers much larger area in the whole color range and could provide an opportunity to extend our data significantly, especially in the area of green-cyan (upper left part of the CIE diagram) and red-purple colors (lower right part of the CIE diagram, bordered by the straight line).

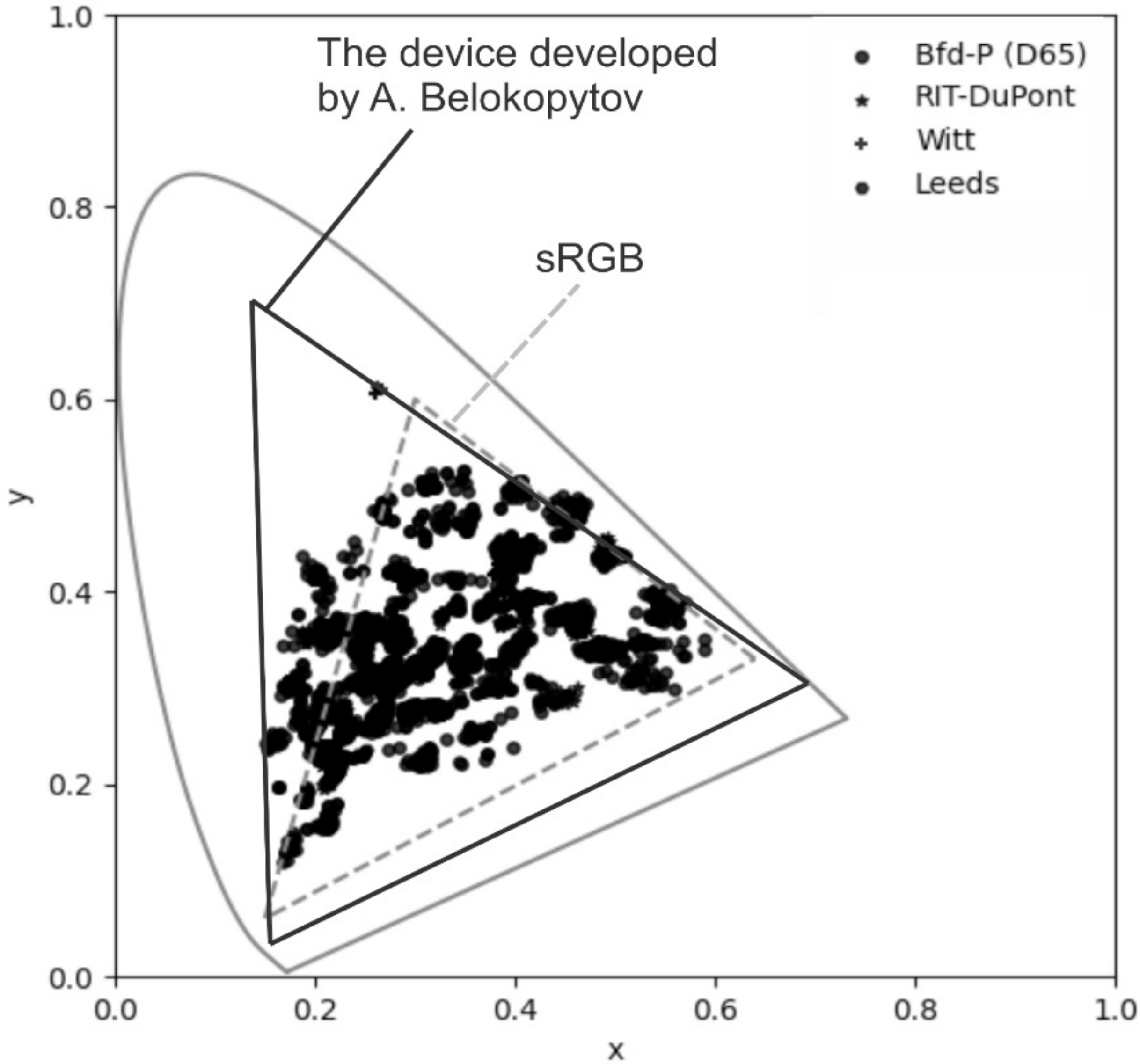


Figure 6. *The diagram presents the CIE xy chromaticity range with constant brightness and color ranges for devices and datasets. The color gamut of the new device (solid line), the standard sRGB gamut (dashed line), and the range of samples in various color difference datasets (the datasets presented are: Bfd-P (D65), RIT-DuPont, Witt, Leeds). The developed device provides great opportunities for color threshold assessment in green-cyan (upper left part of the CIE diagram) and red-purple areas (lower right part of the CIE diagram, bordered by the straight line).*

The procedure

The whole procedure tested was as follows:

1. Participant's color vision was tested by CAD test (City Occupational Ltd, Great Britain). Only participants with normal (trichromatic without abnormalities) color vision may participate in such studies. We use full binocular medical protocol (approximately 20 min).
2. Adaptation to the dark surround (at least 1 min) . The experiment was conducted in the dark surround. According to (Fairchild, 1993), the adaptation of 1 min is enough for such conditions.
3. The initial color of the stimulus was set in xyY coordinates and corresponded to one of the five color centers (Robertson, 1978), see Table 1.
4. The participant changed the chromaticity coordinates of a test stimulus (rotating the knob) until the flicker of test and reference stimuli became distinguishable. The knob rotation changes color in one of eight directions around the initial color center, see Figure 7. Each direction is separated by 45° in the xy diagram. Measuring directions were randomized inside 5 blocks (blocks corresponded to the color centers).

On this stage of research, only one participant was tested.

The whole procedure duration was about 2 hours (breaks are excluded). The sessions were separated into 30-min intervals to lower participant's fatigue and stress.

Table 1. The coordinates of five CIE recommended color centers used in the study to assess threshold values (Robertson, 1978).

Color center	**Y**	**x**	**y**
Yellow	69.3	0.338	0.4228
Green	24.0	0.248	0.362
Blue	8.8	0.219	0.216
Gray	30	0.314	0.331
Red	14.1	0.484	0.342

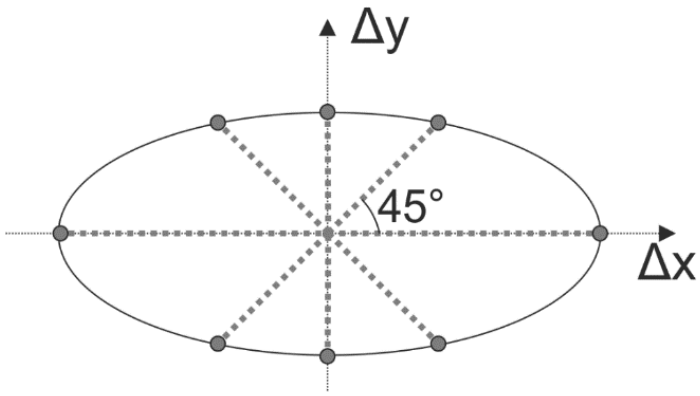


Figure 7. Directions for threshold assessments (around each color center).

Test stimulus chromaticity was changed along eight directions (separated by 45°) on the xy plane.

Results

Results: comparison with CIEDE2000 by STRESS metric

The resulting thresholds were compared with the predictions of the CIEDE2000 color difference formula (Luo et al., 2001). For an assessment of the proximity of perceived and computed color differences, the Standardized Residual Sum of Squares (STRESS) metric is often used (Garcia et al., 2007), see equation 1.

$$STRESS\ (\vec{g},\vec{h}) = \frac{\|k*\vec{g}-\vec{h}\|_2}{\|\vec{h}\|_2} = \frac{\sqrt{\sum_{i=1}^{n}(k*g_i-h_i)^2}}{\sqrt{\sum_{i=1}^{n}{h_i}^2}},\ k* = \frac{\vec{g}^T\vec{h}}{\vec{g}^T\vec{g}}\ , \tag{1}$$

where $\vec{g},\vec{h}$ – vectors of color differences to be compared.

STRESS metric can be computed for two vectors of color differences obtained by arbitrary means. The metric values are always between 0 and 1, where 0 indicates the best agreement, and STRESS < 0.3 may be considered as a good agreement.

The results of STRESS metric for all five color centers are presented in Table 2. We obtained good agreement of our threshold results and CIEDE2000 formula for four color centers out of five (yellow, gray, green, and blue), and marginal agreement for red color center.

Table 2. The comparison of the obtained thresholds with the CIEDE2000 by STRESS metric for five color centers.

Color center	STRESS value
Yellow	0.119
Gray	0.158
Green	0.170
Blue	0.199
Red	0.337

Results: graphical comparison with other researchers' data

Another way to compare obtained results is to plot them against the results of other researchers. To do so, we took summary data from (Berns et al., 1991) and from (Mirjalili et al. 2019). Both studies summarize several other researchers.

Figure 8 presents graphical comparison of results by different researchers for four color centers. The summary results from Berns and coauthors (Berns et al., 1991) are presented as black ellipses. The authors joined various experimental data obtained around particular color centers, and the data contains both threshold and suprathreshold measurements. Obviously, the sizes of ellipses should be different for different procedures, that is why authors normalized all ellipses to equal area. Our data are presented as 8 dots for each color center joined with a dashed line to assess the whole form of the obtained figure. Since the sizes of black ellipses are normalized, there is no sense in size comparison. The whole form and the tilt of the figure is to be compared.

Berns and coauthors noted that some ellipses were significantly different in comparison with other results. These are MacAdam data (for all four color centers) and Wyszecki and Fielder data (for green center).

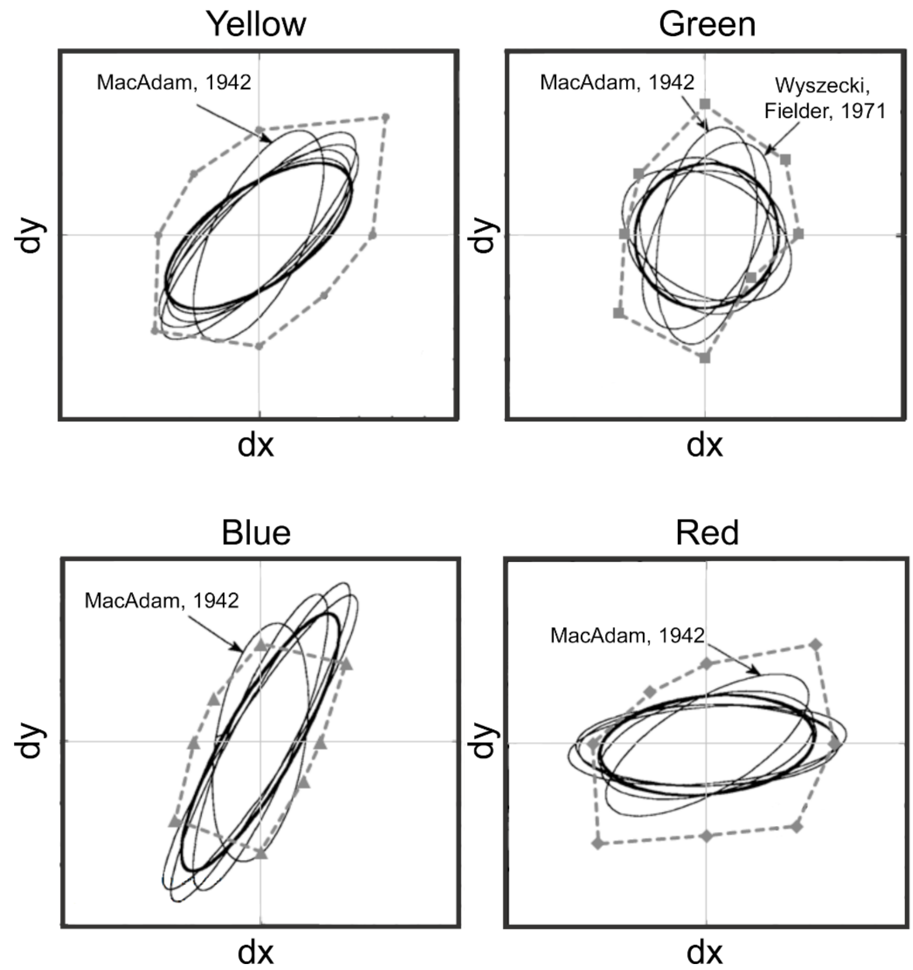


Figure 8. *Comparison of the obtained threshold results with those of other researchers (Berns et al., 1991), plotted in CIE1931 xyY coordinates. Our results are presented as dots (8 dots for each color center), joined by dashed lines for approximation of the whole form of the figure obtained. The results of previous researchers are presented by ellipses (the figures are taken from (Berns et al., 1991)).*

In the plot, different threshold and suprathreshold measurements were joined, that is why the size of the figures is not to be compared: all black ellipses are normalized to equal areas, so the scales are relative and have no numbers. The whole form of figures and the tilt direction are to be compared.

Berns and coauthors marked the ellipses that were different from all other authors, that are MacAdam results for all four color centers (MacAdam, 1942) and Wyszecki and Fielder results for the green color center (Wyszecki, Fielder, 1971).

Figure 9 presents graphical comparison of the results obtained by different researchers for five color centers. The summarized results from the work of Mirjalili and coauthors are presented as gray ellipses (Mirjalili et al., 2019). As in the previous plot, the authors joined various experimental data obtained around particular color centers, and the data contains both threshold and suprathreshold measurements. Our data are presented as 8 dots for each color center joined with a dashed line to assess the whole form of the obtained figure. Since the ellipses from (Mirjalili et al., 2019) paper summarize both threshold and suprathreshold results, the size of the shapes should not be compared, only the form and the tilt of the figure is under consideration. For better visibility, our data were enlarged 5 times and presented by dots joined with black dotted lines.

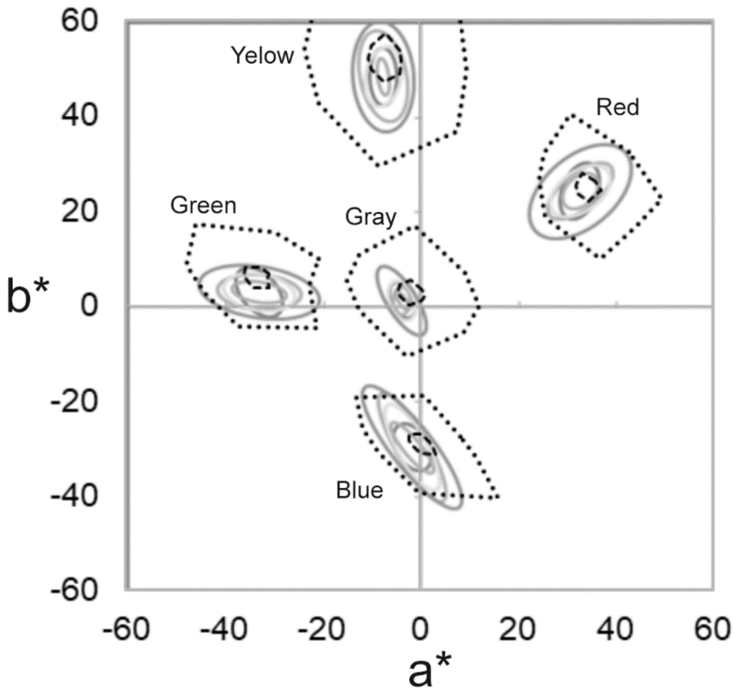


Figure 9. *Comparison of the obtained threshold results with those of other researchers (Mirjalili et al., 2019) plotted in Lab coordinates. Our results (transferred to Lab through D65) are presented as dots, joined by black dashed lines for approximation of the whole form of the figure obtained. For illustration, the same results were enlarged 5 times and were plotted by dotted lines. The results of previous researchers are presented by gray ellipses (the figures are taken from (Mirjalili et al., 2019)) In this plot, different threshold and suprathreshold measurements were joined, that is why the size of the figure is not to be compared. The whole form and the tilt direction are to be compared.*

Discussion

Results of the pilot color thresholds assessment

In this paper we present pilot results of color threshold assessment by a new device developed at the IITP RAS by Alexander V. Belokopytov. The device provides a wide color gamut and is designed for a strict substitution comparison method, in which both stimuli (test and reference) stimulate the same retinal area. This paper provides first experimental results by this new promising device.

The results of STRESS metric for comparison of CIEDE2000 formulas shows reasonable results for all color centers. While for red color center results are slightly over the notional good quality margin, it is not much worse than for other centers (while STRESS < 0.3 is considered as good quality, we obtained 0.337 for red color center). These results show that the new device could give reasonable color threshold assessments.

The results of graphical comparison with the data summarized by Berns and colleagues (Berns et al., 1991) show that even with a scarce amount of pilot data the whole form of threshold ellipses is similar to the ones of previous researchers. It is noteworthy that our threshold figures seem to tend to the ones obtained by MacAdam, especially for red and green color centers. MacAdam used bipartite field (in which one half of the field is filled with test color, and the other half is filled with reference color) and had big white surround of half brightness of the stimulus (the surround was of 40° of visual field and had brightness of 24 cd/m^2 while brightness of stimuli was 48 cd/m^2). In that sense, neither our stimulus structure, nor our dark surround were similar. Nevertheless, in comparison to many other researchers (Alman et al., 1989; Berns et al., 1991; Witt, 1995; Witt, 1999; Mirjalili et al., 2019), both in our work and in the work of MacAdam the test field had 2° size. Since the inhomogeneity of retina is well-known, and may affect the color assessment results significantly, it is possible that the stimulus size was the crucial parameter for threshold ellipses form.

The results of graphical comparison with summary made by Mirjalili and colleagues (Mirjalili et al., 2019) show a similar tendency. The whole form and the tilt of the threshold figures is quite similar for our data and for data of other researchers. The less similarity could be seen for the red color center, that is in agreement with our STRESS metric results, where the red color center also showed less quality. One of the possible explanations has already been discussed above: it is possible that for red stimuli the size of a test field is of critical importance.

Limitations of the study

In this study we conducted only pilot experiments with the main goal in mind to be a validation of the new device. Obviously, the data of one participant is far from being enough to assess reliable color thresholds by strict substitution method.

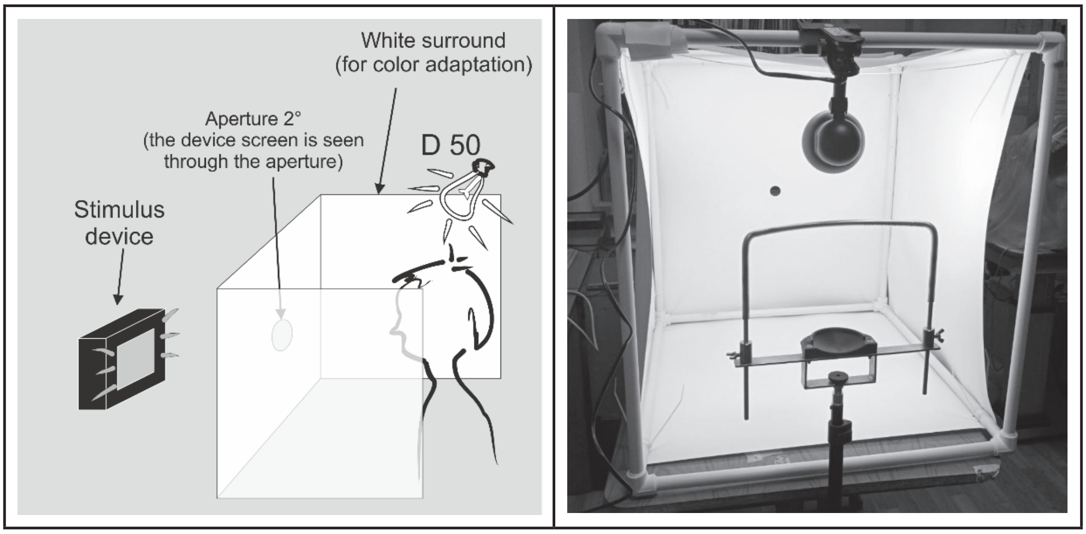
In this study we assessed thresholds only in direction from equal stimuli to the point where the difference is seen (see Figure 7 and the subsection "The procedure" of "Materials and Methods" section). The thresholds may be slightly different if measured in the other direction (from obviously different stimuli to the point of indistinguishable difference). Even though we are aware of the possible discrepancy of various results, the procedure was chosen since it was much easier to conduct, much simpler for participants to understand, and invoked much less stress and fatigue in participants.

Another limitation of the study concerns the transformation of our results to the Lab coordinates. Since we conducted our studies in a darkened room, there is an uncertainty about the light source that should be used for transformation from CIE1931 xyY to Lab. We used D65 for this purpose, though the choice is not supported by our physical conditions. The transformation to Lab coordinates was used for CIEDE2000 results calculation (see subsection "Results: comparison with CIEDE2000 by STRESS metric") and for Figure 9. Even though those results may be different if another light source were used, we strongly believe that the difference would not change the main conclusions of our study.

Further work

The goal of the study was to estimate color discrimination thresholds with strict substitution method for five CIE-recommended color centers and to validate a new device for color threshold assessment. To validate the new device, we conducted threshold assessment around five CIE recommended color centers (Robertson, 1978) since in these areas there are enough data available for comparison. In further research, areas over sRGB gamut would be of most interest.

To improve the experimental conditions in future, we developed an adaptation cabin (Figure 10). The main benefit of the cabin is standardized adaptation conditions for all participants. The cabin has size of about 80*80*80 cm. In the front side, there is a chinrest for better fixation of the participant's head and for stable viewing distance (see Figure 10, b). On the opposite side, there is an aperture providing 2° of visual stimuli. To eliminate any incident light to be reflected by the stimulus display, the display is positioned at some distance from the aperture (see Figure 10, a). The cabin provides a white surrounding field and a homogenous lighting condition by D50 light sources with regulated brightness. The cabin is placed in a dark room with no windows, so the only light source is D50 lamps. In our further research, we are planning to conduct all our experiments on threshold assessment with this adaptation cabin.



a b

Figure 10. *A scheme (a) and a photo (b) of an adaptation cabin developed. To better control adaptation conditions, the adaptation cabin is installed in a dark room (with no windows). Five sides of the cabin are covered with white paper, at the other side there is a chinrest and a forehead support for better fixation of a viewing distance. The opposite side has an aperture of 2° to see the device display. The device display is positioned at some distance from the backside of a cabin to ensure that no incident light is reflected by the stimulus screen.*

To improve the procedure, we are planning to conduct measurements of threshold points in both directions: from indistinguishable difference to distinguishable flickering, and vice versa. This change may be more tiresome for participants, so additional studies are needed to validate the procedure change.

To improve the data obtained and conclusions drawn from it, the main goal is to increase the data set by recruiting more participants to the study.

Conclusions

- The device developed allowed us to obtain color vision threshold assessments by strict substitution method for five CIE recommended color centers.
- The data obtained is in good agreement with CIEDE2000 (by STRESS metric) and with the data from other researchers (by graphical comparison).
- However, agreement for the CIE Red color center was marginal.
- CIE Red color center in our data shows more similarity to the MacAdam 1942 results, than to further investigators.
- The device and experimental procedure with described improvements seems promising for collecting dataset on human color vision threshold in a wide range of colors.

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