MEASURING WAVELENGTH DISCRIMINATION THRESHOLD ALONG THE ENTIRE VISIBLE SPECTRUM

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Abstract

The wavelength discrimination threshold can be characterized by the difference of two monochromatic lights' wavelengths ($\Delta\lambda$) that subject can hardly detect. The detection of small differences in hue, present in a colour simulation is of great interest from a scientific viewpoint. A new instrument was built to measure wavelength discrimination threshold. A bipartite light is located in 2° visual angles within a white adaptation field. A monochromatic reference light is projected into one half of the field, while an adjustable monochromatic target light is projected into the other half of the field. Both lights have the same brightness. The examined subject has to adjust the wavelength of the target light until the difference between the reference and the target light can be seen. Measuring wavelength discrimination threshold along the entire spectrum the $\Delta\lambda(\lambda_{\text{reference light}})$ function can be established. Wavelength discrimination threshold function describes the subject's color discrimination ability. Our experiences with the newly set up instrument are presented in this paper.

Keywords: wavelength discrimination, deficiency colour.

1. Introduction

1.1. Wavelength Discrimination Ability in Case of Normal Color Vision

The human eye can detect electromagnetic radiation called light between the wavelengths range of about 380 and 780 nanometers. People with normal colour vision can see about 150 different colours in this range. Color is defined by the wavelength of the given monochromatic light. Color sensation can be characterized by hue, saturation and brightness. Our ability to discriminate between different hues (ergo wavelengths) is better in the middle range of the visible spectrum than at its boundaries. Wavelength discrimination ability is a kind of sensation threshold, which shows when we can discriminate between two different wavelength lights based on the different hue [1]. The smallest sensible difference of wavelengths is called differentiation minimum, marked as ($\Delta\lambda$). Our wavelength discrimination ability is significantly changing with the wavelength and it is the best in the 490 nm (greenish blue) and 590 nm (orange) range of the spectrum. In these ranges the wavelength discrimination ability of a normal color vision person can be as good as 1 nm. *Fig. 1* shows the wavelength discrimination ability of normal color vision people as a function of the wavelength [2], [3]. Since our color discrimination

threshold is smaller than the minimal wavelength difference between two colors we name differently, the name of a given color covers a wide range of wavelengths.

According to WRIGHT (1946) the stimuli of the long, medium and short wavelength sensitive receptors of the eye differ the mostly from each other at these wavelengths. The characteristics of the wavelength discrimination curve depend on several parameters such as field size, light intensity, stimulated area of the retina, etc. and it significantly changes with these parameters.
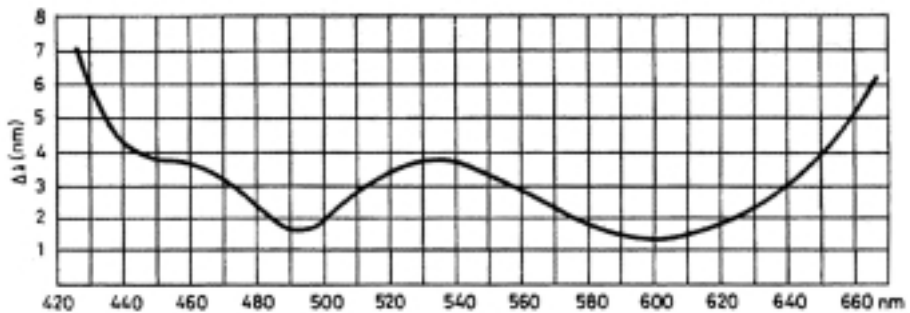

Fig. 1. Wavelength discrimination threshold along the entire visible spectrum in case of normal color vision (WRIGHT (1946) and PITT (1944))

8% of men and 0.5% of women are color deficient. Defective color vision is characterized by abnormal color matching and color confusions. There is also a marked reduction in the number of separate colors that can be distinguished in the spectrum. One of the recently developed methods for testing color vision is the measurement of the wavelength discrimination threshold [4].

1.2. Wavelength Discrimination Ability in Case of Colour Deficiency

1.2.1. Anomalous Trichromats

At the dawn of color deficiency research ENGELKING (1925), later NELSON (1938), furthermore MCKEON and WRIGHT (1940) measured the wavelength discrimination ability of anomalous color vision people [5], [6]. According to their measurements there are significant differences among the wavelength discrimination ability of anomalous trichromats, although it is common that their curve falls within the normal color vision and dichromatic color vision curves, often retaining the position of the two characteristic minimum points, however, with decreased sensitivity. (*Fig. 2*). In anomalous cases the wavelength discrimination ability is usually the best around the 490–500 nm range, where it can reach the value of 4 nm, best approaching the respective value of normal color vision people. The other frequently appearing minimum position is at 600 nm. The sensitivity threshold is significantly

higher though, usually two and a half times higher than the absolute minimum, at least 10 nm.

They have also shown that if the sensitivity of one of the receptors is different from the normal then the peaks of the wavelength discrimination curve are shifted as well both at 500 and at 600 nm. For protanomalous and deuteranomalous subjects the curve is shifting left and right respectively. Although the severity of anomalous trichromacy cases evidently concludes from their wavelength discrimination ability there is only low correlation between these curves and the respective diagnosis of the Nagel anomaloscope.
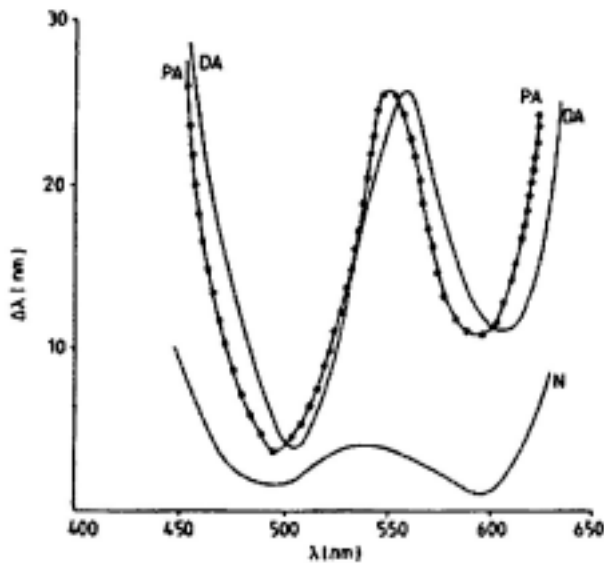

Fig. 2. Wavelength discrimination curves in case of two anomalous trichromats, a protanomalous (PA) and a deuteranomalous (DA) one. Curve N characterizes the normal color vision subjects.

1.2.2. Dichromats

Wavelength discrimination ability of protanopes and deuteranopes is at its best around 490 and 495 nanometers. In their cases this area of the spectrum is considered to be the neutral point. In other spectral ranges the recognition is weak, there is no secondary local minimum, which results in a typical *U* shaped curve [3], [7] (*Fig. 3*).

It was also seen that the wavelength discrimination peak value of deuteranopes and its position is changing with the brightness of the illumination. At 10 troland
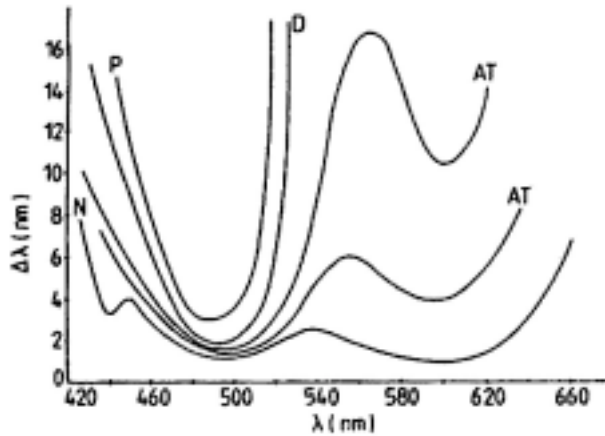
Fig. 3. Wavelength discrimination curves at 2° visual field. N: normal; AT: anomalous trichromat; P: protanope; D: deuteranope

the peak was at around 495 nm, however, at 0.1 troland it shifted closer to 570 nm and the sensitivity decreased.

2. Method

2.1. *Method of the Wavelength Discrimination Threshold Measurement*

Based on research results we have built an equipment capable of measuring the wavelength discrimination threshold. The heart of the equipment is a circular shape bi-partial disappearing sharp edge viewfield shown in a 4° viewfield. We project a given wavelength monochromatic reference light into one part and simultaneously a slightly different wavelength monochromatic measuring light – which can be adjusted by the patient – to the other part of the field. The viewfield is positioned into the middle of a 10° white adaptation field. The bi-partial viewfield is created by a *Y* shaped optical-fiber bound meanwhile the monochromatic lights are generated with continuous interference filters. The preset wavelength values can be calculated from the relative displacement of the optical fiber end and the IF filter which is measured by a computer controlled digital linear scale. The intensity of the two channels is set to be equal. Since the different optical parameters such as viewing angles, light intensity, adaptation field, etc. have significant effect on the measurement results we took special care to choose them properly. The measured subject can set the wavelength of the measuring light relative to the reference light with a certain difference. The $\Delta\lambda(\lambda_{\text{reference light}})$ function, which can be generated sweeping the entire visible spectrum, is the wavelength discrimination threshold function itself.

Based on the measurement results the shape of this function depends significantly on the subject's color vision ability.

2.2. *The Optical System of the Instrument*

Fig. 4. Optical system of the HD Sensometer

The optical system of the equipment is shown in *Fig. 4.* We call the channel set by the measurement leader at one part of the sharp disappearing bi-partial field reference light. The second channel, which can be adjusted by the patient in the other part of the viewfield is called measuring light. Behind these two there is the adaptation field, which will assure the white adaptation status of the patient's eye. The main part of the HD sensometer is a continuous interference filter (FIF), a *Y* shaped optical fiber bound (YSZ) and two digital linear scales. The doubled end of the specially designed *Y* fiber bound functions as two rectangular shape input slots (BA(CF) and BA(MF)). Fibers originating from here end at the single end of the *Y* bound in an output slot forming a disappearing-sharp viewfield (KA(CF+MF)) where both halves of the formed circular field contain the fibers from only one of the input slots. The interference filter is lit from its back on an appropriately large surface. The filter can be moved relative to one of the input slots of the fiber optics (BA(CF)), which is firmly fixed. This linear displacement detected by a digital linear scale defines the wavelength of the light entering to the target channel. The other input slot of the *Y* shaped optical fiber bound which belongs to the measurement light can be moved relative to the target light slot and at the

same time to the interference filter too. The other digital linear scale detects this displacement. Hence with moving the interference filter the wavelength changes in both channels, but when moving the input slot of the measuring light only its own wavelength is changing relative to the wavelength of the reference light by a $\Delta\lambda$. This $\Delta\lambda$ is a function of the displacement of the measuring light input slot. Looking through the ocular (OL) we see the disappearing-sharp $4°$ viewfield in the middle of the $10°$ view field background light. The central $4°$ portion of the $10°$ background field is masked with a black disc positioned into the center of the slot defining the $10°$ viewfield (LH1). Such way the background light is not projected to the disappearing-sharp viewfield and does not result unsaturated colors, which would make the observation more difficult. In practical terms the $4°$ viewfield is the virtual optical picture of the output slot of the Y shaped optical fiber in 250 mm clear view distance. The light of the output slot of the optical fiber and the light of the background are mixed to each other with a 50% beam splitting cube (P). The proper intensity and correlated color temperature of the background light is set with a series of filters (SZ) containing IR filter, whitening filter, gray filter and a diffuse surface as well, which is necessary for adequately homogeneous illumination. The two 12V/20 W halogen incandescent bulbs are supplied by a stabilized power supply therefore the correlated color temperature of the bulbs does not change with fluctuation of the line voltage.

2.3. Computer Controlling

Since the wavelength of the lights entering both parts of the disappearing-sharp viewfield is defined by the linear displacement of elements measured with digital linear scales it is self-indicating the computerized data processing through a serial port. The software custom written for this purpose returns with the actual wavelength of the lights entering to the reference and measurement channels ($\lambda_{\text{reference}}$, $\lambda_{\text{measuring}}$) and the actual difference ($\Delta\lambda$) as well. The actual color of the reference and measuring lights as seen through the ocular is shown on a spectrum on the computer monitor together with the actual wavelength data. This helps the contact between the measurement leader and the patient during the measurement.

3. Results

The first set of measurement results showed significant difference from the referred data [3]. This difference can be caused by the design of the equipment and the measuring method. Studying the design of Wright's instrument it was realized, that our equipment should compensate the relative luminance changes through the visible spectrum. There are two different possibilities to solve this problem. The first possibility is to apply an additive unit to compensate the luminosity, which can be adjusted by the observer. The second one is to build an invert $V(\lambda)$ filter,

which eliminates the luminosity changes because of its transmission characteristics. The main drawback of the first method is the long measurement time and increased fatigue of the observer. The disadvantage of the second possibility is, that the instrument contains an element, which is designed for people with normal color vision, so it cannot function properly in the case of color deficient subjects. However, this inaccuracy is relatively low, so the second possibility was chosen.

A new set of measurements was derived on the redesigned instrument using the modified measuring method. The observers should set the difference threshold as by WRIGHT [3]. The similarity between the measured and referred data can be seen in *Fig. 5*. Our results show good match to the Wright curve.
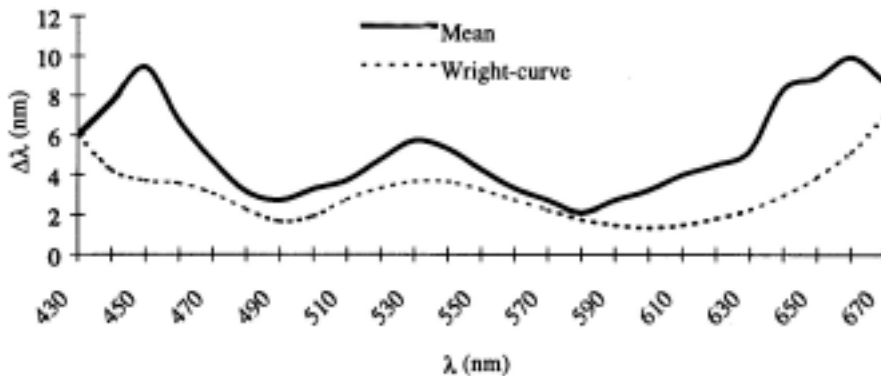
Fig. 5. The mean value of three measured observers with normal color vision compared to the Wright data

4. Conclusions

A new wavelength discrimination measurement instrument was designed and produced. Although the measuring method is widely known, the optical and mechanical design of the instrument is quite different from the previous ones. Test measurements were conducted using the device, and problems were eliminated.

We would like to measure a wide number of observers with normal and anomalous color vision in the future. Based on these results we plan to develop a simplified measuring method. This simplified method should allow us to measure only a few characteristic points without remarkable loss of information, so we should find exact wavelengths where the difference of the discrimination ability between the color normal and defective population is the most significant.

Acknowledgements

References

[1] FLETCHER, R. – VOKE, J.: *Defective Color Vision*, A. Hilger Ltd, Bristol and Boston, 1985.

[2] PITT, F.H.: The Nature of Normal Trichromatic and Dichromatic Vision, *Proc. R. Soc.* **B 132** (1944) pp. 101–117.

[3] WRIGHT, W. D.: *Researches on Normal and Defective Color Vision*. London: Henry Kimpton, 1946.

[4] HURVICH, L. M.: *Color Vision*. Sinauer Associates Inc. U.S.A, 1981.

[5] ENGELKING, E.: Die Tritanomalie, ein bisher unbekannter Typus anomaler Trichromasie. *Graefes Arch. Ophthalmol.* **116**, (1925) pp. 196–244.

[6] NELSON, J. H.: Anomalous Trichromatism and its Relation to Normal Trichromatism. *Proc. Phys. Soc.* **50**, (1938) pp. 661–97.

[7] BALARAMAN, S. – GRAHAM, C. H. – HSIA, Y.: The Wavelength Discrimination of Some Colorblind Persons. *J. Gen. Physiol.* **66**, (1962) pp. 185–201.