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Chromatic discrimination thresholds in terms of chromatic adaptation

Thesis booklet

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1. **DESCRIPTION OF THE TOPIC, OBJECTIVES**

The two pillars of my research are chromatic discrimination and chromatic adaptation. My long-term goal was to model chromatic adaptation based on chromatic discrimination thresholds. In the studies discussed in the thesis, I examined the dependence of the chromatic discrimination thresholds as a function of the reference chromaticity, the measurement directions, and the size of the adaptation field.

Based on the CIE colorimetric system, if two colour stimuli have the same CIE XYZ tristimulus values, the observer perceives them as the same colour. However, certain conditions must be met for this to happen, otherwise the statement fails. These conditions can be related to the part of the retina reached by the stimulus, the visual angle of the stimulus or the luminance level. Furthermore, the environment, the background, the shape, or the size of the stimulus can also be influential factors [1].

However, even under certain conditions, the human visual system can reflect on varied circumstances. One of the most important components of this ability is adaptation, where the visual system adapts to the changes of illumination, so the appearance of a given object does not change, despite the changed circumstances.

The circumstances regarding colour vision can be modelled by stimuli such as different luminance levels and spectral distributions [2]. Therefore, one way to understand adaptation more is to observe and understand the effects of the above-mentioned stimuli [3].

If the difference between two stimuli can be described as the change of the luminance levels, light adaptation is mentioned. Our visual system performs in a range of ~10^{12} levels of luminance, while a typical postreceptoral neuron can operate only over a range of ~10^{3} [4]. Rods are optimised for low (scotopic < 0.005 cd/m2) light levels, while cones are optimised for higher (photopic > 5 cd/m2) light levels [5]. The transition between these two luminance levels is called the mesopic range, where rod and cone vision function together can give an initiative but not a comprehensive solution to maintain the performance over the above-mentioned luminance range.

Moreover, since the photoreceptors used in daylight are the three cones having different spectral sensitivity, the spectral distribution of the stimuli can have different impact on the cones. This is called **chromatic adaptation.**

In general, adaptation can be explained as reduced steady-state responsiveness of neurons, produced by prolonged stimulation [6]. At photoreceptor and transduction level, adaptation is speeding up the visual response, therefore reducing the integration time of the system [4]. From a perceptual approach the phenomenon attending chromatic adaptation is colour constancy: even though the spectral distribution of the light in the environment changes, the perceived colour of the objects remains similar.

A fundamental topic of colour vision assessment is the analysis of **chromatic discrimination**, which can indicate inherited defects in colour vision, such as anomalous trichromacy [7], early stage of diseases, such as diabetes [8], harmful environmental effects [9], or changes in terms of age [10].

Nevertheless, measurement and analysis of chromatic discrimination are important steps on the scientific road towards the colour differences and the uniform colour spaces, and their verification [11]–[13].

The measurement method and the experimental design naturally needs to be in accordance with the objective of the actual research. Therefore, during the decades of the history of colour science several methods has been developed and applied for various clinical and investigational aims [14], [15].

Although in the literature there are studies about definition and comparison of large colour differences [16], [17], the unit of chromatic discrimination measurements is most usually the

just-noticeable difference (JND), hence the smallest colour difference which the observer can perceive.

Several JND measurement methods can be found in literature. In clinical practice pseudo-isochromatic tests are often used. The main concept in these tests is the design of the test figures, built of randomly sized and positioned dots. Within the figure, the dots can be grouped as target and background, based on their chromaticity, while the lightness of the dots is randomised. The task is to read the target, which is possible only if the perceptible difference between the target and the background chromaticity exceeds the JND of the observer.

In the studies described in the thesis I applied an internationally acknowledged, computerized pseudo-isochromatic test: the Cambridge Colour Test (CCT). The advantage of CCT is that it is a computer-based test, so that experimental design can be created beyond the assessment of anomalous trichromacy [18], [19]. The task is to read a Landolt-C character from the test figures and to give its orientation using a remote control. The main parameters of the test are the chromaticities of the background (reference chromaticity) and the Landolt-C figure, as well as the range of luminance noise appearing in the figures.

The test is adaptive, the chromatic difference between the reference chromaticity (unchanged during the test) and the chromaticity of the Landolt-C character is continuously increased or decreased based on the participant's responses. This adaptability, as well as the use of a calibrated CRT monitor and the ViSaGe MkII colour stimulus generator, make it possible not only to examine subjects with defective colour vision, but also to detect differences in the colour vision of normal colour observers.

The native colour system of the test is the CIE 1976 UCS colour chart, so it gives the chromaticity coordinates as $(u'; v')$ coordinates and the thresholds resulting from the measurement as $\Delta E_{u'v'}$ colour differences.

The two test modules of CCT are the Ellipse Test and the Trivector Test. In the case of the Ellipse test, the thresholds are determined in the measurement directions taken in equidistant directions from the reference point, and then, knowing the threshold values and the reference point, the program fits an ellipse using the least squares method to estimate the area within which the observer cannot perceive difference.

The Trivector test gives thresholds from the reference points towards the three confusion directions. Confusion directions are directions from any chromaticity point to one of the three confusion points on the CIE 1931 or 1976 UCS colour diagram.

While the purpose of CCT measurements in the literature is typically to compare different groups at the reference points given in the CCT manual [10], [21], little data can be found on the threshold values at reference points that are very different from neutral grey.

The motivation of this thesis was to investigate changes in chromatic discrimination, hence the chromatic resolution of our colour vision. My long-term goal was to model chromatic adaptation based on chromatic discrimination thresholds. The three main objectives of the research discussed in this thesis were:

1. To map the chromatic discrimination thresholds of colour-normal people within a typical display gamut. Measurements were obtained at systematically manipulated reference points in terms of the distance from white. The measurements had two purposes: to create a reference database, and to describe the distribution of the chromatic discrimination thresholds in a mathematical model.

2. To investigate the role of confusion lines considering chromatic discrimination thresholds of colour-normals. Measurements were obtained both towards the confusion lines and in equally distributed directions in the CIE 1976 UCS to see if chromatic discrimination on the confusion lines is distinguished from other directions. Analysis was executed in different colour spaces to clarify the origin of patterns in the results.

3. To investigate the changes in chromatic discriminative ability related to size and colour of stimuli determining the state of chromatic adaptation. Chromatic discrimination thresholds were measured under different states of chromatic adaptation, defined by visual environments, varying in size and colour. The purpose was to observe the dependence of the chromatic discrimination thresholds on the adapting field size.

Besides the above-mentioned research goals, I investigated possible applications of the changes of chromatic discrimination in terms of chromatic adaptation.

2. OVERVIEW

The thesis discusses characteristics of human chromatic discrimination under different states of chromatic adaptation. Following the introduction and the literature review, the results are presented in three chapters.

The chapter of the literature review covers the topics of the fundamentals of colour vision, colorimetry, chromatic discrimination, and chromatic adaptation. Chapters 3, 4, and 5 are introduced with supplementary literature reviews, discussing literature relevant to the given experiments.

In Chapter 3 chromatic discrimination thresholds measured towards the confusion lines are analysed in terms of the reference chromaticity of the pseudoisochromatic test-figures of the Cambridge Colour Test. Results are analysed in the CIE 1976 UCS diagram, in the MacLeod-Boynton diagram based on cone excitations, and in terms of CIE CAM02-UCS and CAM16-UCS. As the summary of the results, four theses are framed. Results describe changes in discrimination under unchanged lighting environment, based on the change of the reference chromaticity only.

In Chapter 4 chromatic discrimination ellipses measured under different states of chromatic adaptation are compared. The differences in adaptation were defined by the structure of the visual fields. Chromatic discrimination ellipses elongated and rotated in accordance with the stimulus.

In Chapter 5 the phenomenon described in Chapter 4 was applied in sensory testing: the design and verification of a masking environment is introduced. As a result, a general method of designing masking light is formed as a thesis.

3. RESULTS AND THESES

The research described in Chapter 3 can be divided into two main questions: the dependence of the chromatic discrimination thresholds measured in a given direction on the reference points and the dependence of the thresholds measured at a given reference point on the measurement direction.

To answer the former, I performed Trivector measurements at 66 reference points and evaluated them as a function of the position of the reference points in three colorimetric systems. The effect of the measurement direction was examined by comparing the results of the Trivector and Ellipsis tests performed at the same reference points.

Based on the Trivector test series performed in a reference point grid covering the entire gamut of the applied CRT display, it can be stated that by moving the reference points from the neutral point to a confusion direction, the chromatic discrimination threshold measured from the shifted reference point to the above confusion direction increases greatly and this increase can be estimated by mathematical model.

Based on the results I formulated the following theses:

Thesis 1

In the CIE 1976 UCS diagram chromatic discrimination thresholds of normal colour observers measured towards the Protan, Deutan and Tritan confusion directions can be estimated with second order polynomial functions

$$\Delta_{P,D,T} = c_2(x - x_0)^2 + c_0$$

where:

- **Δ is the dependent variable: the chromatic discrimination threshold (just-noticeable difference, JND),**
- **x is the independent variable, denoting the reference distance,**
- **reference distance is the distance between the reference point (background chromaticity) and the neutral white point,**
- **x_0 and c_0 are respectively the coordinates of the vertex, the point at which the function reaches its minimum,**
- **confusion directions are directions towards the confusion points,**
- **the Protan, Deutan and Tritan confusion points are defined as P(0.6579; 0.5013) D(–1.2174; 0.7826) and T(0.2573; 0.0000),**
- **the neutral point is defined as (0.2024; 0.4689),**
- **c_0 constant can be estimated with the JND values measured in the neutral reference point, and**

- **c_2 constant can be estimated with the following ellipses in terms of the reference directions**

$$c_2(\delta) = \sqrt{\frac{a^2 \times b^2}{a^2 \times sin^2(\delta-\vartheta) + b^2 \times cos^2(\delta-\vartheta)}}$$

where:

- **c_2 is the leading coefficient of Eq. (1),**
- **δ is the independent variable: the angle of the reference direction,**
- **the reference direction is the direction of the shift of the reference point from the neutral point,**
- **a is the radius on the major axis,**
- **b is the radius on the minor axis, and**
- **ϑ is the angle of the major axis and the abscissa.**

Related publications: [I-1], [I-4], [II-1]

<u>Thesis 2.</u>

Shifting the reference point towards one of the three confusion points from the neutral point in the CIE 1976 UCS diagram indicates that chromatic discrimination thresholds of colour-normal participants measured towards the concerned confusion point exceed the normative upper-limit of colour-normals and reaches the normative range of anomalous trichromats.

Related publications: [I-4], [II-1]

Considering that the CIE 1976 UCS diagram is known not to be perfectly uniform in terms of perception, I evaluated the results in a MacLeod-Boynton chart based on cone-excitations. The chromatic discrimination thresholds showed a strong correlation in the two colour systems.

Based on the results I formulated the following thesis:

__Thesis 3.__

A positive, significant correlation between the CIE 1976 UCS and the LMS cone spaces indicates that increased colour normal chromatic discrimination thresholds on the confusion lines are detected as changes in photoreceptor signals as well.

Related publication: [I-4]

Comparing the results of the Trivector tests with the results of the Ellipse tests, I found that the Trivector estimates have higher threshold values calculated from the Ellipse measurements at the same reference point in almost all cases. Thus, there were colours outside the estimated chromatic discrimination ellipses, which the participants could not distinguish.

This suggests that the reliability of the ellipse test depends on whether one or some of the measuring directions coincide or approach one of the confusion lines. To overcome this, it is recommended to give the confusion directions a prominent role in the preparation of the experimental design, also in the case of the testing participants with normal colour vision.

Based on the results I formulated the following thesis:

__Thesis 4.__

Chromatic discrimination thresholds on the confusion lines are found to be larger than in other directions. This justifies the measurement of chromatic discrimination ability towards the Protan, Deutan and Tritan confusion points in the modelling and validation of uniform colour spaces.

Related publications: [I-1], [I-4], [II-1], [II-2]

In Chapter 4, I examined the effect of the colour stimulus size determining chromatic adaptation by comparing chromatic discrimination ellipses. In the first case, just as in the experiments described in Chapter 3, I performed measurements in a dark room, where the state of adaptation was determined globally by the dark room and locally by the reference chromaticity of the pseudo-isochromatic test. In the second case, the measurements were performed in a coloured lighting environment implemented in a spectrally tuneable light booth. In both cases, the chromatic discrimination ellipses extended toward the chromaticity of the colour stimulus determining the state of adaptation, but the change in the chromaticity of the reference point had a stronger effect on the elongation of the ellipses than the chromaticity of the light booth.

In Chapter 5 an application-centric research conducted in collaboration with colleagues from the Hungarian University of Agriculture and Life Sciences, Institute of Food Science and Technology, Department of Postharvest, Commercial and Sensory Science is presented. The aim of the research was to optimize a lighting environment for the sensory testing of taste, odour, and texture, and create a test space for sensory assessors. The optimization aimed to eliminate the expectation error caused by the perceived colour differences between the test samples and to minimize the cross-modal effects caused by the colour of the light. In conclusion, a general method is shown for the optimization of masking colour differences for a general line of products.

Based on the results I formulated the following thesis:

Thesis 5.

A spectrally tuneable – ***built as a combination of light sources emitting in different wavelength-ranges*** – **masking environment** – ***defined as a lighting environment in which the expectation error caused by the perceived colour differences between the test samples***

is eliminated, and the cross-modal effects caused by the colour of the light are minimized **– can be individually optimised for sensory testing of taste, odour or texture assessment with the following iterative method:**

1. **Measurement of the wavelength-dependent properties of the samples (spectral transmittance or spectral reflectance, depending on the samples) in the range of 380 nm – 780 nm (sample stimuli).**
2. **Measurement of the spectral power distribution of the channels of the tuneable light source in the range of 380 nm – 780 nm (channels).**
3. **Definition of the spectral range(s) in which the smallest differences can be observed between the values of the sample stimuli, based on the comparison of the spectral distributions and the range of the sample stimuli in terms of wavelength.**
4. **Among the channels, first enhance the one which emits closest to the spectral range defined in step 3.**
5. **Verification of the efficiency of the mask with sensory tests most suitable for the aim and aspect of the colour samples (e.g. discrimination test or colour ranking test).**
6. **In case the mask is efficient, add further spectral channels in accordance with the wavelength-dependent increase of the range of the sample stimuli mentioned in step 3., until the efficiency of the mask reduces.**

Related publications: [I-2], [I-3], [I-5], [II-3], [II-4]

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