Brightness perception of different spectra under mesopic conditions

Sören Schäfer, Franziska Kley: L-LAB, Salzkottener Straße1, 33100 Paderborn
Stephan Völker: TU Berlin, FG Lichttechnik, Einsteinufer 19,. 10587 Berlin

Keywords: *Mesopic Vision, Spectral Distribution, Broadband, Brightness Matching, Programmable Light Source, Energy Efficiency*

1 Abstract

For night-time driving very different light sources are commonly used. They differ in their spectral power distribution. Under mesopic conditions the human perception is affected by a special effect. It is called “Purkinije-Effect” and describes the change of the impression of luminance. By adaptation to a lower luminance level there is a shift of the spectral sensitivity from longer to shorter parts of spectral power distributions. To quantify this effect psychophysical tests with the method of memory based stimuli comparison will be done in laboratory tests. The stimuli are realistic and complex spectra from the field of road traffic and modified spectral power distributions.

A possible research setup will be explained. The results of the experiments will be used to verify present research and to describe a set of reference-linked equivalent luminances.

Future scientific experiments have to attend the fact which part of a spectral power distribution, can be integrated in which special form, to design empowered light based of the effect described above. The effect of specific light colours and their spectra will be inspected with a new method.

2 Introduction

A main part of our life is not only based on photopic, but also in the range of scotopic and mesopic vision. It exists the demand of equal performance of vision at any adaptation levels to solve tasks of vision. The quality of applied artificial illumination is proper.

The artificial illumination is regulated for many kinds of applications with rules, technical feasibilities and requirements for low adaptation levels. Examples are automotive lighting engineering (*Economic Commission for Europe - ECE*, Federal Motor Vehicle Safety Standard - *FMVSS*), street illumination (DIN EN 13201), emergency exit lights (*National Fire Protection*

Association - NFPA, *Canadian Commission on Building and Fire Codes - CCBFC*) and areas of ambient light.

Additional to the regulations, there are existing dimensions, based on requirements and user needs. Aspects of daylight affinity, light colour, recognition distance and brightness [1, 2] are important for users.

To accomplish the illumination task mentioned above, there are existing different technologies of light emission, like the thermal radiator, the electric discharge, the semiconductor elements and the chemical luminescence. With these possibilities of light generation, a huge amount of narrow and broad banded spectra will be created. A combination of those techniques can be more or less efficient. Besides these aspects of regulations, user centred design and the technical realisation, a demand for a higher energy efficiency is a main part of the future research. Not only a development of technologies for light emission, but also a using of psychophysical effects of the human being can contribute to improve the energy efficiency. Imposed by reducing of the luminous flux for different applications, based of a brightness perception of comparative systems, it is possible to realize an energy saving. Therefore the human is setting a brightness perception value for one spectrum as benchmark to another spectral power distribution. Motivation and aim of the present research is the exploration of the brightness perception of established spectral power distributions of luminous sources for street lighting. A focus point is the significance of the specialty of the human visual system. The generation of new spectral distributions is providing another focus point, while using the evaluated data from the brightness perception research. In this connection the regulations must be in mind. Currently extensive analyses for the brightness perception with different spectral distributions under low adaptation levels will be done in the L-LAB.

3 Background

The psychophysical effects of the human visual system are well known at photopic and scotopic conditions: But under low adaptation levels (mesopic range) diffuse and not adequate admitted effects will be found [3]. Under these conditions key facts are the nonlinearities of the receptor interaction and the resultant dynamic shift of the wavelength plus the change of the spectral luminous efficiency in account to the used spectral luminous efficiency function. With decreasing the luminous adaptation level, a shift of the wavelength to shorter ones takes place. This is named the Purkinije-Shift [4]. Furthermore an increasing of the spectral sensitivity for shorter parts of a spectrum exists. For the development of models to describe the signal processing of the visual system under mesopic conditions, lots of scientific analyses are done. A compendium is still available [5, 6]. There existing different methods, research designs and hypothesis etc., but a general for brightness rating has to relate some spectra together in brightness.

Present explorative empirical analyses, which are according to the authors studies, gives a picture about the nature of the expected effects [7, 8]. To generate global data sets with a variation of variables (spectra, visual field sensation, adaptation level, etc.) and the elimination of measurement artefacts, a modification of the used experimental design is needed.

4 Method

The impression of brightness and the its rating dependeds on the size of the stimulus, the adaptation level, the spectral power distribution, the areal localization at the retina and the research method. A selection for the last one is described in Wyszecki&Stiles [9] and the CIE 78 [10]. Humans are not able to rate brightness and luminances as an absolute value, therefore a stimulus rating to a reference is needed[11]. Two methods are preferred.

4.1 Direct brightness matching (DBM)

A special kind of the direct comparison is the presentation of two stimuli in a bipartite field. Fotios [12] discriminates two special forms of equation. The first one is a qualification of brightness, which will be rated on a scale together. The second and the relevant one for the present research, is the brightness matching. The goal of the matching procedure is to produce an equal brightness by matching the test stimulus to the reference stimulus.

4.2 Memory based matching (MBM)

Another approach is to use a method where a time offset is between the reference stimulus after adaptation and the changeable test stimulus. The memory brightness matching is also a method with possible relative ratings between two stimuli is possible [13, 14]. In contrast to the mentioned method above, there is no local diversification, but a time based shift. The rating of the test stimulus is a result from the stimulus which is anchored in the mind of the test person. The usefulness of this method is approved for the current field of research by several studies. A comparison was done and so were smaller and significant standard derivation values found for the MBM – method [15].

5 Experimental Setup

For the research of the relative brightness rating of different spectra, an experimental setup is realized. This was put into practice in relation to the factors, to which brightness depends on [16]. The chance to modify the setup regarding to other investigations is given.

With this experimental setup, there is not the possibility to test narrowband spectra (e.g. LED, metal halide lamp, mercury based lamps), and mixed spectral distributions by monochromats but also no limitation by given spectra of industrial light sources.. Now it is possible to generate every thinkable spectral distribution out of a broadband xenon light source. It underlies regressions of spectral power and the range of the visible part of electromagnetic radiation. In

this case, the daylight like spectrum of the primary Xe-light source will be collimated and transformed by a grating into separately adjustable wavelengths. The spectral dues could be consolidated to a complex distribution. The wavelength is programmable and their spectral power is adjustable. At present, the primary spectral power output is bordered by the 500W Xe light source and the used slit to realize the spectral accuracy of the output of the programmed spectrum. The maximum luminous flux by using 100% of the primary light source (used slit=$150*10^{-6}$m, half width 5nm) is Φ=28lm.
To get a valid evaluation of brightness, the spectral accuracy of the programmed and reproduced spectra of the system is needed, if those are used as stimuli. Also the presentation of stimuli has to be adequate to the factors to which the relative brightness perception is demanded. As an implication, the following assumptions are important to realize:

1. Low and high mesopic adaptation levels (0,1 cd/m² - 10 cd/m²) must be able to generate.
2. An accurate picture of the wavelength distribution of the programmed spectrum is needed and a spectral uniformity across the area of the stimulus (visual angle=perception of the visual field[1]) is requested.
3. Homogeneity of the luminance across the stimulus, the adaptation field.
4. Variable generation of stimuli sizes to accomplish larger fields of vision.
5. The methods of DBM and MBM are practicable.

For the construction of the experimental setup, an integration sphere with a diameter of d=500 mm were modificated and furnished with an optical injection. Because of the nature of an integration sphere the leakage of injected luminous flux is low. In case of the internal coating, a good spectral uniformity of reflection is given. It was measured with a spectroradiometer at four positions (Figure 1). The mismatch between the set to the actual signal is summarized for several peaks of wavelengths (Table 1). For a reduction of the radiance, a stability of the spectral allocation is given.

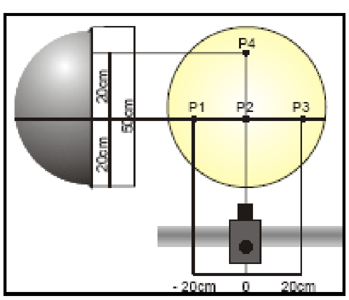

Figure 1: Four points of measurement with the OL 770 spectroradiometer

[1] Visual field perception: strict stimulus attached phenomenon in the centers of vision because of an excitation of one or more optic nerves in form of an isolated stimulus of light or color. You have to vary between a visual field perception that is based on brightness perception or color perception [17].

Table 1: Spectral accuracy of special peaks of wavelength and the maximum deviation Δ λ_{MAX}

Wave-length [nm]	**385**	**400**	**450**	**500**	**555**	**600**	**650**	**700**	**750**	**780**
Measure-ment										
Point P1	384,78	400,15	450,72	501,08	556,06	600,77	650,52	699,68	749,46	778,3
Point P2	385,17	400,15	450,72	501,08	555,61	600,77	650,52	699,68	749,46	778,3
Point P3	384,78	400,15	450,72	501,08	555,61	600,77	650,52	699,68	749,46	778,3
Point P4	385,17	400,15	450,72	501,08	555,61	600,77	650,52	699,68	749,46	778,3
Δ λ_{MAX} [nm]	0,17	0,15	0,72	1,08	1,06	0,77	0,52	-0,32	-0,54	-1,7

The level of the luminance adaptation is determining the brightness perception and is special for the mesopic vision. The test persons viewing direction is not fixable, but it determines the adaptation level, especially by inhomogeneous luminance fields. Therefore it is necessary to create a background which it has an equal luminance at all (viewing) positions. So, one aim for creating the experimental setup, it has to be the same luminance at every position within the stimulus (with marginal derivation). The given homogeneous luminance is listed in table 2. The values are measured with the luminance measuring camera LMK98/3. There are three horizontal and three vertical arrays of evaluation. Each of them with ten areas of evaluation (circles d=50 pixel, enlargement of the projected lines s_x=6,257mm, s_y=6,327mm). An acceptable tolerance of the luminance is around ten percent.

Table 2: Relative maximal deviation of the measured horizontal and vertical luminances Δ L_{MAX} (relation of the minimal an maximal value of one array, analogue to the circles in figure 2)

Horizontal evaluating array		**Vertical evaluating array**	
Evaluation array	**Δ L_{MAX} [%]**	**Evaluation array**	**Δ L_{MAX} [%]**
O	5,67 %	L	22,97%
M	7,42 %	M	31,18%
U	12,18 %	R	24,65%

Especially the maximal deviations of the vertical measurement and evaluation arrays are not tolerable for the future development. A primary cause of these values is the injection which was realized with a light guide in the upper regions of the integration sphere. The visualisation of figure 2 stands for the interpolation of missed evaluation areas in the boarding regions of the integrating sphere surface. The luminance values are interpolated with the surface interpolation method Griddata [18] and are the equivalent of projected and space resolved luminances of the sphere. The resulting, maximum stimulus area has a circular angle of about 170° (based on the diameter of d=500mm).

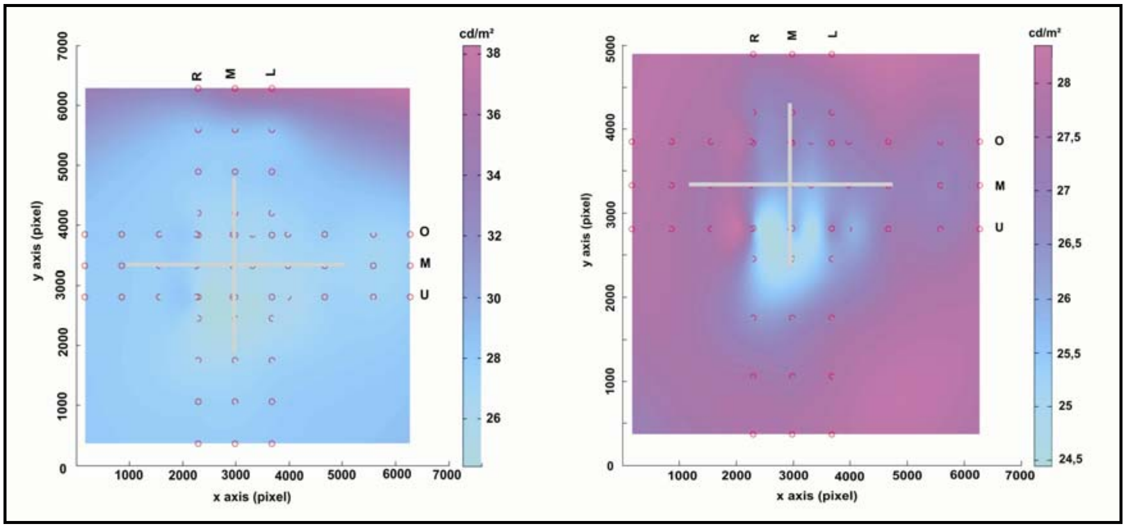

Figure 2: Interpolated luminances with maximal, creatable, circular stimulus area about 170° (left side), about 40° reduced vertical stimulus area (right side), point of cross symbolizes the point of origin P(0;0) for the circular stimulus area

As a result, it is self-evident, that the deviation values for the vertical array suggest the decision to reduce the vertical range of the stimuli (perception of the field of view). But this goes along with the fact that the human field of view decreases with lower luminance levels and the luminance level of the stimulus [19]. According to the present research thesis and the mesopic conditions, the relevant, idealized, circular (the field of view isn't a circle, but rather an ellipse) field of view is reducible in its dimension. The decrease of deviation for the homogeneous luminance of the system is attended by this effect. Detailed facts are listed in table 3.

Table 3: Relative maximal deviation (Δ L_{MAX}) of the measured horizontal and vertical luminance against the dimension of the circular perception of the field of view (PFOW)

Circular PFOW [°]	**Δ L_{MAX} horizontal [%]**	**Δ L_{MAX} vertical [%]**
10,44°	-1,19 %	-3,70 %
50,25°	-4,37 %	-8,65%
90,05°	-6,64 %	-10,74%
129,86°	-7,74 %	-15,40%
169,67°	-13,87 %	-45,31%

In fact, the assumptions 1-4 are fulfilled and the method of MBM can be used. With some modifications assumption 5 could also be realized. In Figure 3 is shown a visualisation of the present development stage of the experimental Setup.

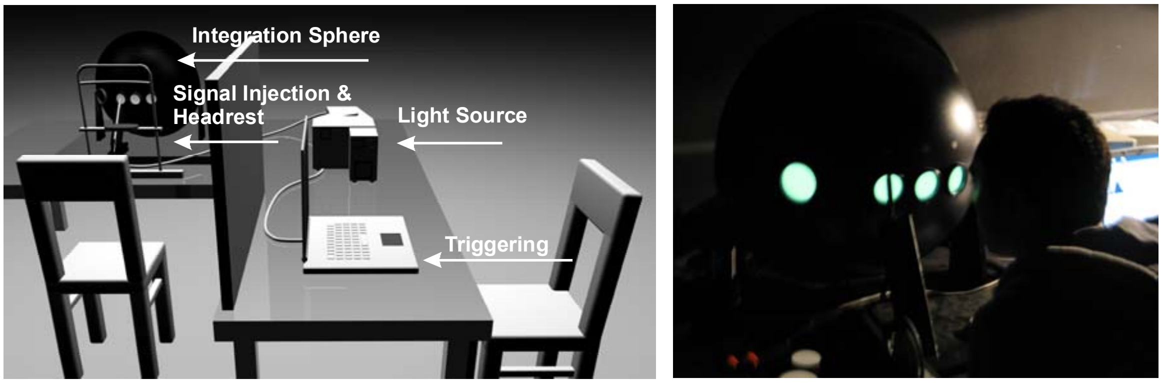

Figure 3: Conceptual design (left) and realized experimental setup (right)

6 Aspects of future research and discussion

In the course of the present work, to do large scale analyses of the brightness perception, an experimental setup and its triggering is realized. Not only the spectral distributions and their special features also, the evaluation of the field size of the stimulus (PFOW) and the contribution of test methods are part of the main research aspects. Because of the done measurements, the named assumptions have to be fulfilled to get valid and reliable results. An implementation of the DBM - method is possible, if the experimental setup is duplicated or a vertical partition is made. As a result the whole integration sphere is divided into two half spheres. With a modification of one of the half spheres, results in a larger field of view perception and so the assumption five is fulfilled as well.

Mentioned in chapter 3, the rating of the brightness perception is not only based to the relative threshold. The more relevant matching criterion is the minimal (absolute) value of the threshold, to get an upper and lower boarder of an area of equal brightness. This is based on the nonlinear (ratio of the improved stimulus intensity against the perceived stimulus intensity) attitude of the visual path [20]. A second point is that a test person can rate easily a minimal difference between two stimuli. It is possible, that the expected results are marked with a lower standard deviation.

In present and future evaluation the broadband spectra are the main kinds of stimuli. Research topics, in association with the effects of the luminance adaptation level, the method, the variation of the spectral setting, the perception of a field of view (especially according to [21, 22]) and other factors, will be traced. In a following step, possible artifacts of the pre-studies [7, 8] should be investigated in detail. With the knowing of effects, benefits for the using and design of new spectral power distributions are possible. Additionally the influence of the spectrum, especially to the parts of short wavelength and in contrast the visual performance mainly in the peripheral regions, are important research topics [23, 24, 25].

In conclusion a design of more efficient light (colours) per application, is possible with the evaluation results of the brightness scaling in variation of the spectral distribution. These are quantifiable and enable valuable clues to aspects of object detection, especially in peripheral regions and also for the calculation of recognition distances of perhaps automotive headlamps.

Acknowledgement

The present research takes place in the L-LAB, Paderborn. The L-LAB is a public private partnership of the University of Paderborn and the Hella KGaA Hueck & Co.. Furthermore is the research supported by a studentship of the Dr. Arnold Hueck Stiftung.

References

1. Köhler, S. (2007). Helligkeitsbewertung von Kfz-Scheinwerfern unter mesopischen Bedingungen. TU Ilmenau: Diplomarbeit.
2. Schmidt, S. (2006). Der Einfluss der Lichtfarbe auf die Blendung und Erkennbarkeit am Beispiel von LED-Frontscheinwerfern. Universität Jena: Diplomarbeit.
3. Stockman, A.; Sharpe, L.T. (2006). Into the twilight zone: the complexities of mesopic vision and luminous efficiency. In: Blackwell Publishing (Hrsg.): Ophthalmic and Physiological Optics. Vol. 26, Nr. 3. Singapur: KHL Printing Co. Pte Ltd.
4. Purkinje, J. (1825). Beobachtung und Versuche zur Physiologie der Sinne. Teil 1: Prag 1823, Teil 2: Berlin 1825.
5. CIE (1989). Commisson Internationale de l'Éclairage. Mesopic photometry: History, special problems and practical solutions , No 81. Vienna: CIE.
6. CIE (2001). Commisson Internationale de l'Éclairage.Testing of supplementary systems of photometry, No 141:2001. Vienna: CIE.
7. Kley, F.; Gottschalk, M.; Kliebisch, D.; u.a. (2007). Ein Helligkeitsvergleich verschiedener Lichtquellen im mesopischen Bereich. LICHT, 7-8/2007. München: Pflaum Verlag.
8. Khanh, T.C.; Böll, M.; Schiller, C.; u.a. (2008). Helligkeits und Kontrastwahrnehmung im mesopischen Bereich. LICHT, 3/2008. München: Pflaum Verlag.
9. Wyszecki, G.; Stiles, W.S. (2000). Color Science – Concepts and Methods, Quantitative Data and Formulae. 2nd Ed. New York: John Wily & Sons Inc. S. 278 ff.
10. CIE (1988). Commisson Internationale de l'Éclairage. Brightness luminance relations. No 78. Vienna: CIE.
11. Bodmann, H.W. (1961). Zur Frage einer allgemeingültigen Hellempfindungsskala. In: Lichttechnik. Nr. 1/1961.13. Jahrgang. S. 19 ff.
12. Foitos, S.A.; Cheal, C. (2007). Evidence for response contraction bias in side-by-side matching tasks. In: Lighting Research Technology. Vol 39, No. 2. p. 159-169.

13. Rinner, O.; Gegenfurtner, K.R. (2000). Time course of chromatic adaptation for color appearance and discrimination. In: Vision Research. Vol. 40, No.14. Great Britain: Elsevier Science Ltd. p. 1813-1826.
14. Mizokami, Y., Werner, J.S., Crognale, M.A., Webster, M.A. (2006). Non-linearities in color coding: compensating color appearance for the eye's spectral sensitivity. In: Journal of Vision. Vol. 6(9). p. 996-1007.
15. Bodrogi, P., Schanda, J. (1999). Heterochromatic memory brightness matches. CIE 24th Session. Warsaw. p. 73-76.
16. CIE (2004). Commisson Internationale de l'Éclairage. CIE Collection in colour and vision, No 118:1995. Vienna: CIE.
17. Mütze, K.(Hrsg.); Foitzik, L.; Krug, W.; Schreiber,G. (1972). ABC der Optik. Hanau/Main: Verlag Werner Dausien.
18. Wolfgang, S. (2008). MATLAB kompakt. Oldenburg: Oldenbourg Wissenschaftsverlag. S. 130 ff.
19. Werner, E. (1991). Manual of visual fields. Churchill Livingstone.
20. Goldstein, E.B. (2002). Wahrnehmunspsychologie. 2nd Ed. Heidelberg: Spektrum Verlag. S. 20.
21. Glaser, H. (2008). Prüfung der Sichtabschattung aus dem Fahrzeug und im Verkehrsgeschehen. Europäische Vereinigung für Unfallforschung und Unfallanalyse, Ländergruppe Österreich. Wien. S. 9-20.
22. Schmidt-Clausen, H.J.; Dmasky, J.; Wambsganß, H. (1992). Einfluß der Helligkeit von Fahrbahnoberflächen auf die Seh- und Wahrnehmungsbedingungen von Kraftfahrern bei Nacht. In: Bundesministerium für Verkehr (Hrsg.): Forschung Straßenbau und Straßenverkehrstechnik. Heft 629. Bonn. S. 2 f.
23. Adrian, W. (1998). The influence of the spectral power distribution for equal visual performance in roadway lighting levels. Fourth International Lighting Research Symposium – Vision at low light levels. Orlando. p. 69-83.
24. Alan, L. (1999). Visual performance as a function of spectral power distribution of light sources at luminances for general outdoor lighting. In: Journal of the Illuminating Engineering Society. Vol. 28, No. 1. S. 37-42.
25. Bullough, J.D.; van Derlofske, J. (2003). Spectral effects of high-intensity discharge automotive forward lighting on visual performance. SAE technical paper series. No. 2003-01-0559.