VILNIUS UNIVERSITY
CENTER FOR PHYSICAL SCIENCES AND TECHNOLOGY

Andrius
PETRULIS

Colour rendition engineering and psychophysical assessment of the multicolour solid-state lighting

SUMMARY OF DOCTORAL DISSERTATION

Technological sciences,
Materials engineering 08T

VILNIUS 2018

This dissertation was written between 2013 and 2018 at Vilnius university.
The research was partially supported by Research Council of Lithuania.

Academic supervisor:
Prof. Habil. Dr. Artūras Žukauskas (Vilnius university, Technological sciences, Materials engineering – 08T).

This doctoral dissertation will be defended in a public meeting of the Dissertation Defence Panel:

Chairman – Prof. Habil. Dr. Sigitas Tamulevičius (Kaunas university of technology, Technological sciences, Materials engineering - 08T).
Members:
Dr. Renata Butkutė (Vilnius university, Technological sciences, Materials engineering – 08T).
Prof. Dr. Aušra Daugirdienė (Vytautas Magnus university, Biomedical sciences, Biology – 01B).
Assoc. Prof. Dr. Sergio Miguel Cardoso Nascimento (University of Minho, Physical sciences, Physics – 02P).
Prof. Dr. Roland Tomašiūnas (Vilnius university, Technological sciences, Materials engineering – 08T).

The dissertation shall be defended at a public meeting of the Dissertation Defence Panel at 2 p. m. on 14th December, 2018 in auditorium A101 of the National Center for Physical sciences and Technology.
Address: Saulėtekio av. 3, LT-10257 Vilnius, Lithuania.
The text of this dissertation can be accessed at the libraries of the Center for Physical Sciences and Technology and Vilnius university as well as on the website of Vilnius University:
www.vu.lt/lt/naujienos/ivykiu-kalendorius

VILNIAUS UNIVERSITETAS
FIZINIŲ IR TECHNOLOGIJOS MOKSLŲ CENTRAS

Andrius
PETRULIS

Daugiaspalvio kietakūnio apšvietimo spalvų atgavos inžinerija ir psichofizikinis vertinimas

DAKTARO DISERTACIJOS SANTRAUKA

Technologijos mokslai,
Medžiagų inžinerija 08T

VILNIUS 2018

Disertacija rengta 2013– 2018 metais Vilniaus universitete.

Mokslinius tyrimus iš dalies rėmė Lietuvos mokslo taryba.

Mokslinis vadovas:
prof. habil. dr. Artūras Žukauskas (Vilniaus universitetas, technologijos mokslai, medžiagų inžinerija – 08T).

Gynimo taryba:
Pirmininkas – **prof. habil. dr. Sigitas Tamulevičius** (Kauno technologijos universitetas, technologijos mokslai, medžiagų inžinerija – 08T).
Nariai:
dr. Renata Butkutė (Vilniaus universitetas, technologijos mokslai, medžiagų inžinerija – 08T),
prof. dr. Aušra Daugirdienė (Vytauto Didžiojo universitetas, biomedicinos mokslai, biologija – 01B),
prof. dr. Roland Tomašiūnas (Vilniaus universitetas, technologijos mokslai, medžiagų inžinerija – 08T),
assoc. prof. dr. Sergio Miguel Cardoso Nascimento (Minho universitetas, fiziniai mokslai, fizika – 02P).

Disertacija ginama viešame Gynimo tarybos posėdyje 2018 m. gruodžio mėn. 14 d. 14 val. Nacionaliniame fizinių ir technologijos mokslų centro A101 auditorijoje.

Adresas: Saulėtekio al. 3, LT-10257 Vilnius, Lietuva.

Disertaciją galima peržiūrėti Fizinių ir technologijos mokslų centro bei Vilniaus universiteto bibliotekose ir VU interneto svetainėje adresu:
https://www.vu.lt/naujienos/ivykiu-kalendorius

SANTRAUKA

Pagrindinis disertacijos tikslas buvo įvertinti dinaminių kietakūnio apšvietimo sistemų spalvinės kokybės parametrus bei pagrįsti juos psichofizikiniais eksperimentais.

Disertacija sudaryta iš 4 skyrių, suskirstytų į poskyrius. Kiekvieno skyriaus išvados yra pateikiamos atitinkamo skyriaus gale, o visos disertacijos išvados išdėstytos prieš cituojamos literatūros sąrašą. Disertacijos autoriaus su bendraautoriais išpublikuotų publikacijų sąrašas yra disertacijos pabaigoje ir šios publikacijos cituojamos tekste su priešdėliu „P“, o konferencijų pranešimai su priešdėliu „K“.

Pirmame skyriuje plačiau aprašyti psichofizikiniai eksperimentai kietakūnio apšvietimo vertinimui ir palyginimui esant žemai apšvietai (3,3 lx – 300 lx). Atlikti trys eksperimentai: pirmojo metu ieškoma maloniausia susietoji spalvinė temperatūra su aukštos atgavos kietakūnio apšvietimu lauko sąlygomis ir tikrinama Kruithofo hipotezė. Antrasis eksperimentas papildo pirmąjį tiriant pradinės adaptacinės spalvinės temperatūros daromą įtaką pasirenkamai maloniausiai spalvinei temperatūrai. Trečiasis eksperimentas susietas su spalvų rikiavimo ir skyrimo įvertinimu žemos apšvietos sąlygomis atliekant Farnsworth-Munsell 100 spalvių testą keičiant apšvietimo spalvinę kokybę ir apšvietos lygį.

Antrame skyriuje aprašoma metamerinių šviesos šaltinių spalvos nesutapimo problematika ir atliekami du eksperimentai, kurių metu vertinami keturspalvės RpcGN sistemos metamerų spalvos skirtumai 10 laipsnių stebėjimo laukui. Pirmuoju eksperimentu atliktas spalvos koregavimas išilgai izotemperatūrinės tiesės, kertančios Planko lanką. Antruoju eksperimentu pademonstruotas tyrimo dalyvių suderintų dviejų šaltinių su CCT ir nuokrypio nuo baltos šviesos valdymu spalvio koordinačių skirtumas.

Trečiame skyriuje aprašomas daugiaspalvio šviestukų telkinio modeliavimas į žmogų orientuotam apšvietimui. Įvertinta apšvietimo spalvinė kokybė, cirkadinis poveikis, pirmenybinio apšvietimo ribos,

kuomet baltas šviestukas atitinka spalvų perteikimą su sumažintu sodriu, o raudonos, žalios ir mėlynos spalvos šviestukų telkinys atitinka spalvų perteikimą su padidintu sodriu. Pademonstruota penkiaspalvė apšvietimo sistema, sudaryta iš raudono, žalio, mėlyno ir dviejų skirtingų CCT baltų šviestukų.

Ketvirtame skyriuje pateikiami fotochemiškai su UV apšvietimu sendintų pigmentų spalvio kitimo rezultatai ir jų atstatymas naudojant matematinį modelį su praktiniais bei teoriniais LED spektrais. Aptariamos kietakūnio apšvietimo ribotos galimybės atstatyti konkrečią spalvinių bandinių aibę. Praktiniam meno kūrinių apšvietimui ir neinvaziniam spalvų atstatymui pagamintas prototipinis 10 spalvinių kanalų šviestuvas, kuris leidžia pademonstruoti doktoranto su grupe sukurtas apšvietimo technologijas.

ACKNOWLEDGEMENT

I would like to thank my supervisor prof. Artūras Žukauskas for the involvement in multicolour solid-state lighting technology and opportunity to create and develop novel lighting technologies.

I express my thanks to the prof. Rimantas Vaicekauskas for the help to create the complex luminaires and control algorithms.

My best thanks to dr. Pranciškus Vitta for the trust and help during the practical tasks and implementation of the solid-state lighting prototypes.

Additionally, I want to thank to all of co-authors and young colleagues for the interdisciplinary collaboration in scientific work.

Finally, I would like to thank my parents, Ieva and little daughter Sofija for the priceless support.

INTRODUCTION

Shuji Nakamura in 1994 demonstrated the high brightness blue light-emitting diode (LED) and the solid-state lighting revolution started. This invention was noticed by the Norwegian Nobel committee and Isamu Akasaki, Hiroshi Amano and Shuji Nakamura were jointly awarded The Nobel Prize in Physics 2014 "for the invention of efficient blue light-emitting diodes which has enabled bright and energy-saving white light sources”.

Spectral power distributions from the quaternary AlGaInAs, AlGaInP ir AlInGaN materials can be mixed into the metameric white light clusters which will appear the same colour for the average observer. Solid-state white light sources based on direct emission blue and phosphor converted (pc) yellow spectral components partially replaced the general light sources like fluorescent or incandescent lamps. Lighting composed of red, green and blue colours disrupted the general colour rendition index [1] which was replaced with more advanced indices [2, 3]. The evaluation of this qualitative lighting colour rendition enabled to adapt solid-state light sources for the art lighting with high colour rendition requirements. The discovery of the intrinsically photosensitive retinal ganglion cells in the eye at the beginning of XXI century related human circadian system with the light [4] and a new idea of human centric lighting was raised.

Light sources can be described using a luminous intensity (lm/sr – cd) and it is the only one of the International System of Units (SI) main units which is directly related to human body by using an eye luminosity function. On the other hand, human colour vision is very subjective as a result of biological, physical and mental characteristics. Therefore, lighting evaluation can differ based on subjective parameters and this should be taken into account. This led to the creation of so called Kruithof curve [5] where the evaluation of correlated colour temperature (CCT) depends on illuminance level and development of the uniform colour space CIECAM02 [6] based on observed colour and the background.

Regardless of variety of LEDs, niche applications of solid-state lighting and subjective lighting evaluation, dynamic solid-state lighting systems are not fully investigated under a low outdoor illuminance levels at different dynamically tuned colour quality and correlated colour temperature.

Main goal

Psychophysical and theoretical assessment of the dynamic LED lighting systems with controlled colour quality parameters.

Objectives

1) To demonstrate the outdoor lighting system with tunable correlated colour temperature and circadian action and perform the most pleasing lighting psychophysical research;
2) To evaluate the colour rendition created chromaticity shifts of juxtaposed colour samples under low illuminance levels;
3) To demonstrate the metameric light source chromaticity matching method;
4) To model solid-state lighting for human centric lighting with minimal independent colour components.
5) To perform the degradation test of merchandise pigments under the UV lighting and to theoretically and practically demonstrate temporal visual restoration under multichannel solid-state lighting.

Scientific novelty

- The Kruithof hypothesis was tested in different outdoor environments using a tetrachromatic solid-state lighting system under a low illuminance levels and the most pleasing correlated colour temperatures were found.

- The Farnsworth-Munsell 100 hue test was done under a different colour rendition lighting at 3000 K and low illuminance level.
- The method for a partially matching metameric RpcAGN cluster chromaticity at 3000 K along the isothermal line was demonstrated.
- The Pentachromatic solid-state lighting system consisted of red, green, blue, warm white and daylight LEDs was created for the human centric lighting with the possibility to control colour quality, colour temperature and preferential colour rendition.
- The non-invasive chromaticity restoration of UV-degraded merchandise pigments was demonstrated using a theoretical multichannel light source model or 10 colour channel practical luminaire.

Statements to defence

1) The most pleasing correlated colour temperature 3000 ± 200 K and 3500 ± 250 K was subjectively chosen in the outdoor environment with a 1900 K adaptation correlated colour temperature at 5 lx and 50 lx illuminance, respectively.
2) A partially correction of the 3000 K metameric RpcAGB cluster chromaticity can be performed by tuning the chromaticity along the isothermal line.
3) A pentachromatic merchandise RGB+W_L+W_H LED system is suitable for human centric lighting, changing correlated colour temperature, circadian action, colour quality and can create preferential colour rendition.
4) A chromaticity renewal of the UV-degraded merchandise pigments can be performed by the illumination device with spatially controlled spectral power distributions.

LAYOUT OF THE THESIS

This thesis is consisted of four chapters and finalized by the concluding summary. The articles and conference contributions of the author with co-authors are listed at the end of the thesis before information about the author. The layout of the chapters is organised as follows.

1. PSYCHOPHYSICAL ASSESSMENT OF THE TETRACHROMATIC SOLID-STATE LIGHTING

The subjective selection of the correlated colour temperature (CCT) at low illuminance level is topical in the outdoor and indoor environments. The most pleasing correlated colour temperature interval and its width based on Kruithof research [5] depends on the illuminance level and those intervals can be found in any case. Here we present the results of the most pleasing correlated colour temperature at 5 lx and 50 lx illuminance levels in three outdoor environments. A lighting system with a tetrachromatic white light cluster of red, phosphor converted amber, green and royal blue LEDs was used in every experiment. The second psychophysical experiment was based on the anchor effect during the chromatic adaptation. The third experiment was done to find the colour juxtaposing at different illuminance levels under colour quality controlled lighting. Results are published at P2, P7, P8, C1, C3, C4, C7, C8, C9, C10.

1.1. Investigation of Kruithof hypothesis at low illuminance levels

Kruithof curve has no experimental verification at low illuminance levels in outdoor scenes [7]. The following research was done to confirm the most pleasing CCTs under the street lighting conditions.

Kruithof hypothesis under low illuminance levels was investigated by using two tetrachromatic street lamps consisted of red, pc amber, green and royal blue (RpcAGN) LEDs [P1]. The luminaires were placed in the outdoor environments at 4.2 metre height with 6 metre spacing. The outdoor scenes were chosen at historical campus and botanical garden of Vilnius university and near the Lithuanian National Gallery of Art. Each scene represents old town, park and modern city, respectively. The illuminance levels were set at 5 lx and 50 lx with starting 1900 K CCT. The research participants (40 at old town, 22 at park and 24 at modern city scene) had to select the most pleasing CCT at 4 illumination modes. The first illumination mode was constant illuminance mode at 5 lx, second – constant circadian irradiance mode at 5 lx, third – constant illuminance mode at 50 lx and final - constant circadian irradiance mode at 50 lx. Constant circadian irradiance mode is the higher dimming with increasing CCT due to the increased melatonin suppression [9]. Colour quality of the luminaire is set to the highest value of a general colour rendition index (CRI). CRI value is above 91 at CCT range from 1850 K to 10000 K (Fig. 1.1.).

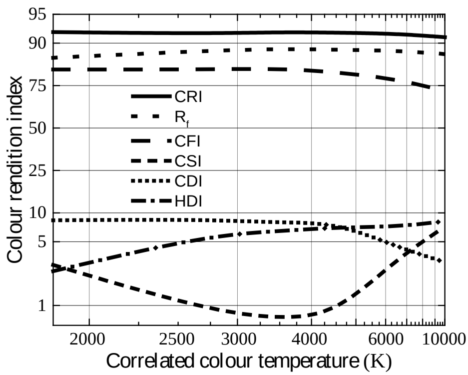

Fig 1.1. Color rendition indices of the tetrachromatic light engine as functions of CCT: general CRI (solid grey line); IES TM-30-15 color fidelity score R_f [8] (solid black line); statistical indices of color fidelity (dashed line); color saturation (dotted line); color dulling (dash–dotted line); and hue distortion (dash–dot dotted line) [P7].

Experiment took place at night with background ambient illuminance below 1 lx. The research participants had to select the most pleasing CCT after adapting to each lighting mode while using a CCT slider in the smartphone app with black background colour. They had a CCT adjustment trail before the experiment to learn the control of the luminaires.

The most pleasing CCT selections were grouped in intervals of 50 mireds (reciprocal CCT) and approximated by Gaussian distribution for evaluation of average mean and standard deviation (Fig. 1.2.). The illuminance at constant circadian mode is described as arbitrary illuminance units (arb. u.). Despite the fact of wide distribution, we can see that mean CCT value change from 2800 K to 3300 K with increased illuminance from 5 lx to 50 lx. Those CCT values are higher than in original Kruithof curve. This can be explained by the different colour quality of used illumination devices and limited CCT interval in the original experiment. In the other hand, our results coincide with other research data [10, 11, 12], where warm white light is preferred in outdoor scenes. The most pleasing CCT increases from 2400 K to 3300 K at constant circadian action mode with 5 arb. u. and 50 arb. u. illuminance, respectively. Research participants at lower circadian illuminance prioritized illuminance than CCT compared to 5 lx constant illuminance mode but at higher circadian illuminance CCT was prioritized than illuminance compared to constant illuminance mode at 50 lx.

The collected data can be defined as a Gaussian distribution using a Lilliefors test except the most pleasing CCTs from averaged data at 5 lx constant illuminance in all the outdoor scenes and city scene at constant 50 lx. This shows that our CCT adjustment interval is not limiting CCT selections. Mann-Whitney test was used to investigate the average CCT difference at different lighting modes to show the statistically significant change. In all cases expect 5 lx to 50 lx and 50 lx to 50 arb. u. in the city scene and 50 lx to 50 arb. u. in the old town scene the average CCT change was statistically significant. It shows, that increased illuminance increased the most pleasing CCT interval. This correlates with Kruithof curve qualitatively but not quantitatively.

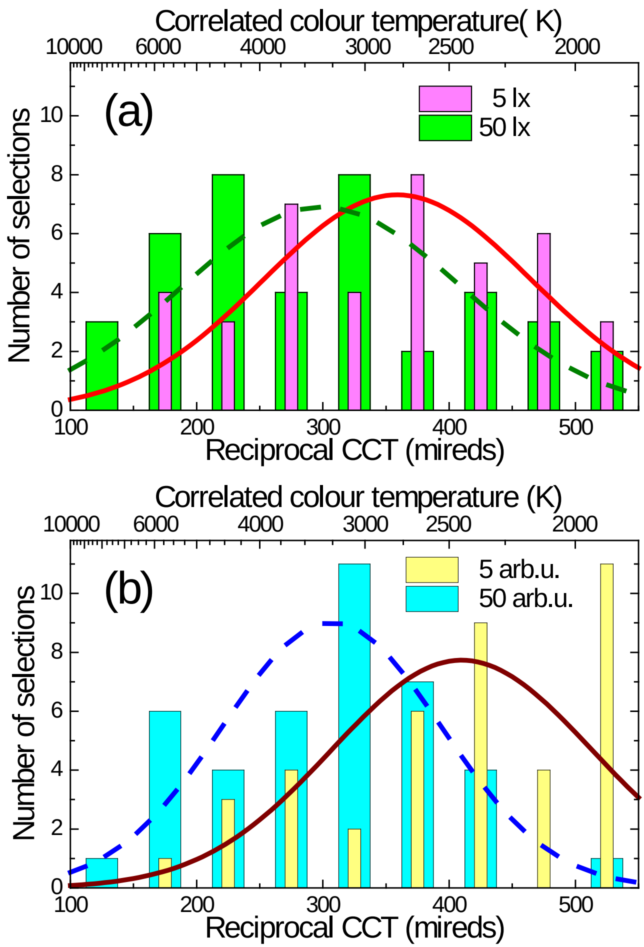

Fig. 1.2. Distributions of selected CCT for the "pleasing" illumination. Columns, experimental data for the university courtyard environment grouped in intervals of 50 mireds; lines, Gaussian distributions with the peaks and widths corresponding to the means and standard deviations of the selections. (a) Constant illuminance conditions for 5 lx (narrow columns and solid line) and 50 lx (wide columns and dashed line). (b) Constant circadian irradiance conditions for 5 arb. u. (narrow columns and solid line) and 50 arb. u. (wide columns and dashed line), corresponding to 5 lx and 50 lx illuminance at 1900 K, respectively [P7].

The most pleasing CCT intervals and average values at 5 lx and 50 lx constant illuminance are shown in Fig. 1.3. The average CCT values are higher than in the original research. This can be related to the anchor [13] of 1900 K adaptation CCT. On the other hand, a standard deviation (green bars) is widely distributed and CCT can be adjustable in some cases as it was done in offices [14, 15].

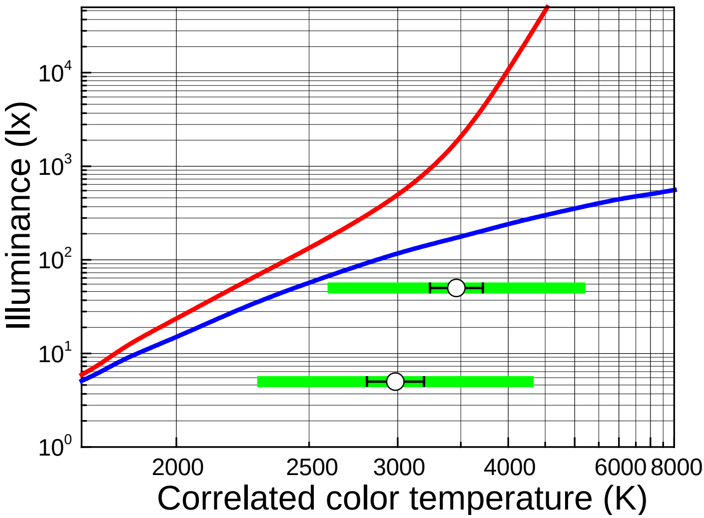

Fig. 1.3. Kruithof hypothesis: the area between two curves is claimed to define the conditions of the “pleasing” illumination, which corresponds to increased CCT with increasing an illuminance level [5]. The points, thin bars, and thick bars show mean values, confidence intervals of the mean values, and standard deviations of “pleasing” CCT established for the cumulative data on three outdoor environments in this work [P7].

1.2. Investigation of the anchor effect at different correlated colour temperatures

The second pilot psychophysical experiment was done after the first experiment with the purpose to investigate the anchor effect of adaptation CCT at different starting CCTs and two illuminances. This experiment was moved to the lab in order to ensure stable conditions.

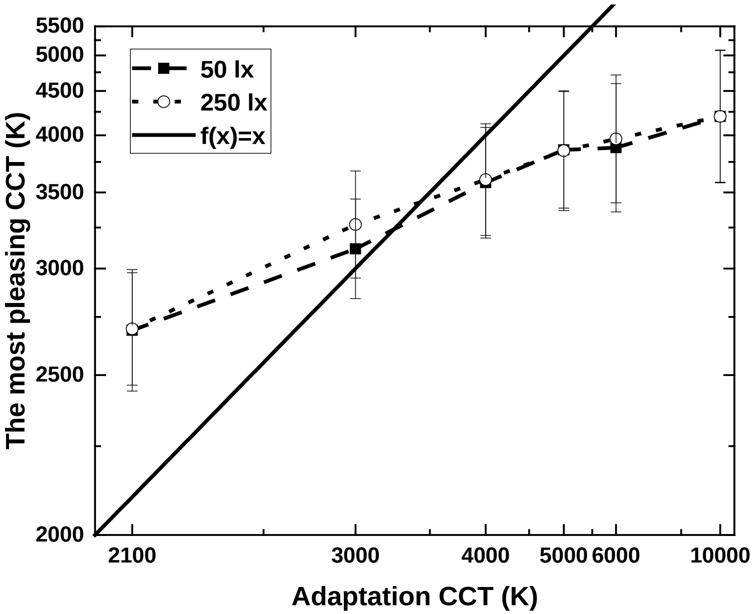

Fig. 1.4. The most pleasing CCT dependence on the adaptation CCT. Dashed line marks the CCT selection at 50 lx and dotted line marks the selection at 250 lx. Black bars correspond to confidence intervals. The black line represents the linear function for finding the identical point for both CCTs.

The experiment was updated with a reciprocal CCT control to represent the real perception of CCT and the smartphone was eliminated in order to avoid other light sources. The RpcAGN luminaire [P1] was mounted on a 70×70×80 cm grey colour lighting booth with no colourful objects and controlled by a gamepad. Two illumination levels of 50 lx and 250 lx was used with randomly selected anchor CCTs of 2100 K, 3000 K, 4000 K, 5000 K, 6000 K and 10000 K. The first illuminance was set to 50 lx and after selecting all six the most pleasing CCTs at each anchor CCTs it was increased to 250 lx and selections repeated. 20 research participants performed the CCT selections and they were tested with Ishihara plates test.

The investigation of the anchor effect shows (Fig. 1.4.) that the adaptation CCT has a significant effect of selecting the most pleasing CCT. It can be seen that two illuminance levels have no difference for selecting CCTs. The most pleasing CCT interval starts at 2700 K with the 2100 K adaptation CCT and continues to 4200 K with the 10000 K adaptation CCT. Universal CCT where a linear function crosses data points is about 3350 K. This neutral adaptation colour temperature should be chosen as the most pleasing CCT. The CCT interval difference from 2700 K to 3350 K and from 3350 K to 4200 K corresponds to Δ72 and Δ60 mireds, respectively. The average value of selected CCTs is 3470 K and 3520 K for 50 lx and 250 lx, respectively. In that case, average CCT independent of illuminance was at 3500 K. This value is close to 3350 K neutral CCT. Our results had the 200 K difference from other research [16] but their adaptation CCT interval was limited from 3000 K to 4400 K. Other research using the 3000 K – 8000 K CCT interval [17] concludes that the selected CCT has the significant impact on adaptation CCT, CCT interval and adaptation time. In our work, we used the widest CCT control interval and the software provided smooth control with no fixed CCT endpoints which helped to get the best results.

1.3. Farnsworth-Munsell 100 hue test results at low illuminance levels

The third psychophysical experiment was done to investigate the colour quality effect on performing colour juxtaposing with the Farnworth-Munsell 100 hue (FM100) test at different illuminance levels. The same tetrachromatic RpcAGN luminaire was used at 3.3 lx, 67 lx and 300 lx illuminances which corresponds to 0.5 cd/m^2, 10 cd/m^2 and 45 cd/m^2 luminances, respectively, in the same grey lighting booth. Luminance values were measured with imaging photometer-colorimeter Lumicam 1300 color because research participants see the luminance but not illuminance. The luminaire was set to one of five colour qualities using a linear equation between colour dulling and saturating LED clusters:

$$S_{TOTAL}(\lambda) = \sigma S_{SAT}(\lambda) + (1-\sigma) S_{DUL}(\lambda) \qquad (1.1)$$

There $S_{SAT}(\lambda)$ ir RGN LED cluster, $S_{DUL}(\lambda)$ is pcAGN LED cluster and σ is a colour quality control parameter. Then σ =0, we have only a pcAGN cluster with low colour quality (CRI = 81) and gamut area (GAI = 55). At σ = 0.15 we have the highest colour rendition with CRI = 93. Then σ = 0.31, colour rendition is set to preferential (CRI = 85) with slightly increased colour saturation [P1]. σ = 1 is a RGN cluster with the highest colour saturation values (CRI = 14) and σ = 0.65 is the values between saturation and preferential colour rendition (CRI = 50).

Five well-trained participants performed the FM100 test 3 times at each colour quality and illuminance levels. There were 225 FM100 tests in total to minimize errors and to achieve a good confidence interval. FM100 error scores of juxtaposed colour caps were averaged and 95 % confidence intervals were calculated. Results at each colour palette with colour caps show that the lowest score is achieved in pallet no. 4. due to constant royal blue spectral component in the spectral power distribution. All hues in this palette are illuminated with a red or a wide pc amber spectral component and it is sufficient to distinguish them. The similar results are in palette no. 1 with red hues. The Narrow red or wide pc amber spectral component is sufficient for juxtaposing red hues. The increased error score at the lowest illuminance is related to the luminosity function shift in ar of? a blue spectral region which determine the worse colour discrimination in red hues. Yellow-green hues in palette no. 2 are not distinguished at higher colour quality control parameter due to the absence of a pc amber spectral component. Green-blue hues in palette no. 3 are not distinguished at the lowest illuminance due to the absence of a cyan spectral component. As we can see, the main errors are determined by the absence of spectral components or the colour vision change in mesopic lighting condition.

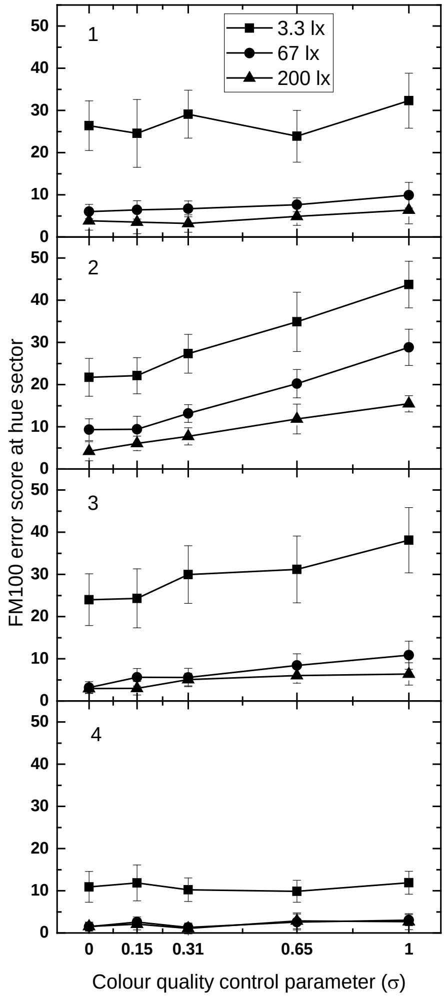

Fig. 1.5. FM100 error scores for each of four colour palettes at three illuminance levels dependence on the colour quality control parameter [P8].

The total error score (TES) of FM100 test is shown at Fig. 1.6. Represented colour rendition indices (R_g – colour gamut score [2], CRI, GAI – gamut area index [18], HDI – hue distortion index [3]) indicate that TES correlates with R_g, GAI and HDI. This leads to the conclusion that hue distortion and a gamut size is related to the colour discrimination and juxtaposing. TES values increases with increasing the colour quality control parameter and can be linearly defined with a high correlation value. On the other hand, TES have no statistically significant difference for $\sigma = 0$, 0.15 and 0.31 and the high fidelity or preferencial colour quality lighting have no advantage over the colour dulling lighting.

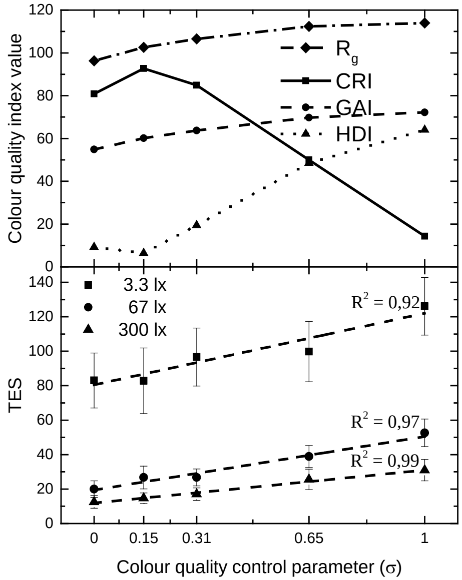

Fig. 1.6. Dependance of colour quality parameters and FM100 test total error scores at diferent illuminance levels on colour quality control parameter. Linear regresion (dashed lines) shows the correlation of collected data [P8].

Our results of TES an be interpolated for other σ and luminance values using a regresion model:

$$TES = 11{,}72 + 36.16/L + 32.71 * \sigma \tag{1.2}$$

There L – luminance value (cd/m^2), σ – colour quality control parameter.

1.4. Chapter summary

Investigation of tuneable high colour quality outdoor lighting system revealed that the most pleasing CCT increases with increasing illuminance level. Those CCT values of 3000 ± 200 K and 3500 ± 250 K qualitatively but not quantitatively coincide with Kruithof curve at 5 lx and 50 lx illuminance, respectively. The average subjectively selected CCT has no dependence on the illuminated outdoor area. The constant circadian irradiance mode at 50 lx has no effect on a CCT selection but at the 5 lx mode CCT values were lower because of higher illuminance.

CCT anchor effect showed that the most pleasing CCTs are from 2700 K to 4200 K at the adaptation CCTs from 2100 K to 10000 K. The adaptation CCT is equal to the most pleasing CCT at 3350 K. Latter effect should be taken into account for the static lighting evaluation.

Farnsworth-Munsell 100 hue test results correlated with the increasing colour gamut size. The main errors of placing colour caps are from the lack of spectral components in spectral power distribution. Total error score is higher at mesopic illuminance due to a lower colour discrimination and a colour dulling: high fidelity and preferential colour rendition lightings have the same colour juxtaposing results. This indicates that natural or preferential colour rendition lighting has no visual benefits at mesopic illuminance.

2. INVESTIGATION OF THE METAMERIC TETRACHROMATIC SOLID-STATE LIGHT SOURCE

Metametic light sources with different spectral power distributions should be the same colour to the observer. The chromaticity discrepancy of metameric white light sources was noticed during the research and also described in a literature. In this case, the 10-degree metameric 3000 K red, phosphor converted amber, green and royal blue LEDs cluster was investigated to find the degree of a chromaticity shift. Research data was published in P6, C11 and C14.

2.1. Metameric light source and experimental booth

There are metameric light sources with the same chromaticity to standard photometric observer, but observers can also be metameres with the different colour vision. It was shown by using a Monte Carlo simulation that a perceived chromaticity shift of theoretical photometric observers can be up to 10 Δa^* in the CIELAB colour space [19]. This shift is more than 10 MacAdam ellipses [20]. In this case, metameric light sources can be a different subject to observers. Third experiment in the previous chapter revealed that metameric RpcAGN spectral power distributions at different colour quality control parameter are not the same chromaticity. Further experiment was done to find a way of matching the chromaticity of metameric light sources at 3000 K with fixed 300 lx illuminance (Fig. 2.1.). In the first part of the experiment two well-trained participants used a monocular vision to adjust the chromaticity of 11 metameric spectral power distributions (random σ value from 0 to 1 with 0.1 step). Another fixed luminaire was randomly set to σ =0, 0.5 and 1. The luminaires, closed eye and adjustable luminaire was changed in order to minimaze the errors. The 3

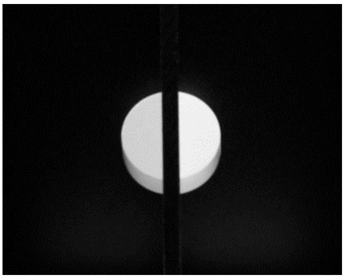

Fig. 2.1. 10 × 10 cm experimental booth with the 3 mm diameter white colour reflectance sample devided into two parts for separate illumination [P6].

mm white colour sample was illuminated from the top with different SPD to the left and right sides. Researh participants were sitting in front of the sample at a 18 cm distance. This distance for observation can be desribed using a 10˚ photometry. Luminaires were calibrated for 10 ˚ colour matching functions at 3000 K to reflect the real sample observation condition. Subjects had to match the chromaticity of two metameric RpcAGN light sources by adjusting one of the along the isothermal line by using a gamepad. Later the experiment was updated with chromaticity control along the Planckian locus (Fig. 2.2). The second part of the experiment was done due to insufficient chromaticity collation using only a D_{uv} adjustment. 20 research perticipants had to match pcAGN chromaticity to RGN with binocular vision one single time at the same observation distance. This time the fixed luminaire was set to around 3000 K using a 2˚ colour matching functions in order to represent current lighting evaluation in common scenes.

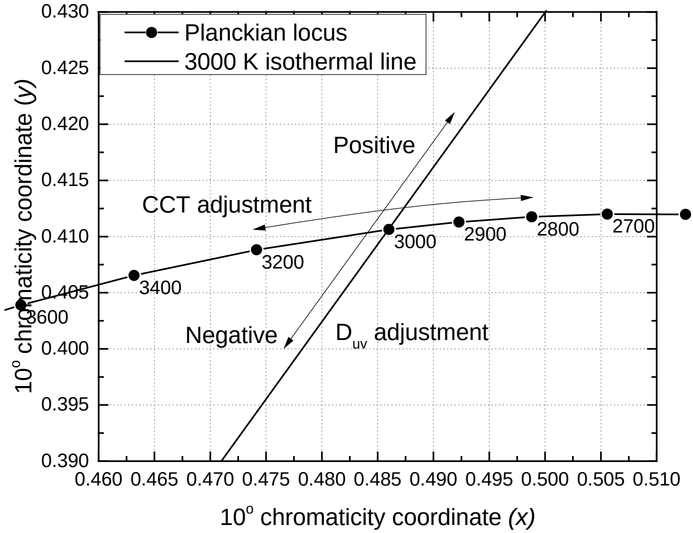

Fig. 2.2. Adjustment of the metameric RpcAGN light source along the isothermal and (D_{uv} adjustment) line and Planckian locus (CCT adjustment) at 3000 K starting CCT point [P6].

2.2. Results of chromaticity matching

Two participants in the first part of the experiment performed over 700 SPD matchings and averaged results with confidence intervals are displayed in Fig. 2.3. The data shows that chromaticity of the RGN LED cluster is shifted to the purple hues in order to compensate greenish appearance. On the other hand, the chromaticity of a pcAGN cluster is shifted to the greenish hue. This shows that the natural lighting at σ = 0.3 was not adjusted compared to pcAGN and RGN clusters. The chromaticity of a RGN cluster is more shifted compared to a pcAGN. Participants stated that adjustment along the isothermal line is not sufficient to compensate the chromaticity difference.

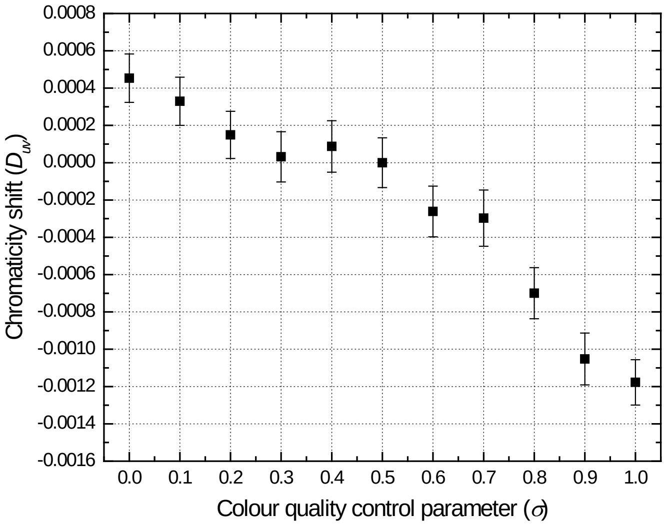

Fig. 2.3. Chromaticity matching of metameric light sources at different colour quality control parameter. Results are normalised to σ = 0.5 [P6].

Results of the second part of experiment (Fig 2.4. and 2.5.) are recalculated by using a 2˚ and 10˚ photometry. Spectral power distributions were measured with Avantes AvaSpec-ULS2048x64T spectrometer. The calculated mean chromaticity shift from the reference RGN point is D_{uv} = 0,0082 ± 0,0027 and 0,011 ± 0,0025 for the 10˚ and 2˚ colour matching functions, respectively. Those shifts have no statistically significant difference but the 10˚photometry is more accurate though it should be ideal.

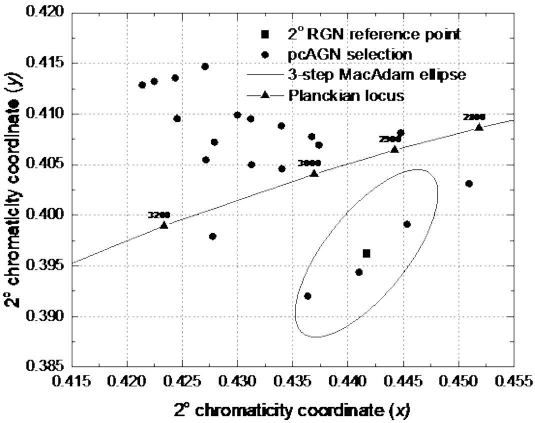

Fig. 2.4. Chromaticity matching of pcAGN and RGN LED clusters at the CIEXYZ colour space using a 2˚ photometry. Fixed RGN reference point is marked as a black square with the 3-step MacAdam ellipse. pcAGN selections are marked as black circles [P6].

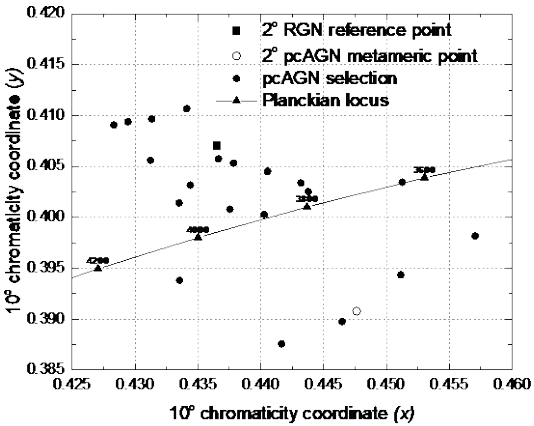

Fig. 2.5. Chromaticity matching of pcAGN and RGN LED clusters in the CIEXYZ colour space using a 10˚ photometry. Fixed RGN reference point is marked as a black square and pcAGN metameric point using a 2˚ photometry is marked as white circle. pcAGN selections are marked as black circles [P6].

Another matter is the wide adaptation of the 2˚ photometry for all colour renditions and colorimetric calculations. We know that human colour vision depends on a high number of factors like age, gender, pregnancy, fatigue, ambient temperature, colour vision deficiencies, ophthalmic or oncological diseases, background colour and brightness, observation angle etc. Despite the possible factors using the different well described photometry colour matching functions we can see that royal blue LED (~450 nm) has about 2 times higher luminous flux using a 10˚ colour matching functions compared to 2˚ colour matching functions. All solid-state light sources have a higher luminous flux at a higher observation angle and this leads to a chromaticity change of the multicolour LED cluster at different observation distance. We recommend the approach of applying the solid-state lighting by a fast lighting approval test with the chromaticity control on-site for selecting the best lighting parameters.

2.3. Chapter summary

Subjective evaluation of metameric white light sources depends on the colour vision of research participant as a photometric observer. Chromaticity of the metameric RGN and pcAGN light sources can be partially matched by using the chromaticity control along the isothermal line. Light sources with a higher red spectral component are more distinguishable from the white light than sources with lower spectral component. Chromaticity matching of the 10-degree photometric observer based white light sources is not precisely described with neither 2-degree not 10-degree photometric functions. The universal tunable metameric light source should be interpreted with caution for the dynamic applications.

3. COLOUR RENDITION ENGINEERING FOR HUMAN CENTRIC LIGHTING

Solid-state lighting has been rapidly developing for the past 25 years and field of applications is expanding. One of them is a human centric lighting. It requires an tunable circadian action and a good colour rendition. The evaluation of the pentachromatic LED cluster is discussed in this chapter. Results were used in the patent [P5].

3.1. Investigation of tetrachromatic LED cluster

Novel light sources are mostly optimised for the highest colour fidelity for a desirable colour quality index [21] or a preferential colour rendition [22]. Another approach to the novel lighting is a CCT tuneable spectral power distribution with the high colour rendition [23, 24, 25].

Human centric lighting raised the question about circadian lighting effects and now requires the same impact for a human circadian system [26] as natural light sources like sun and fire. This requirement of the circadian evaluation can be expanded with a tunable colour quality and the ability to create the preferential lighting. Similar lighting system were adapted for TVs and phones [27, 28, 29, 30], but no ordinary lighting solution was proposed for general lighting based on solid-state light sources. Another example is the tetrachromatic system consisted of 4000 K white, royal blue (~460 nm), green (~530 nm) and deep red (~660 nm) LEDs? for repeating the sun CCT during the day [31]. This system has tunable CCT from 4000 K to 6500 K with a high colour quality and a similar to the sun circadian action factor [32].

We investigated the available tetrachromatic RpcAGN LED cluster [P1] for thehuman centric lighting using a melanopsin response function [33]. The highest colour fidelity was found by optimising the spectral power distribution using a eq. 1.1. Colour quality was calculated using a CRI, colour fidelity index – CFI [3], colour fidelity score – Rf [8] and updated CRI in 2012 [34].

The results (Fig 3.1.) show that CRI is higher than 91 at any CCT. R_f values reaches 90 and CFI is increasing with CCT. Circadian action control cannot repeat the standard illuminant A action and hardly repeats the D_{65} action at the same CCTs. The highest fidelity RpcAGN and colour dulling pcAGN clusters have similar circadian actions and colour dulling is very close to the natural lighting. Those results do not meet energy efficient lighting requirements when high colour quality is not required.

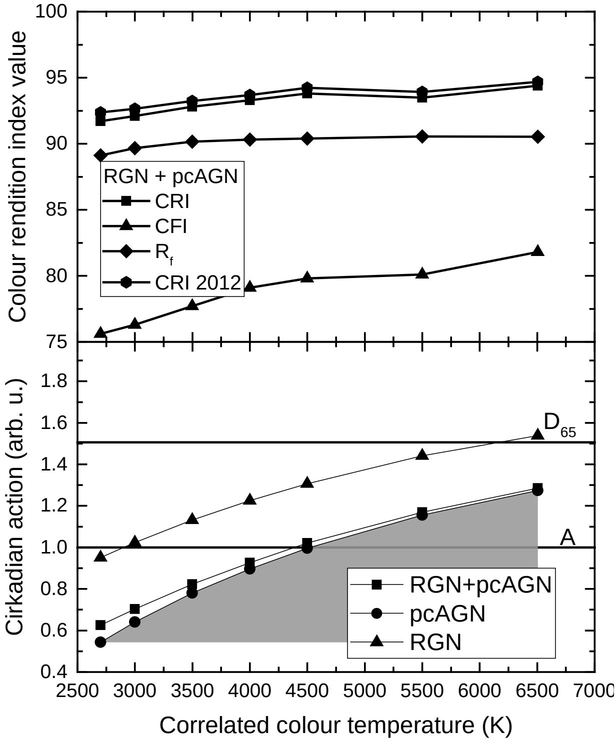

Fig. 3.1. The highest fidelity colour quality and circadian action of the RpcAGN LED cluster at different correlated colour temperatures. The D_{65} and A lines at lower graph show the circadian action of standard illuminants.

Further modelling was done with the RpcAGB LED cluster in order to increase the circadian action. Blue LED has a peak at ~475 nm in electroluminescence spectrum and it is perfect for a melatonin suppression. Results showed that circadian action had increased but at D_{65} CCT the value is too high. The highest colour fidelity is decreasing with increasing CCT and there are almost no colour dulling using only the pcAGB cluster. A pc amber LED was changed with a white LED on purpose to increase the colour dulling and decrease the circadian action

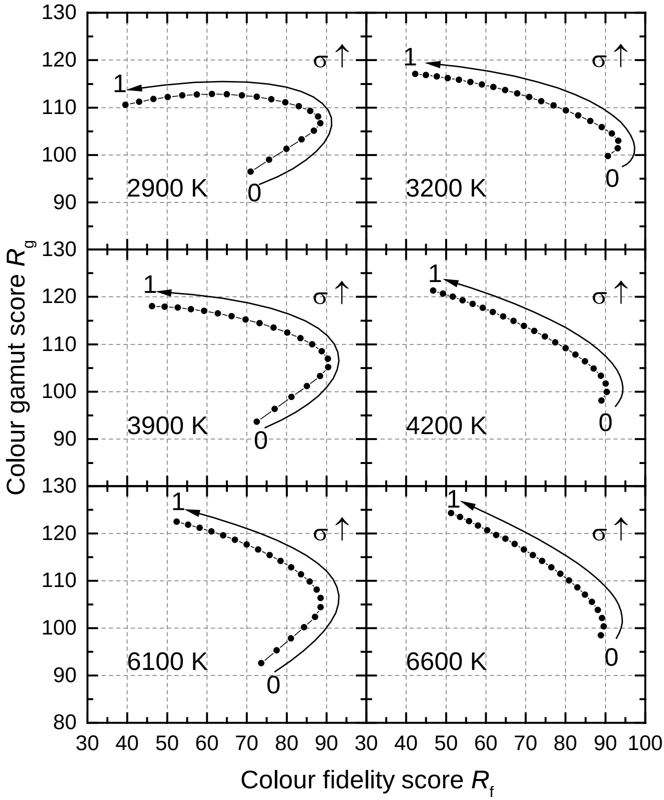

Fig. 3.2. Colour quality parameters of RGB+W LED clusters using a TM-30-15 method [2]. The curved line with an arrow shows the increasing colour quality control parameter.

Six different CCT white LEDs were used with low (CRI < 80) and high (CRI > 95) colour quality. Results (Fig. 3.2.) shows that low colour quality at 2900 K, 3900 K and 6100 K have lower gamut size and fidelity than 3200 K, 4200 K and 6600 K high fidelity white LEDs. In this case, a pc amber LEDcan be changed to a low colour quality white LED. In the other hand, a circadian action depends on a white LED CCT in the RGB+W cluster. A low CCT white LED in the cluster lowers the circadian action but a colour fidelity is decreasing at higher CCT. A 3900 K LED in the cluster limits the circadian action control and has a lower colour fidelity at lower CCT. A 6100 K white LED in the cluster determine almost no circadian action tuning and poor colour quality at low CCT. A colour dulling range at high CCT RGB+W_H cluster is expanded like the 2900 K LED does at low CCT in the RGB+W_L cluster. This led to the conclusion that the replacement of a pc amber to a white LED is not sufficient for the human centric lighting.

3.2. Investigation of the pentachromatic LED cluster

Previously discussed tetrachromatic RGB+W cluster has its limitations and the practical LED system was supplemented by an additional white LED. This LED cluster consisted of red, green, blue, warm white and daylight LEDs (RGB+W_L+W_H) was investigated using the same calculation as in Fig. 3.1. Results in Fig. 3.3. shows that the highest fidelity is rather constant at all CCTs. CRI is above 95, CFI – 87, R_f – 89 and CRI 2012 – 93. It is known that light sources with CRI ≥ 95 can be not distinguished from the natural light sources while comparing the illuminated colours for the unpractised observer. Preferential colour rendition is achieved from σ =0.31 to σ = 0.53 where colour saturation index (CSI) and CFI ration is between 0.3 and 3 [P5]. The pentachromatic LED cluster can be used for general lighting as a natural light source. Circadian action tunability is 4 times from W_L at 2900 K to RGB at 6500 K. Circadian action equal to standard illuminants are at preferential colour rendition and it can be applied to the most lighting cases.

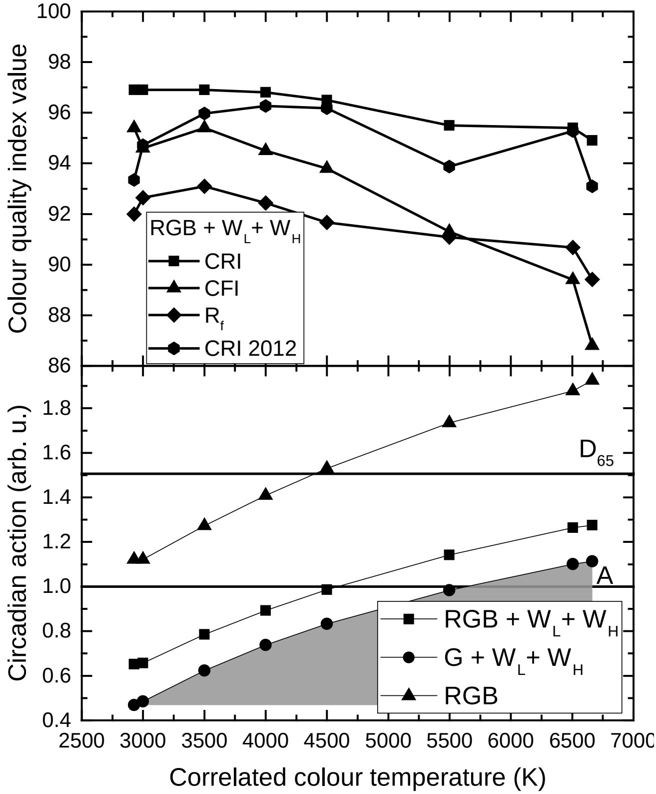

Fig. 3.3. The highest fidelity colour quality and circadian action of the RGB+W_L+W_H LED cluster at different correlated colour temperatures. The D_{65} and A lines at a lower graph show the circadian action of standard illuminants.

The main colour quality parameters are shown in table 3.1. Values are provided for colour dulling, saturation and the highest fidelity lighting at 3000 K and 6500 K CCTs.

Table 3.1. Colour quality parameters of the RGB+W_L+W_H LED cluster.

CCT (K)	σ	CRI	CRI 2012	R_f	R_g	GAI	CFI (%)	CSI (%)	CDI (%)
3000	0	65	64	64	91	53	19	1	62
	0.27	97	95	93	104	62	95	0	2
	1	11	27	35	101	64	4	79	4
6500	0	77	76	74	93	86	24	1	50
	0.21	95	95	91	102	100	89	0	3
	1	23	30	39	105	130	3	74	7

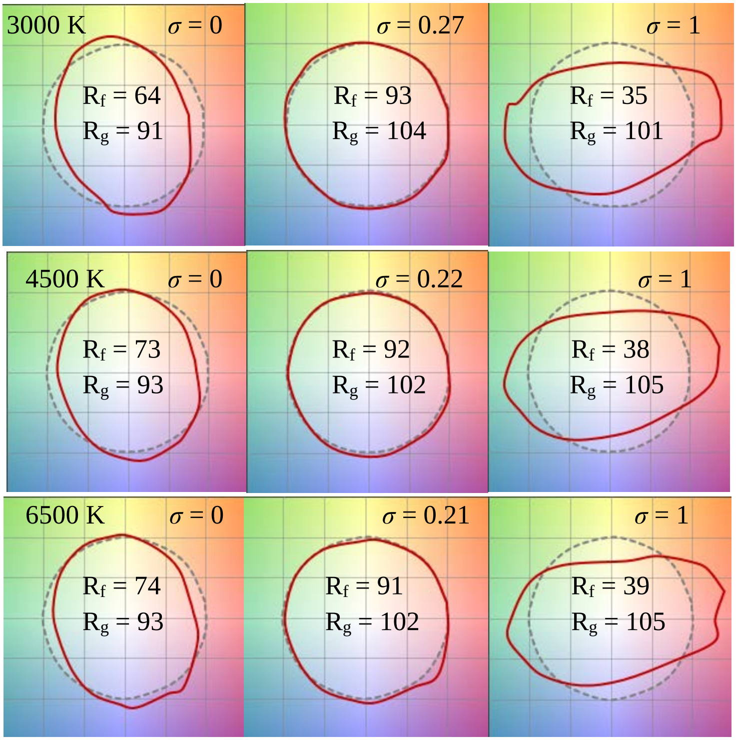

Fig. 3.4. Colour quality icons of colour dulling, saturating and high fidelity RGB+W_L+W_H LED cluster at three CCT. Red curve sshows the chromaticity shift using a testing LED cluster. Grey dashed circle shows natural colours.

Fig.3.4. indicated the chromaticity shifts of illuminated colours based in TM-30-15 method and using a CIECAM02 colour appearance model. Colour dulling decreases the saturation of green and red hues and increases saturation of yellow and blue hues, whereas the saturation behaves conversely but in a higher amount.

3.3. Chapter summary

Practical pentachromatic lighting system consisted of red, green, blue, warm white and daylight LEDs has a tunable correlated colour temperature from 2700 K to 6500 K with high fidelity lighting (CRI > 95) and it is suitable for the human centric lighting. Low colour gamut and quality white LEDs are more eligible for a high colour quality LED cluster than high colour quality white LEDs for having a colour dulling possibilities.

4. NON-INVASIVE COLOUR RENEWAL OF THE UV-DEGRADED PIGMENTS WITH TEN COLOUR CHANNELS SOLID-STATE LIGHTING ENGINE

The chromaticity restoration of the art display now is based on the non- invasive chemical treatment or application of a new coating. The solid-state lighting can restore the chromaticity of degraded pigments by selecting an optimal spectral power distribution. In this chapter the chromaticity restoration of merchandise pigments affected by the UV lighting is investigated using a theoretical and practical LEDs. The ten colour channel luminaire prototype was created to partially restore the chromaticity of UV-degraded pigments. Research results are published and presented: P3, P4, C5, C6, C9, C12, C13.

4.1. Photochemical degradation of merchandise pigments using a UV illumination

Art display lighting has one of the most demanding requirements [35]. Solid-state lighting based on LEDs can naturally satisfy high demands and offer the flexible spectral power distribution control. Paintings can be photochemically degraded over the time [36] and non-invasive chromaticity restoration can be applied [37, 38].

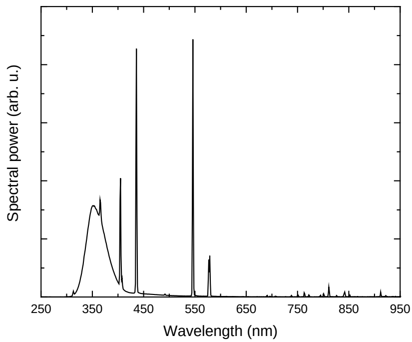

Fig. 4.1. Spectral power distribution of UV lamp .

Our work is related to the practical application of the solid-state lighting. Therefore, 25 merchandise pigments used in artwork restoration were treated with the UV light (Fig. 4.1.) for 153 days under 1000 lx illuminance at 40˚C temperature. This was done to investigate the chromaticity shift after a long-term photochemical degradation. Reflectance spectrums were measured at the beginning and in the end of the UV-treatment. The colour change can be seen for several pigments before and after photochemical degradation (Fig. 4.2.)

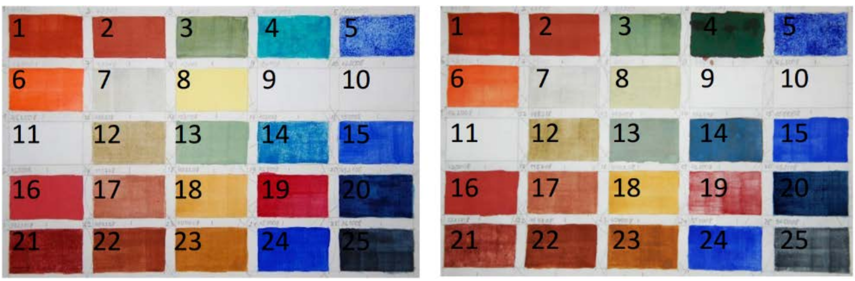

Fig. 4.4. Colour of the merchandise pigments before (left) and after (right) photochemical degradation.

Chromaticity shifts are displayed in CIELAB colour space for the accurate evaluation (Fig. 4.3.). Pigments with copper or lead had the most noticeable chromaticity shifts.

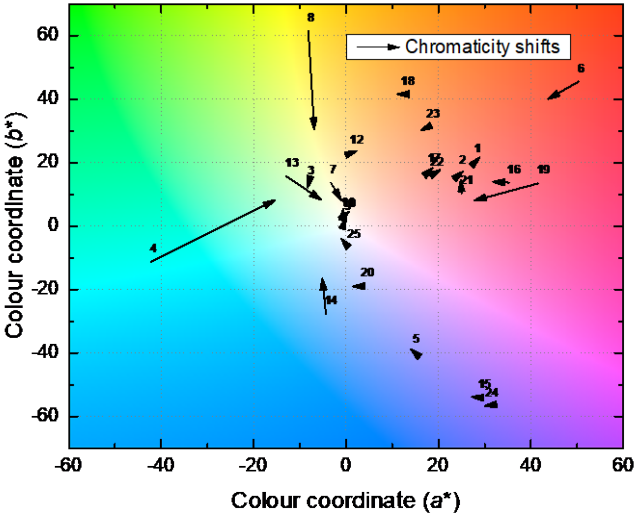

Fig. 4.3. Chromaticity shift of degraded pigments under UV lighting in CIELAB colour space.

Pigments are used with a vehicle though it has no impact for chromaticity shift. It was investigated by measuring the reflectance spectrum only from vehicle.

4.2. Modelling an optimal solid-state lighting for chromaticity restoration

Simulation of spectral power distributions for the non-invasive restoration of collected reflectance spectrum can be performed in two ways: a) by using theoretical LEDs; b) by using merchandise LEDs. We did it/this in the both ways. LED SPD of a Gaussian distribution was used to create theoretical light sources. It was shown that all pigments can be illuminated with no chromaticity distortion as in the natural lighting by using 15 different colour theoretical LEDs. Metameric SPDs of such theoretical light sources at 6504 K CCT are displayed in Fig. 4.4. CRI of such metameric SPDs varies from 99 to 99.7. LED peak wavelengths are distributed from 414 nm to 669 nm. Simulation of chromaticity restoration showed that only three or less pigments from the 1, 2, 3, 5, 9, 18, 20, 22, 23, 24 set can be restored using theoretical or practical LEDs. Any pigment from the 4, 7, 8, 13, 14, 19, 21 set makes it impossible to restore the chromaticity together with other pigments. Simulation for restoring four or more pigments at the same time was unsuccessful. Each pigment can be restored separately by using trichromatic LED clusters calculated to white or other chromaticity point. The reflectance from the original and degraded pigments are displayed in Fig. 4.5. We can conclude based on the results that the accurate

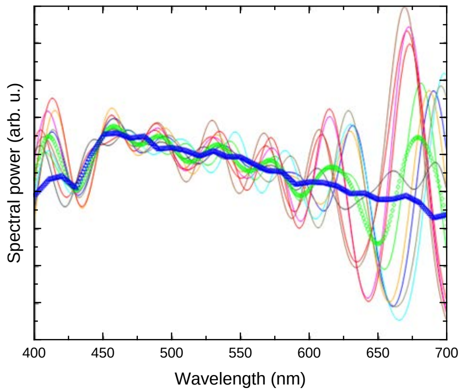

Fig. 4.4. Metameric daylight spectral power distributions, their average SPD (green curve) and D_{65} SPD (blue curve).

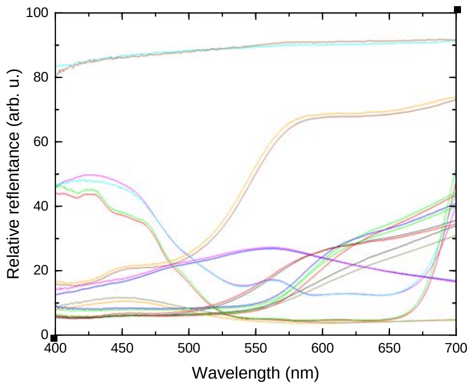

Fig. 4.5. Original and restored reflectance from 1, 2, 3, 5, 9, 18, 20, 22, 23, 24 pigments.

chromaticity restoration of degraded pigments can be done in a very limited set of pigments with the same solid-state lighting. Each colour can be restored separately but most of the practical scenes are not single coloured. In this case, ordinary luminaire with tuneable SPD is inappropriate and spatial SPD control for each pigments should be used.

4.3. Universal prototype luminaire with a ten colour channels

Simulation in the previous section was partly done with merchandise LEDs. Those 10 different colour LEDs (Fig. 4.6.) were selected for a prototype luminaire in order to create the natural lighting and have a wide colour gamut control. A 730 nm far red LED was not used due to a low luminous efficacy of the radiation. LEDs below 450 nm were not included because they cause a high photochemical damage.

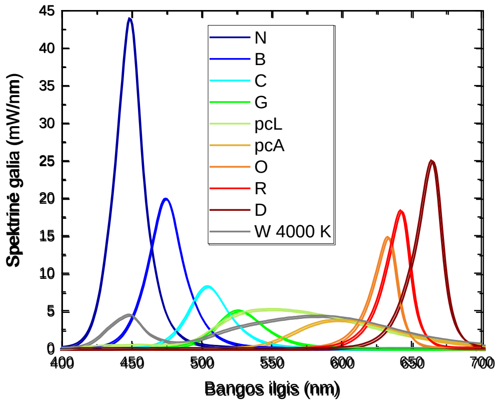

Fig. 4.6. Spectral power distributions of the merchandise LED used in prototype luminaire.

Luminaire prototype was created to have a high light output and a compact functional design. 38 Philips Lumileds Color C and Cree XQ-E family LEDs were used with 10 current drivers and a ATxmega16U4A microcontroller and a Bluetooth 2.0 module. A membrane fan was used to cool the heatsink. A One-layer metal core printed circuit board was designed using an Altium Designer software (Fig. 4.7.). LEDs were mixed in the centre of the board to maximize the colour mixing. 3D drawing of the assembled luminaire prototype was drawn using a SolidWorks software.

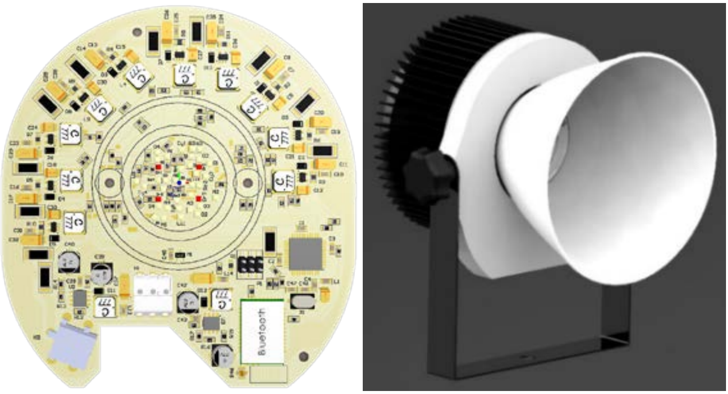

Fig. 4.7. Soldered metal core printed circuit board (left) and 3D drawing of the assembled luminaire prototype (right).

Luminaire control software was created using a Visual Basic.NET programing language in a Visual Studio software. User interface has two windows. In the first window the lighting pre-sets and three dynamic modes are presented. Second window is called as advanced control (Fig. 4.8.) with the precise white point or the independent each colour channel control. Eq. 1.1. was adapted for controlling 10 independent channels. Blue channel is a linear combination of royal blue and blue LEDs. Green channel consists of cyan, pc lime and green LED combination. Pc amber channel is a linear combination of a pc amber or

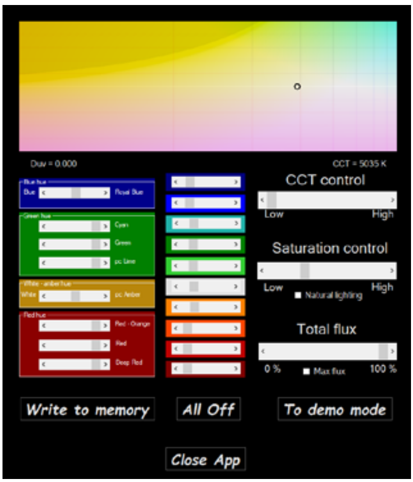

Fig. 4.8. Advanced mode window of the user interface.

a 4000 K white LED. Red channel consists of red-orange, red and deep red LEDs. Software allows changing the CCT, σ, D_{UV} and each LED luminous flux in the composed SPD. It has implemented natural lighting mode at any CCT from 2100 K to 10000 K (Fig. 4.9.). Theoretical CRI value is above 99 at any CCT. Those SPDs are consisted of 8 LEDs – N, B, C, pcL, W, pcA, O and D (Fig. 4.6.). Green and red LEDs were not used as they have no effect for higher CRI value at all CCTs.

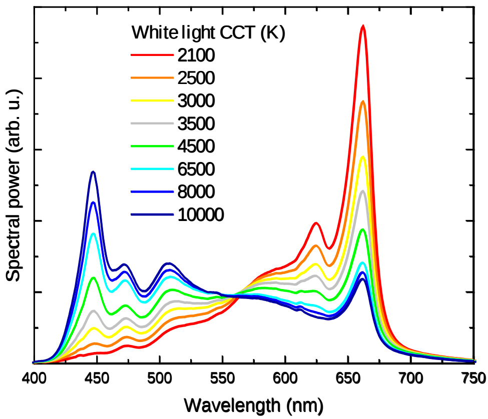

Fig. 4.9. Simulated spectral power distributions for natural lighting at different CCTs.

The colour quality icons for available trichromatic SPDs at 3000 K is shown in Fig. 4.10. The chromaticity shift of illuminated colours can be shifted in various ways and general gamut size can be turned. The highest colour dulling is achieved with N, W and pcL LED cluster is not shown in the figure. Colour saturation in yellow hues can be increased by adding the direct emission of an AlGaInP yellow LED with ~595 nm peak wavelength. However, this LED is one of the most instable and temperature sensitive due to the high Al amount in AlGaInP.

This prototype luminaire combines all solid-state lighting technologies created by the author and lighting research group at Vilnius university. Luminaire can create firelight spectrum [P2], has a tuneable colour quality [P1], can limit photochemical damage using a software [P3, P4], reproduce preferential colour rendition [P5], be tuned along the isothermal lines [P6] and used in psychophysical experiments [P7, P8].

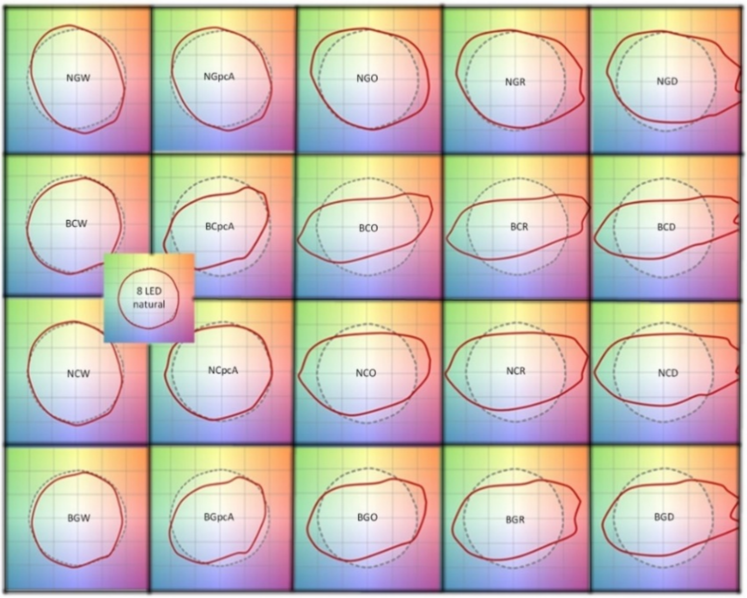

Fig. 4.10. Colour quality icons of trichromatic LED clusters from the luminaired at 3000 K CCT. Red curve shows the chromaticity shift using a testing LED cluster. Grey dashed circle shows natural colours.

4.4. Chapter summary

Photochemical degradation of merchandise pigments due to UV illumination depends on chemical structure. Non-invasive chromaticity restoration can be done for a limited number of pigments using a theoretical or practical spectral power distribution of LEDs. Chromaticity of each pigment can be restored with a merchandise LEDs. Full set of pigments can be restored by using an illumination device with spatially controlled spectral power distribution. Demonstrated illumination device with 10 independent colour channels can be used for a partially chromaticity restoration of UV-degraded pigments.

CONCLUDING SUMMARY

1. The average most pleasing correlated colour temperature using a tetrachromatic lighting system was found to be 3000 ± 200 K and 3500 ± 250 K at the 1900 K adaptation colour temperature with 5 lx and 50 lx outdoor illuminance, respectively.
2. The most pleasing correlated colour temperature coincides with the adaptation correlated colour temperature at 3350 K.
3. Tetrachromatic lighting with colour dulling, high fidelity and preferential colour rendition was evaluated with comparable colour juxtaposing and rendition at low illuminance.
4. A colour gamut size correlates with the incorrect colour juxtaposing and it depends on the chromaticity distortion.
5. The chromaticity of the metameric red, phosphor converted amber, green and royal blue LED cluster at 3000 K can be partially matched by adjusting the chromaticity along the isothermal line.
6. The practical and dynamically controlled pentachromatic lighting system consisted of red, green, blue, warm white and daylight LEDs is suitable for human centric lighting with an adjustable circadian action, a correlated colour temperature and a colour quality.
7. The chromaticity of UV-degraded pigments can be restored by using a solid-state lighting for each tested colour separately.
8. The chromaticity of three or more photochemically damaged pigments cannot be restored using a single illumination device and each pigments should have an independent lighting with the controlled spectral power distribution.
9. The luminaire prototype with ten independent colour channels can partially restore UV-degraded pigments and is characterised with flexible colour gamut and rendition control.

REFERENCES

[1] Commission Internationale de l'Eclairage, „Colour rendering of white LED sources," *Pub. CIE* 177 (2007).

[2] A. David, P. T. Fini, K. W. Houser, Y. Ohno, M. P. Royel, K. A. G. Smet, M. Wei and L. Whitehead, „Development of the IES method for evaluating the color rendition of light sources," *Optics Express* **23**(12), 15888-15906 (2015).

[3] A. Žukauskas, R. Vaicekauskas, F. Ivanauskas, H. Vaitkevičius, P. Vitta ir M. S. Shur, „Statistical approach to color quality of solid-state lamps," *IEEE J. Sel. Top. Quantum Electron.* 15, 1753–1762 (2009).

[4] G. C. Brainard J. P. Hanifin, J. M. Greeson, B. Byrne, G. Glickman, E. Gerner, M. D. Rollag, „Action spectrum for melatonin regulation in humans: evidence for a novel circadian photoreceptor," *The Journal of Neuroscience* 21, 6405-12 (2001).

[5] A. A. Kruithof, „Tubular luminescence lamps for general illumination," *Philips Techn. Rev.* 6, 65–73 (1941).

[6] N. Moroney, M. D. Fairchild, R. W. G. Hunt, C. Li, M. R. Ronnier, T. Newman, „The CIECAM02 Color Appearance Model," *IS&T/SID Tenth Color Imaging Conference*, The Society for Imaging Science and Technology, Scottsdale, Arizona (2002).

[7] S. Fotios, „A Revised Kruithof Graph Base on Empirical Data," *LEUKOS* 13, 3-17 (2017).

[8] Illuminating Engineering Society of North America, „IES Method for Evaluating Light Source Color Rendition," *New York, NY: IESNA (* 2015).

[9] D. Gall, „Circadiane Lichtgrößen und deren messtechnische Ermittlung," *Licht* 54, 1292–1297 (2002).

[10] C. Knight, "Field surveys of the effect of lamp spectrum on the perception of safety and comfort and night," *Lighting Res. Technol. 42*, p. 313–329, 2010.

[11] M. S. Rea, J. D. Bullough ir Y. Akashi, „Several views of metal halide and high-pressure sodium lighting for outdoor applications," *Lighting Res. Technol. 41*, p. 297–320, 2009.

[12] H. Nikunen, M. Puolakka, A. Rantakallio, K. Korpela ir L. Halonen, „Perceived restorativeness and walkway lighting in near-home environments," *Lighting Res. Technol. 46*, p. 308–328 (2014).

[13] Á. Logadóttir, S. A. Fotios, J. Christoffersen, S. S. Hansen, D. D. Corell and C. Dam-Hansen, „Investigating the use of an adjustment task to set the preferred colour of ambient illumination," *Color Res. Appl.* 38, 46–57 (2013).

[14] M. Miki, Y. Motoya, H. Ikegami and S. Fujimoto, „Combination of preferred illuminance and preferred color temperature for work," *IEEE International Conference on Systems, Man, and Cybernetics*, Manchester, United Kingdom (2013).

[15] Y. Taniguchi, M. Miki, H. Tomoyuki and M. Yoshimi, „Preferred illuminance and color temperature in creative works," *IEEE International Conference on Systems, Man, and Cybernetics (SMS)*, Manchester, United Kingdom (2011).

[16] M. Scuello, I. Abramov, J. Gordon and S. Weintraub, „Museum lighting: Why are some illuminants preferred?," *J. Opt. Soc. Am. A* 21, 306–311 (2004).

[17] Á. Logadóttir, J. Christoffersen and S. A. Fotios, „Investigating the use of an adjustment task to set the preferred illuminance in a workplace environment," *Lighting Res. Technol.* 43, 403–422 (2011).

[18] M. S. Rea and J. P. Freyssinier-Nova, „Color rendering: A tale of two metrics," *Color Res. Appl.* 33,192–202 (2008).

[19] M. D. Fairchild and R. L. Heckaman, „Measuring observer metamerism: The Nimeroff approach," *Color. Research and application* **41**(2), 115-124 (2016).

[20] D. L. MacAdam, „Visual sensitivities to color differences in daylight," *J. Opt. Soc. Am.* **32**(5), 247–274 (1942).

[21] W. Zhang, W. Yang, P. Zhong, S. Mei, G, Zhang, G, Chen, G, He and R. Guo, „Spectral optimization of color temperature tunable white LEDs based on perovskite quantum dots for ultrahigh color rendition," *Optical Materials Express* **7**(9), 3065 – 3076 (2017).

[22] Y. Lin, M. Wei, K. A. G. Smet, A. Tsukitani, P. Bodrogi and T. Q. Khanh, „Colour preference varies with lighting application," *Lighting Res. Technol.* 49, 316–328 (2017).

[23] G. He, L. Zheng and Y. Huafeng, „LED white lights with high CRI and high luminous efficacy," *LED and Display Technologies, edited by Gang Yu, Yanbing Hou, Proc. of SPIE Vol. 7852,* 78520A-1 - 78520A-9 (2010).

[24] E. E. Dikel, G. J. Burns, J. A. Veitch, S. Mancini and G. R. Newsham, „Preferred Chromaticity of Color-Tunable LED Lighting," *LEUKOS* 10, 101-115 (2014).

[25] I. Speier and M. Salsbury, „Color Temperature Tunable White Light LED System," *Sixth International Conference on Solid State Lighting Proc. of SPIE Vol. 6337,* 63371F-1 - 63371F-12 (2006).

[26] Well Building Institute, „The WELL Building Standard," internet source: https://standard.wellcertified.com/light. [seen in 10 09 2018].

[27] K. L. Kwon, M. B. Kim, C. Heo, S. G. Kim, J. S. Beak, Y. H. Kim, „Wide color gamut and high dynamic range displays using RGBW LCDs," *Displays* 40, 9-16 (2015).

[28] A. D. Arnold, P. E. Castro, T. K. Hatwar, M. V. Hettel, P. J. Kane, J. E. Ludwicki, M. E. Miller, M. J. Murdoch, J. P. Spindler, S. A. Van Slyke, K. Mameno, R. Nishikawa, T. Omura. S. Matsumoto, „Full-color AMOLED with RGBW pixel pattern," *Journal of the SID* **13**(6), 525-535 (2015).

[29] L. Wang Y. Tu, L. Chen, K. Teunissen, I. Heynderickx, „Trade-off between Luminance and Color in RGBW Displays," *SID,* **38**(1), 1142-1145 (2007).

[30] M. E. Miller, J. W. Hamer, J. E. Ludwicki, A. D. Arnold, „Exploiting the Flexibility of RGBW OLED Displays:," *SID* **40**(1), 935-938 (2012).

[31] J. Bohar, G. Fernandes and J. Xu, „Spectral-Temporal LED Lighting Modules for Reproducing Daily and Seasonal Solar Circadian Rhythmicities," *2017 IEEE International Conference on Smart Computing (SMARTCOMP)* Hong Kong, China (2017).

[32] A. Žukauskas, R. Vaicekauskas and P. Vitta, „Optimization of solid-state lamps for photobiologically friendly mesopic lighting," *Appl. Opt.* 51, 8423–8432 (2012).

[33] R. J. Lucas, S. Peirson, D. M. Berson, T. M. Brown, H. M. Cooper, C. A. Czeisler, M. G. Figueiro, P. D. Gamlin, S. W. Lockley, J. B. O'Hagan, L. L. A. Price, I. Provencio, D. J. Skene and G. C. Brainard, „Measuring and using light in the melanopsin age," *Trends Neurosci.* 37, 1-9 (2014).

[34] K. Smet, J. Schanda, L. Whitehead and R. M. Lou, „CRI2012: A proposal for updating CIE colour rendition index," *Lighting Research & Technologies* 45, 689-709 (2013).

[35] Commission Internationale de l'Eclairage, „Control of damage to museum objects by optical radiation," *Pub. CIE 157 (*2004).

[36] S. M. Pinilla, D. Vazquez, A. A. Fernandez-Balbuena, C. Muro, J. Munoz, „Spectral damage model for lighted museum paintings: Oil, acrylic and gouache," *Journal of Cultural Heritage* 22, 931-939 (2016).

[37] S. Nascimento and O. Masuda, „Best lighting for visual appreciation of artistic paintings—experiments with real paintings and real illumination," *,” J. Opt. Soc. Am. A* **31**(4), A214-A219 (2014).

[38] F. Viénot, G. Coron and B. Lavedrine, „LEDs as a tool to enhance faded colours of museums artefacts," *J. Cult. Herit.* **12**(4), 431-440 (2011).

LIST OF PUBLICATIONS RELATED TO THE THESIS

P1. A. Žukauskas, R. Vaicekauskas, P. Vitta, A. Tuzikas, **A. Petrulis**, and M. Shur, "Color rendition engine", Opt. Express 20(5), pp. 5356–5367 (2012).

P2. A. Žukauskas, R. Vaicekauskas, A. Tuzikas, **A. Petrulis**, R. Stanikūnas, A. Švegžda, P. Eidikas, P. Vitta, "Firelight LED source: Toward a balanced approach to the performance of solid-state lighting for outdoor environments," IEEE Photonics J. 6(3), 8200316 (2014).

P3. A. Tuzikas, A. Žukauskas, R. Vaicekauksas, **A. Petrulis**, P. Vitta, M. S. Shur, "Artwork visualization using a solid-state lighting engine with controlled photochemical safety," Opt. Express 22(14), 16802–16818 (2014).

P4. A. Žukauskas, R. Vaicekauskas, A. Tuzikas, P. Vitta, **A. Petrulis**, "Daugiaspalviai kietakūniai šviesos šaltiniai skirti fotochemiškai jautrių objektų apšvietimui", Patent no. LT6238 (2015 12 28).

P5. A. Žukauskas, R. Vaicekauskas, P. Vitta, A. Tuzikas, A. Zabiliūtė, **A. Petrulis**, "Solid-state sources of light for preferential colour rendition", patent no. US9370072 B2 (2016-06-14).

P6. **A. Petrulis**, P. Vitta, J. Aglinskaitė, R. Vaicekauskas, A. Žukauskas, "Metameric Light Sources: A Recent Paradigm for Functional Lighting," Proceedings of the Latvian Academy of Sciences. Section B. Natural, Exact, and Applied Sciences 71(5), 366-371 (2017).

P7. **A. Petrulis**, P. Vitta, L. Petkevičius, R. Vaicekauskas, A. Žukauskas, "Exploring preferred correlated color temperature in outdoor environments using a smart solid-state light engine", LEUKOS 14(2), 95-106 (2018).

P8. **A. Petrulis**, J. Aglinskaitė, P. Vitta, R. Vaicekauskas, A. Žukauskas, "Colour rearrangement and colour gamut

tunability with multicolour solid-state light engine under low luminance levels," submitted to press.

Conference contributions:

C1. P. Vitta, A. Žukauskas, R. Vaicekauskas, P. Eidikas, A. Zabiliūtė, R. Stanikūnas, A. Švegžda, A. Tuzikas, and **A. Petrulis**, "Extra low colour temperature solid-state sources for artificial night lighting," 1 st International Conference on Artificial Light at Night (Berlin, Germany, October 28-30, 2013). Abstract Book, p. 111.

C2. A. Zabiliūtė, R. Vaicekauskas, P. Vitta, A. Tuzikas, **A. Petrulis**, and A. Žukauskas, "Phosphor converted light-emitting diodes with advanced color rendition properties," Conference on LED and Its Industrial Applications (Pacifico Yokohama, Japan, April 22-24, 2014). Extended Abstracts, p. 24p-LEDp6-32.

C3. **A. Petrulis**, A. Tuzikas, P. Vitta, R. Vaicekauskas, and A. Žukauskas, "Validation of the Kruithof rule in an outdoor environment using a smart solid-state lighting engine," 14th International Symposium on the Science and Technology of Lighting (Como, Italy, June 22-27, 2014). LS14 Conference Program, CP117.

C4. **A. Petrulis**, R. Vaicekauskas, A. Žukauskas, "Optimization of a polychromatic solid-state source of light for the dynamical control of circadian rhythms," 14th International Symposium on the Science and Technology of Lighting (Como, Italy, June 22-27, 2014). LS14 Conference Program, CP75.

C5. A. Tuzikas, A. Žukauskas, R. Vaicekauskas, **A. Petrulis**, P. Vitta, and M. Shur, "Smart lighting for artworks with controlled photochemical safety," 14th International

Symposium on the Science and Technology of Lighting (Como, Italy, June 22-27, 2014). LS14 Conference Program, CP75.

C6. A. Tuzikas, **A. Petrulis**, R. Vaicekauskas, M. S. Shur, and A. Žukauskas, "Smart restorative illumination of artwork and museum exhibits," 13th International Conference on Solid State Lighting and LED-based Illumination Systems SPIE Optics+Photonics (San Diego, California, USA, August 17-21, 2014). Conference Program, Paper 9190-23.

C7. **A. Petrulis**, A. Tuzikas, P. Vitta, R. Vaicekauskas, A. Žukauskas, „Kruithof Rule and Circadian Lighting Tests in an Outdoor Environment using a Smart Solid-State Lighting Engine," 16th International Conference-School Advanced materials and Technologies (Palanga, Lithuania, August 27-31, 2014) program and abstract book, p. 95.

C8. P. Vitta, **A. Petrulis**, A. Tuzikas, R. Vaicekauskas and A. Žukauskas, "Finding "pleasing" illumination condition in outdoor environments using an intelligent lighting installation,' international conference on the effects of light on wellbeing, Experiencing light (Eindhoven, The Netherlands, 10-11 November, 2014), Proceedings Experiencing light 2014, p. 136.

C9. **A. Petrulis**, P. Vitta, R. Vaicekaukas, A. Žukauskas, "Išmanaus kietakūnio apšvietimo tyrimai ir taikymai Lietuvoje," 41-oji Lietuvos nacionalinė fizikos konferencija (Vilnius, Birželio 17–19 d., 2015), Programa ir pranešimų tezės p. S2-48.

C10. **A. Petrulis**, P. Vitta, R. Vaicekauskas, A. Žukauskas, "Selecting "pleasing" correlated color temperature for illumination of outdoor environments," 13th International Conference on Solid State Lighting SPIE Optics+Photonics (San Diego, California, USA, August 9-13, 2015), paper 9571-9.

C11. J. Aglinskaitė, **A. Petrulis**, „Investigation of the Colour Differences Using Metameric Light Sources,“ 18th International Conference-School Advanced materials and Technologies (Palanga, Lithuania, August 27-31, 2016) program and abstract book, p. 89.

C12. **A. Petrulis**, J. Senvaitienė, J. Bagdzevičienė, R. Vaicekauskas, „Non-invasive Restoration of UV-treated Pure Watercolor Pigments Using a Smart Lighting,“ 18th International Conference-School Advanced materials and Technologies (Palanga, Lithuania, August 27-31, 2016) program and abstract book, p. 90.

C13. **A. Petrulis**, P. Vitta, J. Bagdzevičienė, J. Senvaitienė, and R. Vaicekauskas, „Restoration of the Photochemically Degraded Watercolour Pigments Using a LED Based Light Source,“ International conference OSA Light, Energy and the Environment Congress (Leipzig, Germany, November 14-17, 2016), Solid-state lighting 2016, JW4A.3.

C14. **A. Petrulis**, P. Vitta, R. Vaicekauskas, „Metameric light sources: a recent paradigm for functional lighting,” 1st International symposium on visual physiology, environment, and perception VisPEP2016 (Riga, Latvia, October 6-8, 2016), Conference program, P1-7.

List of publications not included to the thesis:

P9. P. Vitta, R. Stanikūnas, A. Tuzikas, I. Reklaitis, A. Stonkus, **A. Petrulis**, H. P. Vaikevičius, and A. Žukauskas, “Energy-saving approaches to solid state street lighting”, Proc. SPIE 8123, Art. No 81231H, p. 7 (2011).

P10. P. Vitta, L. Dabasinskas, A. Tuzikas, **A. Petrulis**, D. Meskauskas, and A. Zukauskas, “Concept of intelligent solid-state street lighting technology,” Elektron. Elektrotech. 18(10), 37-40 (2012).

P11. V. Kulbokaitė, R. Stanikūnas, A. Švegžda, A. Žukauskas, A. Tuzikas, R. Vaicekauskas, P. Vitta, **A. Petrulis**, P. Eidikas, A. Zabiliūtė, “Visual performance in the mesopic range of outdoor lighting”, Perception 42, 65 (2013).

P12. A. Žukauskas, R. Vaicekauskas, P. Vitta, A. Zabiliūtė, **A. Petrulis**, and M. Shur, “Color rendition engineering of phosphor-converted light-emitting diodes”, Opt. Express 21(22), pp. 26642-26656 (2013).

P13. V. Viliūnas, H. Vaitkevičius, R. Stanikūnas, P. Vitta, R. Bliumas, A. Auškalnytė, A. Tuzikas, **A. Petrulis**, L. Dabašinskas, and A. Žukauskas, “Subjective evaluation of luminance distribution for intelligent outdoor lighting,” Lighting Res. Technol. 46(4): 421-433 (2014).

INFORMATION ABOUT THE AUTHOR

Name and surname: Andrius Petrulis

Natal day and place: 1988, 2th of August, Panevėžys, Lithuania

Work address: Saulėtekio av. 3, LT-10357,
Vilnius, Lithuania

Email: andrius.petrulis@tmi.vu.lt

Education:

2003-2007 Panevėžys Juozas Balčikonis gymnasium

2007-2011 Bachelor studies at Vilnius university,
Faculty of physics

2011-2013 Master studies at Vilnius university,
Faculty of physics (Magna Cum Laude)

2013-2017 PhD studies at Vilnius university,
Faculty of physics

Scientific experience:

2010-2015 Engineer at Institute of Applied Research,
Vilnius university (part-time)

2015-till now Junior scientific researcher at Institute of
Photonics and Nanotechnology,
Vilnius university (part-time)

Work experience:

2012-till now Production department director
at JSC "Ledigma" (part-time)

Specialization: Application of LEDs in Solid-State lighting systems. Optical characterisation and colour quality assessment of LED clusters.

Vilniaus universiteto leidykla
Universiteto g. 1, LT-01513 Vilnius
El. p. info@leidykla.vu.lt,
www.leidykla.vu.lt
Tiražas 30 egz.