New experiments on color in context and organic-based artificial photoreceptors

Davide Gadia, Gianluigi Lasco; Dip. di Informatica e Comunicazione, Università degli Studi di Milano, Milano, Italy
Alessandro Rizzi; Dip. di Tecnologie dell'Informazione, Università degli Studi di Milano, Crema, Italy
Daniele Marini; Dip. di Informatica e Comunicazione, Università degli Studi di Milano, Milano, Italy
Maria Rosa Antognazza, Stefano Perissinotto; Center for Nano Science and Technology-IIT@POLIMI, Milano, Italy
Guglielmo Lanzani; Center for Nano Science and Technology-IIT@POLIMI, Milano, Italy and Dip. di Fisica, Politecnico di Milano, Milano, Italy

Abstract

In recent years, organic semiconductors have been used to develop a new generation of photodetectors; in some cases their outstanding properties, especially in terms of spectral tuning, have been exploited in order to reproduce human cone sensitivities.

To date, however, it is still not clear if the spectral differences between real and artificial cone responses, unavoidable at a certain extent, may lead to real, corresponding differences in the final color perception. As a matter of fact, one should note that perception is the final result of a complex analysis and elaboration made by our visual system at a superior level respect to the color sensation, as detected in the retinal photoreceptors layer. Therefore, aiming at the development of an artificial retina, the way how human perception actually works can not be disregarded.

In this paper, we focus in detail on the role and effect of spatial normalization, when applied to a set of tristimulus values obtained using different integration curves, derived by different organic semiconducting materials.

In a recent work, we proposed an experimental setup to investigate this issue. We used a multispectral rendering of a virtual scene as a simulation of incoming light spectra, and a set of artificial cone sensitivities to obtain different tristimulus values for each combination of integrating curves. Finally, we applied different computational models with and without spatial color computation to partially simulate human perception. A preliminary analysis of the values showed that the application of a spatial color algorithm leads to a normalization of the differences in artificial cones spectral sensitivities.

In this paper we present the results of a new session of experiments, based on the same experimental setup, but using new multispectral test images of real scenes, and a different selection of organic active materials. We analyze the values obtained after the application of the processing methods, trying to define some latex in the selection, among the many available organic semiconductors, of their most effective combination. Moreover, we introduce some hypothesis regarding the effect of different frequency cut points and overlapping areas between the photoresponsivity curves.

Introduction

Color perception is the result of complex elaborations made by our visual system. The input to this process is the retinal response: the light spectral distribution comes to the retina, and here it is integrated by the three different cone spectral sensitivities [1], giving tristimulus values as result. These are further processed by the higher cortical areas.

As a basic principle, an artificial retina should mimic as much as possible the spectral sensitivities of the real cones. In last years, organic semiconductors were employed in the fabrication of photodetectors with spectral responsivities that closely resemble the human cone sensitivities [2]. Organic sensors are a good choice in developing an artificial vision system because natural pigments and semiconducting polymers share similar features in molecular and electronic structure. Organic sensors can operate at zero bias and have reduced dissipation. Moreover, it is possible to fine-tune their optical absorption, and to fabricate them on fully flexible substrates. They can also be made compatible with a biological environment [2].

Even though organic photodetectors' response may be close to the real cone sensitivities, spectral mismatching are unavoidable. To understand if these discrepancies between real and artificial spectral sensitivities lead to relevant differences in the final perception, the whole perception process should be taken into consideration, not only the retinal input signal difference.

In a recent work [3], we addressed this problem introducing an experimental setup, in which we simulated the process of retinal response generation and of color perception. We did not want to address extensively the whole visual system and all its features, but we focused our attention only on the spatial aspects of color perception.

We hypothesize that some sort of perceptual robustness mechanisms should exist, able to normalize the final perception of observers. An interesting outcome, strongly supporting our premise, is that the relevant interdifference in retinal cones distribution in male population (up to 40% and even more) does not lead to a corresponding difference in the final perception [4]. Previous works [5, 6] suggested that the spatial nature of the human color perception [7, 8, 9, 10] plays a fundamental role in this inter-subjective normalization process.

In [3], we simulated light spectral distribution of a test scene using a photometric raytracer to generate a multispectral synthetic image, with 80 samples per pixel in the visible spectrum. Then we integrated the values in each pixel using different combinations of the artificial Cone Sensitivities Curves (CSC) derived by the organic materials available at that time for each cone types (long, medium, short). Therefore, we obtained different triplets of tristimulus values (simulating different possible retinal responses), each derived by the different spectral curves. We also used real cone sensitivities by Smith and Pokorny [1].

To investigate the relationship between the spatial aspects of color perception and the spectral differences among sensor sensitivities, we need to partially simulate human perception. To this aim, we applied three different data processing methods to the triplets, with and without spatial color computation.

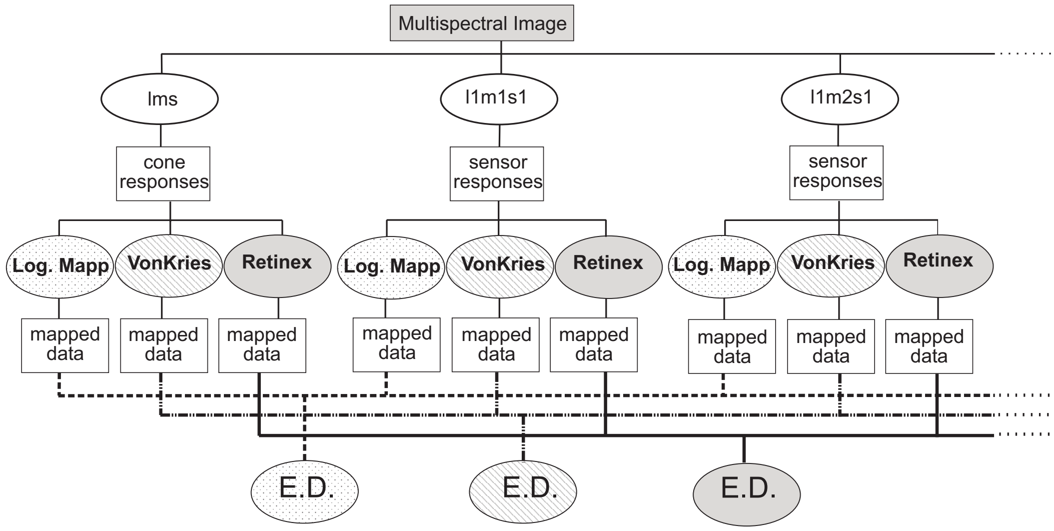

Figure 1. *Experimental setup scheme*

Then we evaluated the interdifferences among the various CSC with and without spatial computation. To this aim, we analyzed the euclidean distances in the sensor space between the triplets obtained by real and artificial CSC after the processing stage. A preliminary analysis showed that these distances are lower if a spatial color computation is applied. This is an important point in the process of determining the more appropriate materials for an artificial retina, together with other technological choice factors [2].

In this paper we present the results of a new session of experiments, based on the same experimental setup. We use three multispectral test images of real scenes, with different level of contextual complexity in order to test the normalization effect found in [3], under different context situations. The images were chosen in the multispectral database of the University of Joensuu [11]. We use new CSC derived by a new selection of organic materials currently tested in the artificial photodetectors development. We analyze the distances after the application of the processing methods, and we try to find some indications on the more effective combination of artificial CSC. Moreover, we consider in a preliminary way the effect of different frequency cut points and overlapping areas between the curves.

In the next sections we give more detail on each step of the experimental setup, and we discuss the obtained results.

Experimental setup

The overall steps of the experiments are the same as in [3], and they are illustrated in Figure 1.

First of all, we choose the multispectral test images simulating the light spectrum impinging the artificial retina. Then we apply different combinations of CSC, simulating different possible artificial retina responses. Finally, we apply to each triplets of values three different data processing methods, with and without spatial color computation, simulating in an approximate way the elaboration made by the human visual system.

In the following subsections we give a detailed description of each step.

Multispectral test images

For the new experiments, we consider three multispectral images in SPB and AIX formats from the well-known database of University of Joensuu in Finland [11]. Figure 2 shows a preview of these images, obtained integrating the spectral data using CIE RGB curves [1].

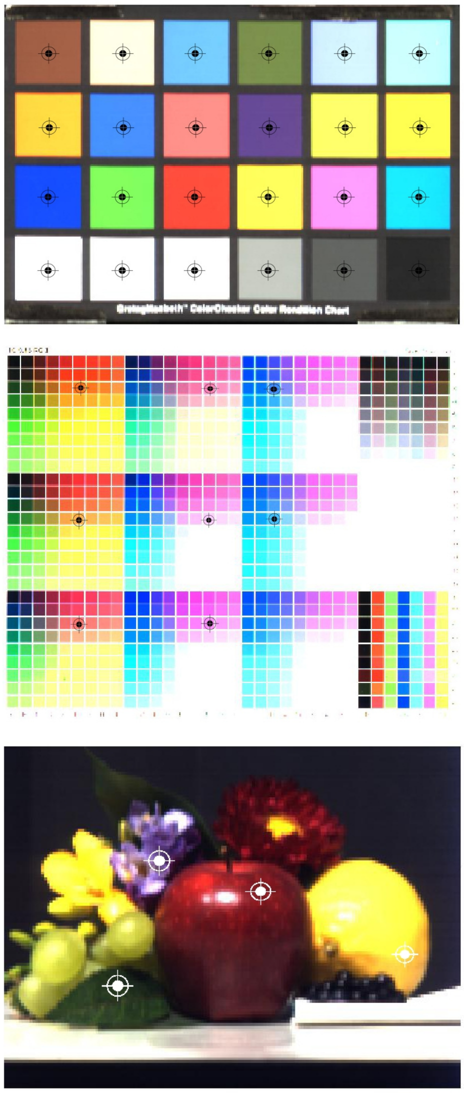

Figure 2. *RGB preview of the test images: Macbeth Color Checker (top), Printer Chart (center), Fruits and Flowers (bottom). The points considered for the presented measures are indicated using black or white crosses*

We chose the MacBeth Color Checker image (because it is a commonly used target, with known spectral data), the Printer Chart image, and the Fruits and Flowers image (as example of a real scene). In each pixel of these images, spectral information between 380 and 780 nm is available, with a sampling step of 5 nm.

CSC for an organic-based sensor

Each pixel of the multispectral test images is converted in tristimulus values using different combinations of CSC from different organic photodetectors. In our experimental setup, this stage simulates the beginning of human perception.

In this paper, we use spectral response of new materials, with respect to those used in [3]. Research on design and fabrication of organic-based sensors is still ongoing, with continuous developments but also open issues. Suitable materials must fulfill many requirements, like e.g. photocurrent spectral response, good solubility and processability, stability at room temperature and atmospheric pressure, high efficiency in electric charge generation [2]. In Table 1 we list the materials considered in the proposed experiments.

We adopt the same labels we used in [3]: we use *lms* (where *l*, *m*, *s* stands for *long*, *medium*, *short*) to refer the normalized CSC by Smith and Pokorny [1], and we called *l1m1s1*, *l1m2s1*, *l2m1s1*, *l2m2s1* the different combinations of artificial CSC (see Table 1 for correlation between labels and materials).

In Figure 3 we show the plots of the spectral response of the considered CSCs. The spectral responses were measured by standard photocurrent action spectra measurements: the light from a tungsten lamp passes through a monochromator and is focused onto the photodiode, at 0° incidence, through the transparent anode of the device. The light is chopped by a mechanical chopper (operating frequency 130Hz) and the reference signal is fed to a lock-in amplifier. System calibration is performed by replacing the organic photodiode with a silicon photodiode of known efficiency, taking into account the dark current and the spectral response of the light source and the monochromator gratings.

Tested organic-based materials for the artificial retina

ID curve	Material
l1	rr-P3HT (poly(3-hexylthiophene-2,5-diyl)) high active layer thickness
l2	rr-P3HT (poly(3-hexylthiophene-2,5-diyl)) low active layer thickness
m1	MEH-PPV (poly[2-methoxy-5-(2'-ethyl-hexyloxy)-p-phenylene vinylene]) applied reverse bias
m2	MDMO-PPV (poly-[2-3,7-dimethyloctyloxy)-5-methyloxy]-para-phenylene-vinylene)
s1	MLPPP (methyl-substituted ladder-type para-polyphenylene C61-butyric acid methyl ester)

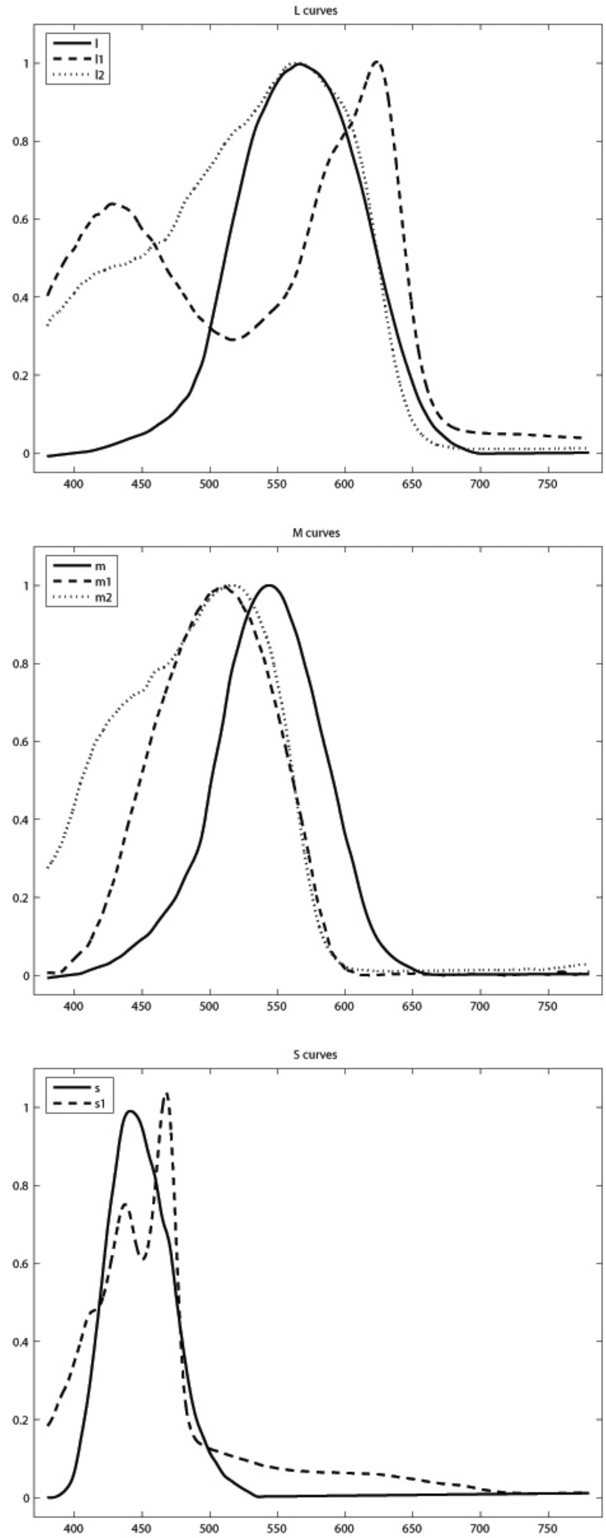

Figure 3. CSC (normalized) by Smith and Pokorny [1] and the organic-based sensor CSC (refer to Table 1)

Artificial retina responses processing

A simulation of the whole visual system is a very complex, and still not solved, task. In other works [5, 6], it was suggested that spatial color computation plays a relevant role in the normalization of inter-subjective differences between observers. Therefore, we focus our attention only on the mechanism of color perception.

As in [3], we apply three different algorithms to process the triplets values. First of all, in order to compare and validate the actual effect of color perception, we have to choose an algorithm without color spatial computation. To this aim, we choose logarithmic mapping to follow Weber's law of human perception. The other two computational models both apply spatial color computation, but with different approaches. To consider global spatial color computation, we apply the classic Von Kries [12] method. To consider a spatial color computation with both global and local characteristics, we choose a Retinex [9] computational model. There are many variants of Retinex color model and multiple implementations. We use the recent Random Spray Retinex (RSR) [13] algorithm.

These are three representative algorithms of three different color visualization treatments. In the experiments we are not proposing any judgment or consideration on the color processing in itself. Alternative algorithms with similar characteristics could be applied, and will be subject of future research.

Results and discussion

The aim of this paper is not to consider the resulting triplets from a colorimetric point of view. We are interested in measuring the triplet differences across the various CSC chosen sets in the context of the spatial or non spatial normalization. Since we are not working in colorimetric spaces, no particular color difference metric has been chosen. For this reason, we present only differential measures within each normalization method.

We consider the euclidean distance in the sensor space between *lms* and each artificial CSC set as a measure of the variation among the differences introduced by the characteristics of the integration curves. This measure is calculated separately for each patch in the MacBeth Color Checker image, and for some selected points in the other two test images. In Figure 2 we show a RGB preview of the test images, with an indication of the points considered in the experiments.

In Figures 4 and 5 we show the average of the euclidean distances among all the considered pixels. For the Macbeth Color Checker, in Figure 4, we show the average of the distances among all the patches, but also the average of the distances for the gray patches only, in a similar way of what we have done in [3]. We consider the gray patches separately because in humans the departure from perfect color constancy (characteristic of our visual system) is larger for non neutral colors [14]. Therefore, the best results on these patches is in line with the behaviour of human visual system and of spatial color computational algorithms [14].

Presented results are in line with the data in [3]: differences between original *lms* and the different sets of artificial CSC are lower if a spatial color computation is applied. This is an important point in the process of determining the more appropriate materials for an artificial retina. The main consideration is that the normalization effect is confirmed also in the cases of multispectral images of real, non synthetic, subjects.

We can introduce some preliminary consideration regarding

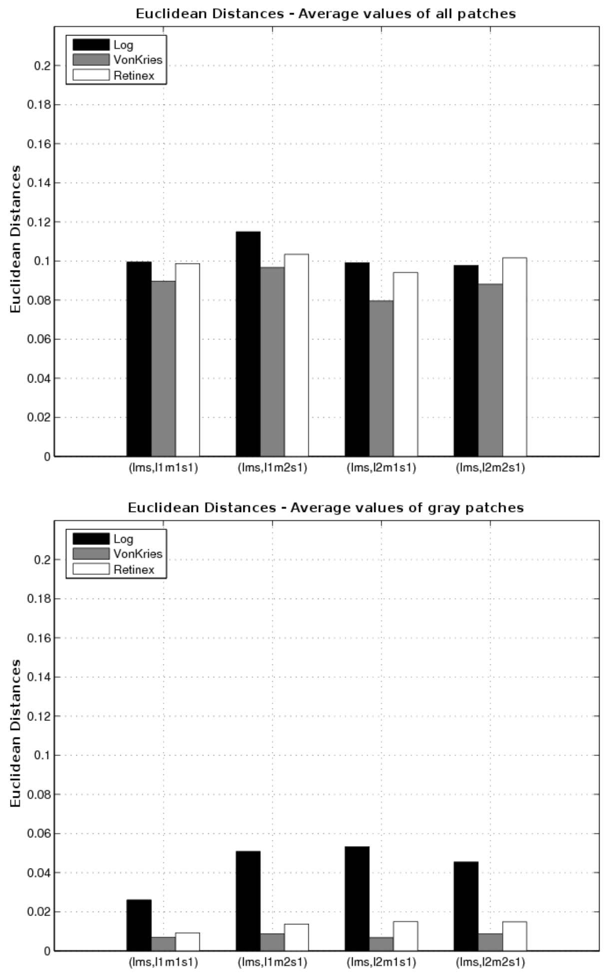

Figure 4. Average Euclidean Distances for all the patches (top) of Macbeth Color Checker, and for the gray patches only(bottom).

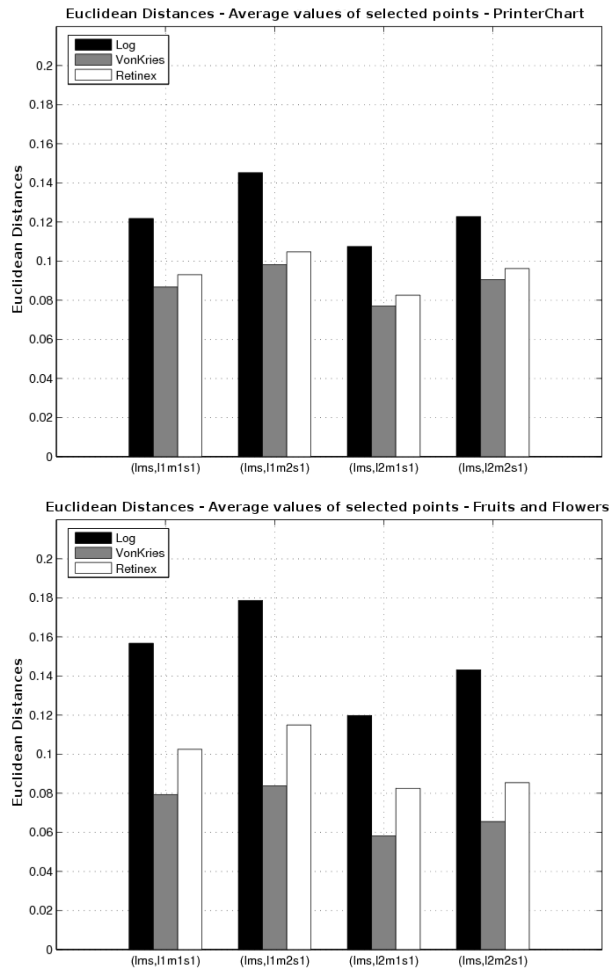

Figure 5. Average Euclidean Distances for the considered points in Printer Chart (top) and Fruits and Flowers (bottom).

the effect of the various combinations of the artificial CSC. For example, *l2m1s1* combination has the lowest euclidean distance average values when the two spatial color computation methods are applied. This may suggest that the characteristics of this combination of organic materials are closer to the behavior and robustness of human vision.

On the other side, the *l2m2s1* combination is the only case in which, in the MacBeth Color Checker image, we find slightly lower values when no spatial color computation (logarithmic mapping) is applied. This is in contrast with the other cases where the application of local computational models leads to a higher normalization of the introduced spectral differences. This seems to support the hypothesis introduced in [3] that a deeper investigation is needed about the relation among the frequency cut points and mutual overlap areas of the artificial integration curves. For example, Figure 3 shows that *m2* integration curve

has higher values at low frequencies than the original *m* curve, and its overlapping area with the other curves is greater. In future works we will focus on these aspects, considering also a detailed analysis of the distance measures in each point.

The normalization effect of spatial color computation is more evident in the Fruits and Flowers image than in the other test images. Looking at the average distance values for this image, we can notice that in all the combinations the values when logarithmic mapping is applied are higher than in the other test images, and the values for spatial color processing methods are significantly lower.

Of the three test images, Fruits and Flowers is the only one with a real context (in terms of frequency distribution, gradients of colors, etc), rather than a sequence of similar patches with uniform stimuli. A natural test image should be considered more representative, and this behavior is in line with the differences found in [15].

To further investigate this difference, we will use in future works more images with natural, complex, high detailed contexts, and we will consider a larger number of points in the measures.

Conclusion

In this paper we presented new experiments on the relation between the effect of spatial color algorithms, and the choice of organic-based materials for the development of a new generation of photodetectors. A set of organic-based material is available, with spectral responses mimicking the human cone sensitivities .

We used the same experimental setup presented in a previous work [3], with new multispectral test images, and new integration curves derived from a different selection of the active materials. The results are in line with those presented in [3], and they confirm a significant normalization in spectral sensitivities differences when a spatial color correction is applied.

There are other hints supporting the hypothesis that some frequency cut points in the integration curves may be more critical, and that eventual differences in the overlapping areas of the different response curves may lead to a change in human vision robustness. Future work will be concentrated on such features, also analyzing multispectral images of real scenes.

References

[1] G. Wyszecky, W. S. Stiles, Color Science: Concepts and Methods, Quantitative Data and Formulas, J.Wiley & Sons, New York, 1982.

[2] M. R. Antognazza, U. Scherf, P. Monti, G. Lanzani, Organic-based tristimuli colorimeter, Appl Phys Lett, 90(16), 163509 (2007).

[3] A. Rizzi, D. Gadia, D. Marini, M. Antognazza, S. Perissinotto, G. Lanzani, Investigation on the relationship between cone sensitivities and color in context for an organic-based artificial retina, Proc. of IS&T/SPIE's 20th Symposium on Electronic Imaging : Science and Technology (2008)

[4] H. Hofer, J. Carroll, J. Neitz, M. Neitz, D. R. Williams, Organization of the human trichromatic cone mosaic, J. of Neuroscience 25(42), 9669–9679 (2005).

[5] A. Rizzi, D. Gadia, D. Marini, Spectral information and spatial color computation, Proc. of IS&T/SPIE's 17th Symposium on Electronic Imaging : Science and Technology, 22-29 (2005).

[6] A. Rizzi, D. Gadia, D. Marini, Analysis of tristimulus interdifference and contextual color correction, J. of Electronic Imaging 15(4), (2006).

[7] J. Albers, Interaction of colors, Yale University Press, 1963.

[8] S. Zeki, A Vision of the Brain, Blackwell Scientific Pub., Oxford, 1993.

[9] E. Land, J. McCann, Lightness and retinex theory, J.Opt.Soc.Am 63(1), 1–11 (1971).

[10] G. Buchsbaum, A spatial processor model for object color perception, J.Franklin inst. 310(1), 1–26 (1980).

[11] http://spectral.joensuu.fi/multispectral/spectralimages.php

[12] J. von Kries, Sources of color science, in Chromatic adaptation, 109–119, MIT Press, Cambridge, MA, 1970.

[13] E. Provenzi, M. Fierro, A. Rizzi, L. De Carli, D. Gadia, D. Marini, Random Spray Retinex: a new Retinex implementation to investigate the local properties of the model, IEEE Trans. on Image Processing 16(1), 162-171 (2007).

[14] A. Rizzi, J. McCann, On the behavior of spatial models of color (invited paper), Proc. of IS&T/SPIE's 19th Symposium on Electronic Imaging : Science and Technology, (2005)

[15] N. M. Grzywacz, X. Cao, J. Rapela, D. Merwine, "Comparison of responses of retinal ganglion cells to natural and artificial images", Proceedings of ECVP, (2007)

Author Biography

Davide Gadia received his degree (2003) and Ph.D. (2007) in Computer Science from the University of Milan. Currently he is assistant professor at Department of Informatics and Communication at University of Milan. His research interests regard mainly the application of visual perception principles in Image Processing, Computer Graphics and Virtual Reality fields. He is also interested in the analysis of perceptual issues in the interaction with Virtual Environments. He is member of SPIE.

Gianluigi Lasco received his degree in Digital Communication in 2008 from the University of Milan. His main interests are digital imaging and computer graphics applications (in particular, 3D animation).

Alessandro Rizzi took degree in Computer Science at University of Milano and PhD in Information Engineering at University of Brescia. Now he is assistant professor, and senior research fellow at the Department of Information Technologies at University of Milano. Since 1990 he is researching in the field of digital imaging and vision. His main research topic is color information with particular attention to color perception mechanisms.

Daniele Marini graduated in Physics in 1972. He is an associate professor of Computer Graphics at University of Milan. In Italy pioneered the field of digital imaging. In 1982 founded Eidos, the first Italian company specialized in computer animation till 1988. During 1997-2007 has been member of the National University Council. In 1998 was appointed supervisor and coordinator of multimedia activities of Triennale di Milano. During 2007-2009 leaded research groups of the European project VIRTHUALIS. He published more than 140 papers and three books.

Maria Rosa Antognazza took the Laurea degree in physics from

Università degli Studi of Milano and the PhD degree in Physics from Politecnico of Milano. She is now a Senior Post Doc researcher at CNST of IIT@POLIMI. Her main research interests concern the optical spectroscopy of organic semiconductors, the realization and characterization of organic optoelectronic devices, with special focus onto photodetectors arrays, the study of the vision mechanisms at a molecular level, color science and imaging technology.

Stefano Perissinotto graduated in Telecommunications Engineering at Politecnico di Milano (2005), where he obtained his Ph.D. in Physics in 2009. During his Ph.D. he mainly worked on organic lasers and ultrafast spectroscopy of organic materials. He was also at Philips Research Labs Eindhoven working on molecular junctions. He is now researcher at Center for Nano Science and Technology of IIT@PoliMi. His research activity is mainly focused on self assembly and organic photovoltaics.

Guglielmo Lanzani is Director of the nascent Center for Nanoscience and Technology of the Italian Institute of Technology, and associate professor in physics at the Politecnico di Milano. His activity in experimental physics regards the science and technology of carbon based and nano-structured semiconductors, in particular photo-physics, optoelectronics ad photonics, including device manufacturing and characterization. He co-authored more the 180 papers in international journals and review books.