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Feasibility of Magneto-Encephalography Scan under Color-Tailored Illumination

Charitha Weerasuriya [1,*], Soon Hock Ng [1,2,*], William Woods [3], Tom Johnstone [3], Pranciškus Vitta [4], Laila Hugrass [5] and Saulius Juodkazis [1,6,*]

[1] Optical Sciences Centre and ARC Training Centre in Surface Engineering for Advanced Materials (SEAM), School of Science, Swinburne University of Technology, Hawthorn, VIC 3122, Australia
[2] Melbourne Centre for Nanofabrication, 151 Wellington Road, Clayton, VIC 3168, Australia
[3] School of Health Sciences, Department of Psychological Sciences, Swinburne University of Technology, Hawthorn, VIC 3122, Australia
[4] Institute of Photonics and Nanotechnology, Faculty of Physics, Vilnius University, Saulėtekio al. 3, LT-10257 Vilnius, Lithuania
[5] School of Psychological Science, La Trobe University, Melbourne, VIC 3086, Australia
[6] WRH Program International Research Frontiers Initiative (IRFI), Tokyo Institute of Technology, Nagatsuta-cho, Midori-ku, Yokohama 226-8503, Kanagawa, Japan
* Correspondence: weerasuriya@gmail.com (C.W.); soonhockng@swin.edu.au (S.H.N.); sjuodkazis@swin.edu.au (S.J.)

Abstract: Color plays an important part in human activities, and it also affects circadian cycle and the decision making process. Therefore, it is important to investigate human judgment under different color of illumination, especially because color perception is subjective. In this study, we developed required instrumentation to control the red (R), green (G), blue (B), and amber (A) colored light emitting diode (LED) lamp for carrying out magneto-encephalography (MEG) brain scans. We developed a software to generate all the colors in the visual spectrum, predefined white light combinations and saturation of an illuminated objects by using RGBA color pallet. The lamp is required to control from outside of the MEG electromagnetically shielded room with the LED lamp located inside the MEG room. Hence, USB is used for the communication mode. The feasibility of using LED lamp with MEG brain scanner has been validated for bio-medical and psychological MEG experiments.

Keywords: MEG; LED; color perception

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1. Introduction

Color plays a vital part in day today human communication activities. For instance, color is used as a marketing tool, teaching method, passing messages and many other ways. Different tone and shards of color can influence human emotions and activities [1,2]: stopping vehicles at a red traffic light, wearing a white gown at wedding, and wearing black for a funeral. The influence of color on human is very individual and is dependent on cultural background [3]. Color is linked to a psychological meaning in different ways, e.g., red symbolizes danger, but in color psychology, it is yellow and black. There is no single theory which defines psychological meaning of colors. When it comes to specific color judgments, person, age, sex, culture, and any other factors may be involved [3]. This study is motivated by creating color control software and hardware compatible with a magneto-encephalography (MEG) brain scanner and can be used to study judgements affected by illumination color. Such an instrumentation solution is not trivial due to a low electromagnetic (EM) noise requirement for highly sensitive MEG measurements. Recently, metasurfaces, which can be controlled by brainwaves in real time and can transmit information wirelessly between human brains, were reported [4,5]. It is imperative to establish a low-noise and high quality readout of minute brain currents and to determine effects which can alter them, e.g., a color ambience effect, for such brain–computer interfaces.

Color plays a significant role in consumer decision making and judgment. As soon as it has been seen by eyes, color creates, first, excitement about the object. The lighting source is a very important factor in producing an initial impression on consumer products. The natural color of the product is deviated by the lighting source [6]. As a result of lighting source, products may give different color quality, such as rich or dull visual effects on a consumer. However, color judgement is very individual and subjective [7]. It is very difficult to compare color quality with different lighting sources. Therefore, the International Commission on Illumination (Commission International de éclairage—CIE) has introduced a new color rendering index (CRI) for quantification of lighting sources, e.g., a temperature of source is widely used in lighting LED appliances defined as cold and warm white. The CRI index can be used to reveal the color of an object and to compare it with natural light. Halogen and incandescent light sources have the highest CRI. However, recent research verified that light emitting diode (LED)-based solid state lights were preferred than halogen and incandescent lights [8]. Due to technological development in the solid state lighting, there are two more color rendition properties introduced, which are color fidelity index (CFI) and color saturation index (CSI). The CFI defines an ability, which makes color more natural, and CSI is the ability to make color distinguishable [9]. In conventional lighting lamps, CFI is optional, and CSI properties are not available. In LED lighting, white light can be generated by the combination of red (R), green (G), blue (B), and amber (A) LEDs. By changing the ratio of RGB–amber LEDs, it can generate different types of white light. As result of this, it is easy to change CSI and CFI [6].

The aim of the presented work is to design software for the control of chromaticity of illumination by a four basic color RGB–A lamp (Ledigma Ltd., Vilnius, Lithuania) in MEG experiments. The MEG brain scanner maps brain activity by capturing magnetic fields produced by minute electrical currents in the brain [10]. This MEG scanner is located inside an EM-shielded room to reduce interference from external EM sources , and it was tested for feasibility to make MEG scans under RGB–A lamp illumination. Lamp control was changed from wireless to USB connection to meet requirements of a low noise environment required for MEG.

2. Experimental

The LUME-20R lamp has 20 LEDs grouped into four colored clusters, with each cluster made of five LEDs. These four colored clusters are red, green, blue, and amber. A four 10-bit pulse width modulation channel controls the fluxes generated by each group of LEDs [6]. The LUME-20R lamp uses LEDs from LUMILEDS LUXEON Rebel family with peak wavelength 452 nm (B), 523 nm (G) InGaN LEDs, InGaN-based phosphor converted amber LED at 589 nm, and direct-emission AlGaInP LED at 637 nm (R) [6]. The lamp can be controlled by setting specific values of hue, saturation, and brightness (or value) (HSV) presented as a color cone (see details on conversion of the color coordinates in Appendix A). Hue is the term which defines a dimension of color, with specific wavelength, while brightness defines the lightness or darkness of the color, and saturation defines the intensity of the color [11]. The HSV is widely used in computer graphics and printing applications. Hue denotes the angular dimension starting from red at 0° and passing through green at 120°, blue at 240°, and back to red at 360°. The brightness (or value) evolves along the axis of color cone, with 0 representing black, and white has the value of 1. The radial dimension of the cone is saturation, which gives a pure color at 1 (at the outside edge of the color cone) and $S = 0$ at the center of cone (on its axis).

The aim of this project is to control the LUME-20R LED (Ledigma Ltd., Vilnius, Lithuania) bulb from outside the EM-shielded room (Figure 1). The main reason to select this bulb is that it has a capability to change lighting parameters quantitatively and qualitatively, such as CSI and CFI. This LUME-20R LED bulb can be controlled only via Bluetooth. However, the Bluetooth communication is not applicable due to the bulb being located inside the EM-shielded room. Therefore, it requires a wired method to communicate and to control the bulb from the outside-shielded MEG room. Figure 1 shows a block diagram of the organization of the devices used in this study (Figure 2).

Protocol. The MEG scanner is very sensitive to magnetic fields. Therefore, to verify the impact of the four-color LED lamp (LUME-20R) and its control software on the MEG scanner, an initial test was conducted with the help of a MEG expert team. At this stage, eight different combinations of MEG scanner data were measured over a minute period. Those combinations were used to test the changed condition of MEG operation and the reference. The main tests were the following combinations: (1) empty the MEG scanner itself, (2) have the MEG scanner have a person inside (a normal operation), (3) put a person inside the MEG scanner with a candle light, (4) MEG scanner with a candle light (5), and MEG scanner with primary color lights at a time (RGB+Amber); values obtained were 1500 K (candle light), 3500 K (halogen), and 6500 K (daylight).

The person has to sit in the MEG scanner to measure brain magnetic fields during the session, with different (in color) lighting conditions defined by the LED lamp (Figure 1).

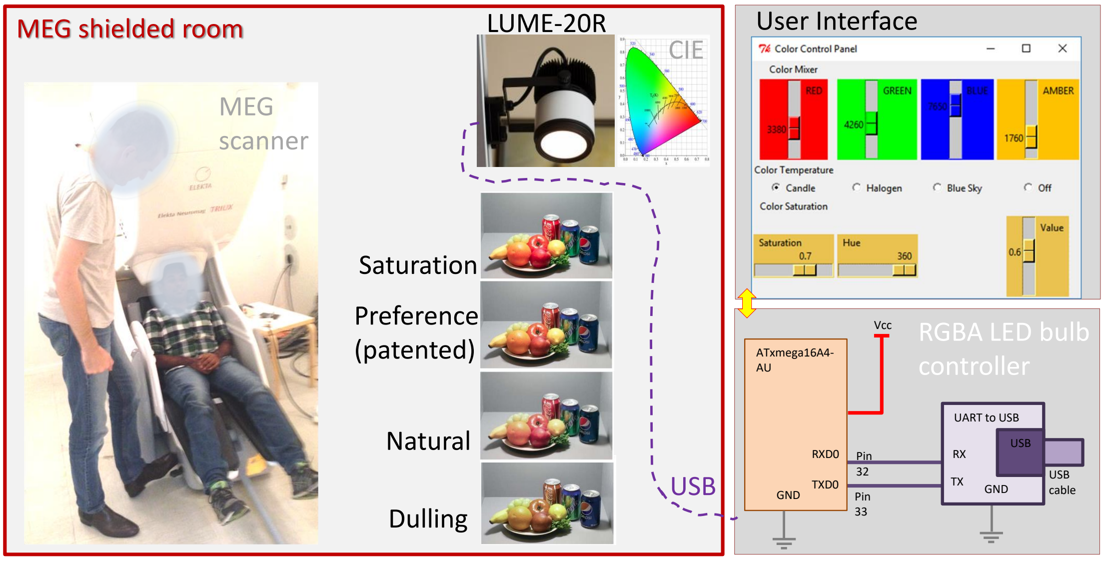

Figure 1. A magneto-encephalography (MEG) brain scanning experiment carried out with four-color RGBA (amber is added) illumination; the Elekta/Neuromag 306 channel MEG system was used. Different illumination was defined as: saturation, preferential, natural, and dulling [6], which were selected by RBGA mixture from the CIE 1931 chromaticity diagram; the preferential illumination was patented. The LUME-20R lamp was used in this study; its control via USB connection and the user interface were developed in this project (see details in Figure 2). Photo: C.W. in MEG scanner and W.W. setting MEG up.

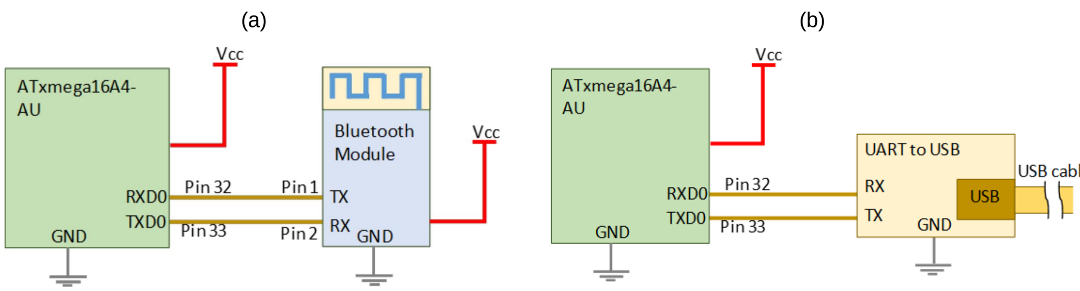

Figure 2. LUME-20R Bluetooth connection (**a**) and wire connection for USB communication (**b**).

3. Results

This study was carried out to answer the question whether a LED lamp with color-flexible RBG+amber illumination can be used in a room with a MEG scanner. The lamp is intended for color perception research, where it illuminates familiar objects with natural colors (see the "light box" scene in Figure 1) at a distance ~2 m from the face of a person in the MEG scanner seat. The LED lamp was controlled via USB link, which was expected to cause lesser magnetic B-field disturbance and intervened with MEG sensors capable of sub-1 fT magnetic B-field detection.

3.1. Lamp Control

LUME-20R lamp is designed to be controlled via Bluetooth communication, as displayed (Figure 2a). However, in this application, it is impossible to communicate with the lamp via a wireless signal because the lamp is installed inside the MEG-shielded room. The only available method of communication with the lamp is via wired mode. For that reason, the USB communication method has been selected from USB and serial RS232 (Figure 2).

There were few factors involved in the selection of USB as the communication mode. Firstly, USB is the most common communication method these days, and most of the laptops do not have serial communication ports. Secondly, the distance is too long to control via serial communication with higher baud rate. A LUME-20R lamp micro-controller is configured to UART's baud rate as 115,200 bit per second. RS232 is able to communicate up to 1.2 m, when it is operating at 115,200 bit per second. However, USB 2.0 can communicate up to 5 m. The distance from the lamp to the outside controller is roughly 3 m. Therefore, for these two reasons, USB is the best method of communication available. LUME-20R lamp was connected via UART to USB converter to avoid noise associated with Bluetooth, as shown in Figure 2b.

The software was developed using the Python software language. Python is a high level language, which has object oriented capabilities, and it supports other different styles of coding, too. Furthermore, it runs on any platform, such as Windows, Linux, Mac. It requires a very small amount of memory because Python is a scripting language [12]. In addition to that, the Python language interpreter is free, and many libraries are freely available. This project has used Python packages, such as ColorPy, Colorsys, and Tkinter. ColorPy is a free Python package, which converts physical attributes of light to RGB color space by using standard color mixing formulas presented in Appendix A [13]. The Colorsys package gives bidirectional conversion color values, such as hue, saturation, brightness, and HSV to RGB colors, according to formulae presented in Appendix A. Hue H has a range of $0°$ to $360°$, saturation S is from 0 to 1, and brightness value is V; chroma C is given by $C = V \times S$. Appendix B shows a practical example illustrating that the xy-chromaticity is independent from the luminance (brightness).

3.2. Lamp in MEG Room Controlled via USB

The software has been designed to control the lamp from outside of the shield chamber. The software has features to control RGB+amber colors' individuality (Figure 1). This gives an opportunity to illuminate objects with diversified color combinations. Moreover, the developed software is capable of setting predefined CCT settings, which are 1500 K (candle light), 3500 K (halogen), and 6500 K (daylight). That enables us to set the lighting system to different modes. In addition to that, software is capable of controlling saturation of the illuminated objects. This is one of the strong features available in our system, which gives opportunity to increase the color fidelity of the objects. This feature has many commercial implications, such as for use in display lights, art galleries, etc. The above measurements were taken to find out electromagnetic or other noise effects on the MEG scanner-measured data. During this test, data were captured from 102 magnetic sensors for a one-minute period (see MEG scanner Elekta/Neuromag in Figure 1).

3.3. Data Analysis

Measured MEG sensor data were uploaded into Matlab data format, with each data set around 0.5 GB in size. These data were first plotted onto a color map based on its amplitude to make it easier to compare with each data set. A Matlab command was used to plot the color map of the data. In some cases, it was necessary to omit some sensors due to faulty values, e.g., sensor 29 had too large of values compared to other sensor channels. After removed outliers, data were mapped into Matlab surf plot and can be used for qualitative analysis (Figure 3). No brain function is analysied in this current study, but rather, technical capability to use MEG scanner in the shielded room and USB controlled LED lamp is used.

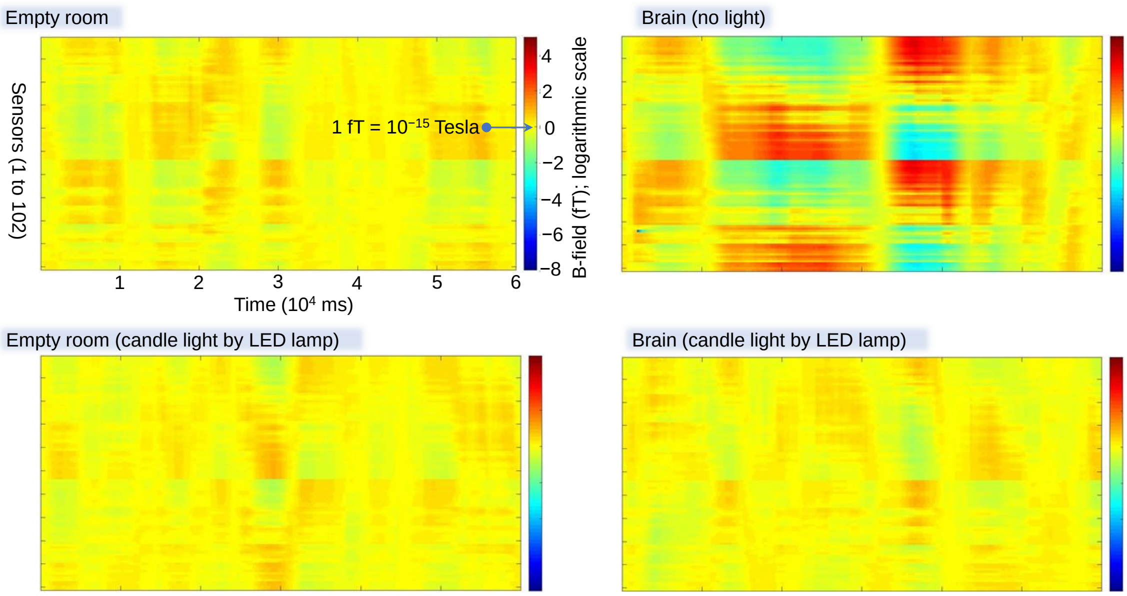

Figure 3. Raw experimental data. Magneto-encephalography (MEG) setup test with and without LED-lamp and person in the MEG scanner; LED-lamp is set for the candle light 1500 K color temperature. Scanner No. 29 is excluded from the plot due to erroneous data. Data color-maps are plotted on the same intensity scale.

Since colors are produced using different pigments and intensities in LEDs, it was necessary to compare MEG equipment response under different LED colors. Figure 4 shows a summary of results for the RGB+amber single colors (no person in a MEG seat). Apparently, there was approximately ∼10 s higher readout currents in half of the sensors for the blue illumination. This can be taken into account in real settings, when experiments usually start even after a longer delay. The background signal of sensors was fluctuating at 1–10 fT level, while 1–10 pT are usually measured under on–off color stimulations in similar MEG experiments [14].

The MEG operates in a very low frequency range. Therefore, the noise levels in a low-frequency domain up to 50 Hz were checked. Experimental data in the time domain (Figures 3 and 4) were converted to the frequency domain by using fast Fourier transform (FFT) in Matlab and were plotted as color maps. The absolute value was plotted, which is calculated from a complex number FFT result (amplitude and phase), as shown in Figure 5. The amplitude values on the linear scale are shown in insets for an empty room and a person in the MEG scanner without LED lights (top row in Figure 5). This corresponds to the standard operation conditions and related noise levels. The test of the empty room (no person in MEG) with operated LED lamp via USB link showed the acceptable level of noise (bottom row in Figure 5) for real MEG scans under different color settings.

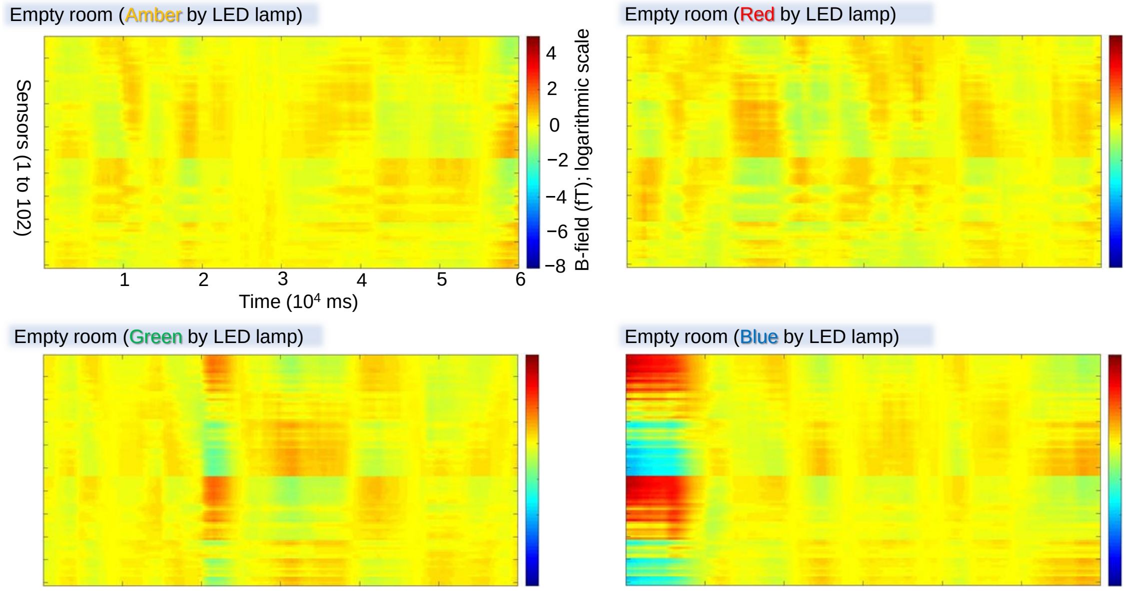

Figure 4. Magneto-encephalography (MEG) setup test with LED-lamp at different color illumination RGB+amber. Data color-maps are plotted on the same intensity scale.

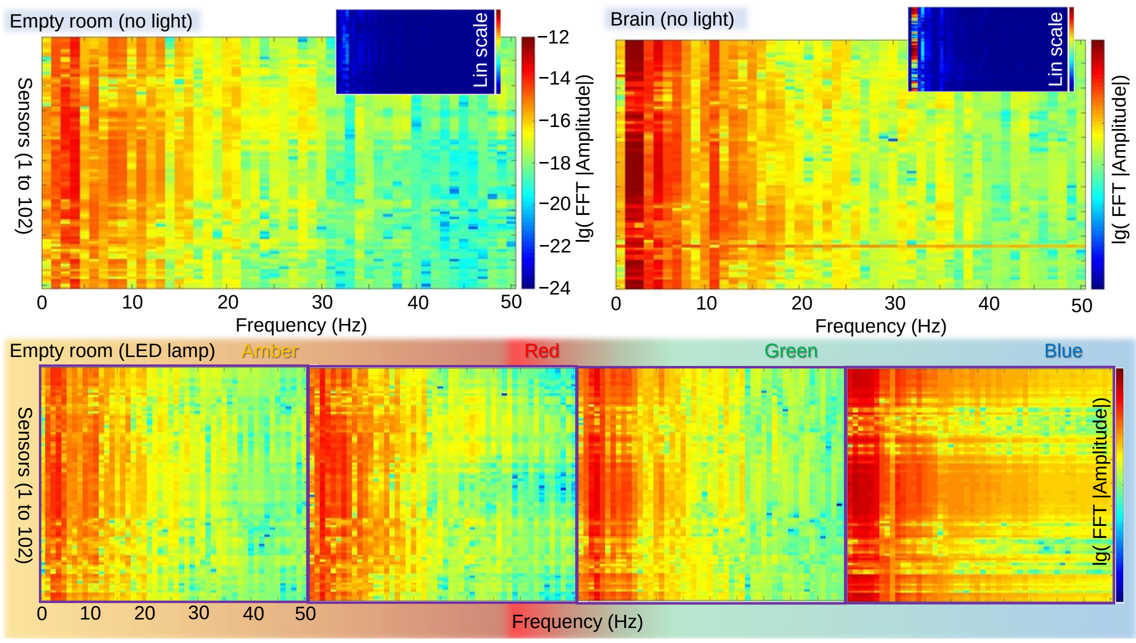

Figure 5. Magneto-encephalography (MEG) sensor frequency response. The top row shows Figure 3. The top row measurement is an absolute value of fast Fourier transform (FFT) filtered data at 1 Hz sampling step; insets show the same plots in linear intensity scale. The bottom row is a MEG setup response to the RGB+amber illumination (Figure 4) without a person in the MEG seat. Note that the MEG room's shielding was effective by design against 50 Hz power supply noise.

Brain activity is most pronounced at frequencies < 5 Hz, as evident for most of MEG scanners (Figure 5), especially in linear intensity scale (insets). Most of the background signal is expected from the blue component of the LED lamp channel. The frequency response due to usage of the blue channel was expanding to higher frequencies that are stronger as compared to amber, red, and green (Figure 5). Timing protocols of color changes in actual MEG experiments need to take into account the frequency of the illumination change, reaction time, and neural activities.

4. Discussion

Based on experimental results (Figure 5), we can conclude that the LED-lamp and the controller via USB connection can be used in conjunction of brain and color-related research. Further improvements of USB wire shielding can be implemented to further reduce noise amplitude at low $f < 10$ Hz frequencies, usually referred to as a building/structure noise.

The color mixing by developed software and the LED-lamp can be calibrated by a colorimeter and measured in color temperature from tristimulus values (see Figure A1b). The desired color is generated by regulating the intensity of the LEDs with four colors. Concurrently switching clusters of LEDs may cause electromagnetic interference (EMI). Hence, it is compulsory to measure EMI of the lamp and controller software together [15] , as it was carried out in this feasibility study.

The created software and hardware control tools can serve future research in a wide range of applications, from brain functions and psychological behavior relevant to learning of hyperactive kids, mood control of prisoners, and in age care facilities, as well as a marketing tool and street lighting for the quality and safety of driving and walking [1–3,16,17]. In terms of neuro-scientific questions, it is interesting to use the LED lamp to investigate colour constancy, which is the tendency to perceive surface colour of objects as relatively constant under changing illumination conditions [17]. Previous studies have shown that warm or cool illumination can influence perception of colours. By use of brightening illusion, it is possible to shift the point at which observers switch between seeing the same dress as white/gold vs. blue/black. The challenge is in differentiating between signals associated with neuro–physiological responses to illumination vs. decision processes about illumination quality. Cognitive neuroscience researchers are using machine learning algorithms to decode patterns of EEG/MEG/fMRI data associated with different perceptions/tasks/decisions [16,18]. Computer graphics and data visualisation strategies [19] could find more intuitive and informative presentations based on color rendering.

A similar kind of a controller and LED lamps can serve other applications for greenhouse lighting system design. It has been scientifically proven that harmful nitrate can be significantly reduced by 20% to 40% in lettuce by red LED illumination two days before harvesting [20]. It was demonstrated that a "light box" with three RGB colors only were delivering viable conditions (similar production of biomass) to grow Christmas poinsettia *Euphorbia pulcherrima*, a popular pot-plant, as well as to develop color change of leaves to red by only such artificial lighting [21].

5. Conclusions

This project successfully developed a controller for the LUME-20R lamp via USB from outside the electromagnetic-shielded room. Based on test data, it shows that LUME-20R lamp and MEG scanner combination can be used in brain and color related research using MEG scanners.

The color controller software is capable to tune color saturation of an illuminated object; a voice control can be used to alter color of scene illumination during MEG scans. Furthermore, the software gives a comprehensive range of color combinations, such as all the colors in the spectrum, white light options and color hue, saturation, and brightness.

It is proven that the LUME-20R lamp and USB color controller software are feasible to apply MEG scanner-related research. Exact protocols for timing of illumination change and judgement of illumination preference (color, brightness, etc.), as it was carried out earlier without MEG readout [6], need separate dedicated investigations for distinction between a brain reaction to a change of illumination and/or decision making.

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Data Availability Statement: Data are available upon reasonable reque.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Method and Notations of Color Conversion

Presently, red, green, and blue (RGB) are considered the primary colors based on biological makeup of the human eye, which contains three types of color receptors, the cone cells. Color matching or mixing is adding colors together to match the target color. The three primary RGB colors (known as tri-stimulus values) are used to define other colors, e.g., if R and G are mixed in equal proportions, it will produce yellow color. However, it is not possible to match all the colors in the spectrum by adding RGB primary colors; some colors require negative red light to match with the target color (reflected by the first Grassmann law). Additionally, there are different possibilities to mix colors for the same target color. e.g., the color generated by adding R to cyan is similar to the color created by adding G and B colors [22,23].

James Clerk Maxwell was the first to quantify color measurements and proposed RGB as primary colors forming an orthogonal coordinate system, which define a color triangle [11]. The color triangle is obtained by cutting the RGB color space. Any color in the triangle can be determined by the color coefficients r, g, b of the RGB components. In this description, the brightness is ignored, and coefficients $r + g + b = 1$ [24].

To overcome negative RGB values required to define some colors and to describe brightness of the colors, the International Commission on Illumination (CIE), in 1931, introduced X, Y, and Z imaginary primary colors. Here, Y represents the luminance or brightness, Z represents the blue stimulation (the S cone response in eye), and X represents the linear combination of cone response curves chosen to be non-negative. According to this CIE XYZ model, the XZ plane has all the possible chromaticities, while Y presents its brightness [22,23]. The spectral power distribution (SPD) provides the visual profile of a light source and gives the radiant power emitted by the sources at each wavelength λ or the range of wavelengths. The SPD describes the power per unit area A per unit wavelength λ of an illumination $M(\lambda) = \frac{\partial^2 \phi}{\partial A \partial \lambda}$, where ϕ is the radiant flux [23]. The CIE color matching functions are defined for the visible spectral window 380–780 nm in such a way that $X = \int_{380}^{780} M(\lambda) \times \tilde{x}(\lambda) d\lambda$, $Y = \int_{380}^{780} M(\lambda) \times \tilde{y}(\lambda) d\lambda$, $Z = \int_{380}^{780} M(\lambda) \times \tilde{z}(\lambda) d\lambda$, where $\tilde{x}(\lambda), \tilde{y}(\lambda), \tilde{z}(\lambda)$ are the CIE defined color matching functions. The CIE chromaticity diagram (inset in Figure 1) is based on Maxwell's color triangle, which is projected onto two dimensional xy-plane. As a result, all the colors can be represented with two coordinates xy as $x = \frac{X}{X+Y+Z}$, $y = \frac{Y}{X+Y+Z}$, $z = \frac{Z}{X+Y+Z} \equiv 1 - x - y$.

To identify color in practice, the CIE's xyY presentation is widely adopted, where x and y are the coordinates of the chromaticity diagram of a given color and Y is its luminance. Therefore, X, Z tri-stimulus values can be calculated by $X = \frac{x}{y} Y$, $Z = \frac{Y}{y}(1 - x - y)$ and $Y = Y$. Chromaticity xy-coordinates do not depend on the luminance (see a practical example in the Supplement Figure A1).

Grassmann proposed that color matching can be treated as algebraic equations, i.e., any given wavelength is naturally denoted by the linear combination of the given set of primary colors (P_1, P_2, P_3). This given set of color can be represented as a linear sum of another primary set of colors (Q_1, Q_2, Q_3) using matrix notation [11,22,23]. Based this linear transformation theory, CIE specified the standard that can convert RGB color space to XYZ color space and vice versa:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \frac{1}{b_{21}} \times \begin{bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{bmatrix} \times \begin{bmatrix} R \\ G \\ B \end{bmatrix} \equiv \frac{1}{0.1769} \times \begin{bmatrix} 0.49 & 0.31 & 0.20 \\ 0.1769 & 0.8124 & 0.0106 \\ 0.00 & 0.01 & 0.99 \end{bmatrix} \times \begin{bmatrix} R \\ G \\ B \end{bmatrix}. \quad \text{(A1)}$$

Inverse of the Equation (A1) is used to calculate R, G, B color space from X, Y, Z:

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 0.4184 & -0.1586 & -0.0828 \\ -0.0911 & 0.2524 & 0.0157 \\ 0.00092 & -0.0025 & 0.1786 \end{bmatrix} \times \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}. \quad \text{(A2)}$$

The presented nomenclature allows us to transform color spaces between RBG, XYZ, and chromaticity xy (with Y brightness). Those conversions were coded using readily available Python libraries [13]. Adding amber color with fixed intensity to the RGB LED spectrum was handled by the same Equations (A1) and (A2), with the mixing rule defined below (Equation (A3)). For example, 1500 K (candle light) RGBA values are obtained by, first, calculating x, y coordinates correlated to 1500 K from CIE 1931 chromaticity diagram: $x = 0.585725205$, $y = 0.39311745$. Then, X, Y, and Z are derived by applying the x, y data from Equation (A1) with setting $Y = 1$ for the calculation. Those calculated X, Y, Z defined RGB colors by applying Equation (A2). The correlated RGB values for 1500 K (candle light) are $(R, G, B) = (0.4603, 0.1175, 0.0084)$. The RGBA values for 1500 K are obtained from the following consideration. The AGB triangle $R(AGB) = 0$, $A(AGB) = 1$ and similarly for the RGB triangle $R(RGB) = 1$, $A(RGB) = 0$. The amber, red, and green colors are in a straight line. Therefore, the amber ratio can be considered as $A = (1 - R)\sigma$, assuming that green color is constant (see, next paragraph and Equation (A4) where $\sigma = 0.64$ for 1500 K light is a weight parameter used in LUME-20R lamp). One arrives at $A = (1 - 0.4603)0.64 = 0.3454$. This method was applied to obtain RGBA values for any correlated color temperature (CCT) values.

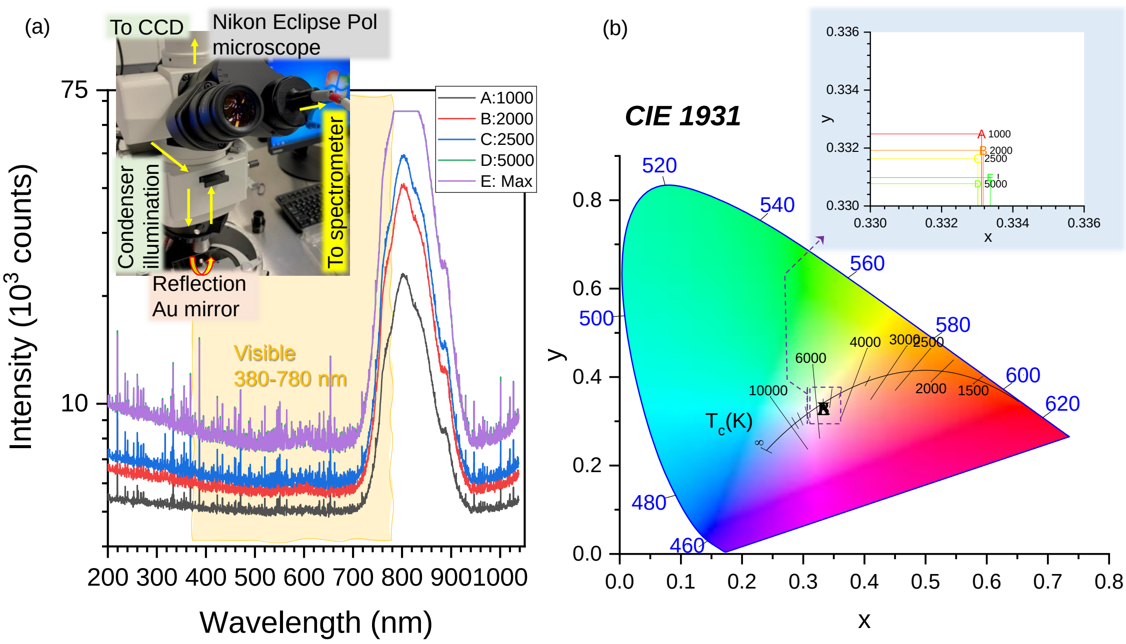

Figure A1. Chromaticity plot of a white light condensor (Xe-lamp) illumination upon reflection from a Au-mirror; note logarithmic intensity scale. Saturation occurred at 64×10^3 counts. (**a**) Spectra at different intensity settings. Inset: photo of the microscope. (**b**) Chromaticity xy-coordinates and zoom-in region in the inset for spectra shown in (**a**). Color temperature T_c [K] is overlayed over the CIE 1931 chromaticity map.

Color rendering was made by controlling intensity of separate RGB+amber contributions via current defining the intensity (power) of the corresponding color LED. Unlike RGB LED lamps available in the market, blending RGB+amber colors provides extra control of color fidelity, color saturation, and dulling effects (Figure 1). Color rendering was based on varying spectral power between the G and R regions of CIE 1931 xy chromaticity diagram at the wavelength from 530 nm to 620 nm. The white light falls on AGB and RGB triangle [6]. Hence, the white light can be generated with the mixture of spectral powers S_{AGB} or S_{RGB} or a linear mixture of both by controlling R and A color ratio [6]:

$$S_{RGBA} = \sigma S_{AGB} + (1 - \sigma) S_{RGB}, \tag{A3}$$

where σ is the weight parameter $0 < \sigma < 1$. The radiant flux is calculated by the following equations:

$$R_{RGBA} = (1 - \sigma) R_{RGB}, \tag{A4}$$

$$A_{RGBA} = \sigma A_{AGB}, \tag{A5}$$

$$G_{RGBA} = \sigma G_{AGB} + (1 - \sigma) G_{RGB}, \tag{A6}$$

$$B_{RGBA} = \sigma B_{AGB} + (1 - \sigma) B_{RGB}. \tag{A7}$$

The rule above was used to set individual color intensity by the electrical current of the corresponding LED.

Appendix B. Chromaticity of Reflection from a Mirror

Figure A1 shows that xy-chromaticity is independent from luminance (brightness). A white light condensor Xe-lamp was used at intensity settings corresponding to integral intensity different by five times (1000–5000 counts). The back reflected light for a Au-mirror, which performs close to perfect reflector over visible spectral ranger with reflectance $R \approx 100\%$, was recorded using optical fiber coupled Ocean Optics (Ocean-FX-VIS-NIR-ES, spectral resolution $\sim$2.5 nm) portable spectrometer and laptop computer. The chormaticity xy-coordinates of the recorded spectra are plotted over the CIE 1931 color triangle; $x + y + z = 1$. All five spectra of intensity differed by five times are almost overlapping (minor differences are only revealed in the zoomed-in plot in the inset Figure A1b). The RGB prime colors correspond to $R(x, y) = (0.64, 0.33)$, $G(x, y) = (0.30, 0.60)$ and $B(x, y) = (0.15, 0.06)$.

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