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EXPERIMENTAL SETUP FOR STUDYING THE BLUE LIGHT EFFECT ON SENSE OF TIME AMONG THE PERSONS WITH DIFFERENT TYPE OF VEGETATIVE REGULATION

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The effect of blue illumination (wavelength is about 460 nm) on human perception of short-time intervals of light, depending on a person's predominance of activity of the sympathetic or parasympathetic parts of the autonomic nervous system has been studied using an experimental setup based on the LED dynamically controlled lighting system. The persons measured the duration of a minute before and after exposure to white (a control group) or monochromatic blue light. The effect of blue light was manifested in the predominance of excitability of the sympathetic part of the autonomic nervous system. The same persons showed a tendency to shorten the duration of the subjective minute after the light exposure. A similar effect of white light did not lead to significant changes in the same characteristics. The results of the study suggest that the individual effect of blue light on the function of time perception can be mediated through the regulation of the heart rate.

Keywords: light exposure, sense of time, LED, blue light, dynamically controlled light source

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ЭКСПЕРИМЕНТАЛЬНАЯ УСТАНОВКА ДЛЯ ИССЛЕДОВАНИЯ ВЛИЯНИЯ СИНЕГО СВЕТА НА ФУНКЦИЮ ВОСПРИЯТИЯ ВРЕМЕНИ У ЛИЦ С РАЗНЫМ ТИПОМ ВЕГЕТАТИВНОЙ РЕГУЛЯЦИИ

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С помощью экспериментальной установки на основе светодиодной, динамически управляемой системы освещения исследовалось влияние светового воздействия монохроматическим синим светом (длина волны – около 460 нм) на восприятие человеком коротких интервалов времени свечения, в зависимости от преобладания в его организме активности симпатического или парасимпатического отделов автономной нервной системы. Испытуемые отмеряли длительность минуты до и после светового воздействия белым (контрольная группа) или монохроматическим синим светом. Влияние синего света проявилось в преобладании возбудимости симпатического отдела автономной нервной системы. Выявлена тенденция к укорочению длительности субъективной минуты после светового воздействия. Аналогичное воздействие белым светом не привело к изменениям соответствующих показателей. Результаты исследования позволили предположить, что индивидуальный эффект влияния синего света на функцию восприятия времени может быть опосредован через регуляцию сердечного ритма.

Ключевые слова: световое воздействие, восприятие времени, светодиод, синий свет, динамически управляемый источник

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Introduction

Light is one of the environmental factors affecting human health: both natural and artificial light are important for the state of body, and not just for visual perception. Light exposure has both short-term effects, manifesting as rapid changes in functional indicators, and long-term consequences, affecting biological rhythms (circadian and circannual, associated primarily with natural fluctuations in the illumination level). It was found in recent years that the long-term effects of light exposure are largely associated with activation of the retinohypothalamic tract originating from photosensitive retinal ganglion cells containing the visual pigment melanopsin [1–3]. Information about the illumination level is transmitted to suprachiasmatic nuclei of the hypothalamus, coordinating cyrcadian output [4], and also affects melatonin secretion in the pineal gland and activation of the cerebral cortex through other morphological pathways [5, 6]. This mechanism explains the effect of lighting parameters on wakefulness and activity [7, 8], cognitive functions [5, 9], emotions [10] and much more. It is important to develop technologies and designs for modern light sources based on these data [11].

It seems logical to assume that individual perceptions of time may also vary depending on the lighting parameters; however, this issue has remained virtually unexplored in literature. Perception of time can apparently depend on changes in physiological and emotional state of a person [12–14]. Signals from an endogenous pacemaker are supposedly used for estimating time intervals [15, 16], so changes in rhythmic physiological activity (for example, heart rate) may be adjusted by an internal clock. Increased heart rate due to increased sympathetic tone (for example, from stress or excitement) should lead to subjective acceleration of time, and a slowdown in heart rate should lead to a slowdown in time.

In this case, light exposure can affect time perception either through changes in the cortical tone [6], or through heart rate variability [17, 18]. Light with wavelengths corresponding to peak sensitivity of melanopsin-containing receptors can have a pronounced effect [3]. This type of exposure is recommended, for example, for treating seasonal affective disorders: dimmer (illuminance of 750 lux) white light saturated with a blue component produces the same therapeutic effect as bright white light (10,000 lux) used traditionally [19, 20]. Similarly, experimental studies revealed that blue LED light ($\lambda = 468$ nm) had a noticeable effect on suppressing melatonin synthesis in horses even at low illuminance (10 lux) [21].

Peak sensitivity of melanopsin-containing receptors corresponds to a wavelength of $\lambda \approx 480$ nm [21].

The goal of our study has consisted in assessing the effect of blue light on perceptions of minute-long intervals.

Experimental procedure

The study was performed on 18 healthy volunteers (12 males and 6 females) aged 18 to 28. The experiments were carried out mainly in the evening, when the participants felt psychologically and physically rested. Seventeen of the eighteen volunteers repeated the experiments after 3-4 weeks, with the difference that exposure to blue light was replaced by exposure to white light. Thus, 17 people made up the control group. It was divided into two subgroups in the course of the studies (referred to as Group 1 and 2 throughout the text). A detailed description of the experimental procedure is given below.

Light exposure. The subjects were exposed to 20 minutes of white light from a dynamically controlled LED source with a wide range of correlated color temperatures (CCT) (T_s = 2,800–10,000 K), with a high total color rendering index ($R_a > 90$). The device was developed at the Submicron Heterostructures for Microelectronics, Research & Engineering Center, RAS (St. Petersburg) [22, 23], striving to create environmentally friendly lighting optimal for life in residential and industrial buildings. In particular, the device can generate lighting that corresponds to the natural diurnal cycle that regulates the biological circadian rhythms. This function is achieved by smoothly changing the color temperature.

High color rendering indices of the light source are achieved through using a set of LEDs: red (630 nm), blue and green (460 and 520 nm), white warm W_w (CCT of 2,800 K), white cold W_s (CCT of 8,000 K).

The latter two components (phosphor LEDs) largely generate the light flux, while the former three (monochromatic LEDs) allow to smoothly adjust the color temperature in a wide range and maintain high values of all special color rendering indices R_1–R_{14} [22].

The CCT values were (in degrees K): 2,800, 3,500, 4,000, 5,000, 6,500 and 10,000. The optical system provided high transmittance of radiation from the LEDs to the output window of the luminaire, a preset spatial distribution of radiation, and uniform color in the far and near fields, i.e., good mixing of the radiation from individual LED arrays. The problems with uniform and wide angular distribution and homogenization of color characteristics over the emitting surface and angle have been solved [22].

The software and the remote control system for the light source can generate the required lighting over a radio link in a radius of 35 m, setting any time-based algorithms for the intensity and color temperature of the light. Blue light was generated by 460 nm LEDs, the remaining LEDs were turned off while the light control system kept operating.

We previously studied [24] the biological effects of different LED sources, assessing their effect on the concentration of melatonin in the blood of subjects, with the same visual effect (CCT and illuminance) using the known function $V(\lambda)$, the relative spectral luminous efficacy and the function $B(\lambda)$, the spectrum of biological action (suppression of melatonin secretion) (see [24, Fig. 3,*b*]). As follows from the figure in [24], peak intensity of $B(\lambda)$ lies in the range of 446–477 nm, i.e., it is shifted approximately 200 nm to the left from the $V(\lambda)$ peak and coincides with the peak of the strong blue band for white phosphor LEDs.

Calculations of the biological equivalent in [24] indicate that LEDs with CCTs below 3,500–4,000 K, where the fraction of blue light is not more than those of yellow and orange, carry the least risks of suppressing melatonin. White LEDs with CCTs above 4,000 K are rather dangerous during the hours with active melatonin secretion.

The CCT of emitted neutral white light in our experimental setup was 4,000 K. The areas under the spectral curves for white light with temperatures of 2,800, 3,500 and 4,000 K with wavelengths λ = 400–800 nm significantly exceed (by more than an order of magnitude) those for blue light with wavelengths λ = 460–480 nm. This means that the blue component of white light should have less effect on the functional state of a person compared to monochromatic radiation of a blue LED with $\lambda \approx 460$ nm. This was confirmed experimentally.

Estimation of time intervals. The test for subjective duration of a minute is a classical technique for studies of time perception, well known in experimental psychology. It is believed that the accuracy of measuring subjective minutes is linked to psychophysiological aspects of time, i.e., with the biological clock [14]. Different people tend to overestimate or underestimate the time interval equal to an astronomical minute. The subjective minute is a relatively stable value, reflecting specifics of how an individual perceives time.

Estimation of body functions. Changes in the functional state of volunteers were assessed by variability and spectrum of the heart rhythm. Heart rate variability (HRV) was assessed by the sequence of *RR* intervals in ECG, providing data on the effect of the autonomic nervous system on heart function. A computer ECG was recorded with three standard leads (I, II, III) in subjects who were sitting and breathing normally for 5 min; the Poly-Spectrum ECG system (Neurosoft LLC, Ivanovo, Russia) was used [25, 26]. ECG readings taken in lead II were used for data analysis. The notations for the indices of spectral HRV analysis chosen in the study are in accordance with international standards for assessing the HRV based on predictive values [27]. The experimental setup is shown in Fig. 1.

Spectral analysis yields an objective quantitative estimate for the functional state of HRV regulation systems by the following characteristics:

total power of the neurohumoral regulation spectrum, TP, $(\mathrm{ms})^2$;

contribution of fast high-frequency oscillations to the spectrum, HF, 16–0.4 Hz, characterizing the activity of the parasympathetic department of the autonomic nervous system (ANS);

contribution of slow low-frequency oscillations, LF, characterizing the activity of the sympathetic department;

contribution of very low frequency oscillations, VLF, less than 0.05 Hz, characterizing the humoral, metabolic and cerebral ergotropic effects on heart rate modulation.

The LF/HF ratio is used to assess the sympathetic-parasympathetic balance of ANS function at the beginning and at the end of the experiment.

The following HRV indicators were used to assess the sympathetic-parasympathetic balance:

standard deviation of *RR* intervals (SDNN);

mode amplitude (MA);

vegetative equilibrium index (VEI) [26].

Additionally, blood pressure indicators were measured with an electric tonometer, and the Kйrdц Vegetative Index (KVI) was calculated.

The subjects were asked to complete the Eysenck Personality Questionnaire (EPQ) to determine the levels of extraversion/introversion and neuroticism/stability.

Experimental procedure. Let us describe this procedure in detail. First, blood pressure was recorded for each volunteer. Next, an ECG was recorded for 5 min (300 s) for subsequent analysis of heart rate variability and determination of the dominant regulatory effect of sympathetic/parasympathetic ANS division at the beginning of the experiment. The subject was then asked to time an “individual (subjective) minute” using a special computer program, namely, press a key to indicate the beginning of a time interval, wait 60 s, observing subjective feelings, and mark the end of a time interval by pressing a key again. The subjects were allowed to choose any method for timing a minute, including counting silently, but the same method was to be used for repeating the test. The volunteers measured the “individual minute” twice; then they were exposed to blue light for 20 minutes (the wavelength was about

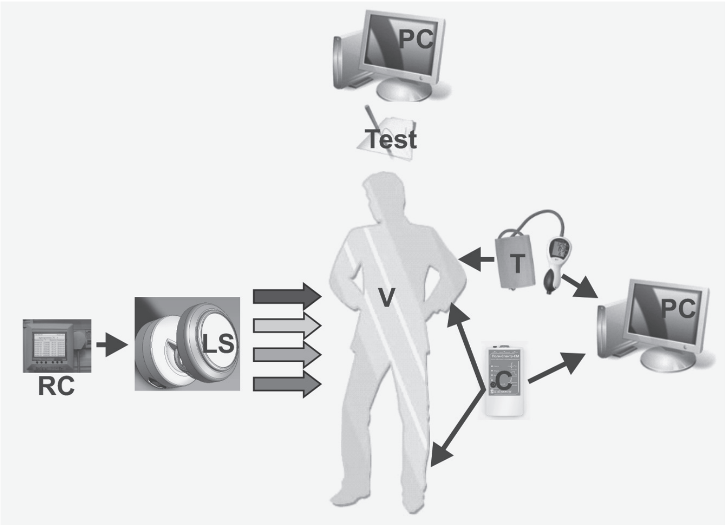

Fig. 1. General scheme of experimental setup for studying effect of blue light on time perception in subjects with different types of autonomic regulation:
remote control of luminaire RC, dynamically controlled light source LS, volunteer V, subjective minute test (Test), cardiograph C, tonometer T, personal computer PC

440–485 nm, the illuminance of the body was 150–200 lux). The subject was offered an Eysenck questionnaire to determine the levels of neuroticism during light exposure. The first three steps were repeated in reverse order after light exposure: the test for subjective minute, ECG recording for 5 minutes, measurement of blood pressure. The difference in the experiment for the control group was only that blue light was replaced with white daylight with a color temperature of 4,000 K, similar in duration and intensity of exposure.

The individual data obtained were statistically processed using methods of parametric statistics for calculating standard deviation and mean deviation. The significance of differences in the compared indices was found by Student's *t*-test.

Results and discussion

Exposure to blue light led to significant changes in the vegetative balance of the subjects' bodies. The total powers of the ECG spectrum and the vegetative equilibrium indices changed significantly compared to the background values. The individual variation of TP after exposure ranged from −91% to +130%, amounting to 45% on average in absolute value. The individual variation in VEI after exposure ranged from −68% to +128%, amounting to 43% on average in absolute value. However, both increases and decreases were observed, so the average value of these indicators after light exposure did not change considerably ($p > 0.05$).

Averaged TP values characterize the total activity of the autonomic effect on heart rhythm: activation of the vagus nerve leads to an increase in TP, while an increase in the activity of sympathetic ANS division causes the opposite effect [25]. It could be hypothesized that the increases and decreases observed are linked to different types of autonomic response. Based on this hypothesis, we formed two groups of subjects.

The average value of TP decreased significantly ($p < 0.05$) in volunteers of Group 1 (two males and nine females) after exposure to light; this indicated predominant activity of the parasympathetic division of the ANS at the beginning of the experiment and a shift in autonomic balance towards predominant sympathetic division of the ANS at the end of

Table 1

Comparison of light exposure effect on two groups of test subjects

Indicator	Parameter value			
	Group 1		Group 2	
	Before exposure	After exposure	Before exposure	After exposure
TP. (ms)^2	5043.6 ±2078.69 3845.5 ±2309.00	2539.6 ±1047.11 4340.8±٢٥٥٤,٣٦	3914.3 ±1660.90 4376.9±1826.69	5056.3 ±1321.22 3810.3±1767.47
LF/HF	3.70±2.80 4.10±2.67	5.20±3.96 4.90±2.55	5.50±2.42 5.70±2.28	3.50±2.02 4.30±1.62
SDNN. ms	61.30 ±15.16 57.70±17.90	49.50±9.79 62.50±18.20	61.10±13.59 63.30±14.61	68.30±7.96 60.70±15.39
MA. %	35.00±8.09 35.20±12.36	41.40±7.50 38.50±11.29	35.60±4.71 34.90±7.79	26.40±7.88 40.60±9.97
VEI. c.u.	92.80±32.43 151.20±98.14	149.30±61.58 117.00±٥٣,٠٠	123.60±39.96 130.60±84.33	56.80±18.04 149.60±92.76

Notes 1. Data on the spectral indicators for heart rhythm and pulse rate variation correspond to those given by Baevsky. 2. The statistical significance by Student's *t*-test is $p < 0.05$; 3. The upper and lower numbers in the cells of the table refer to exposure to blue and white light. respectively.

Notations: TP is the total spectral power of neurohumoral regulation. LF/HF is the ratio of low-frequency to high-frequency intensity. SDNN is the standard deviation of the *R R* intervals. MA is the mode amplitude. VEI is the vegetative equilibrium index.

the experiment.

Volunteers of Group 2 (four males and three females) exhibited the opposite scenario: the average value of TP slightly increased, pointing to a corresponding increase in the activity of the parasympathetic division of the ANS after exposure to light.

Other indicators characterizing the vegetative balance also varied by similar patterns but the magnitude of the shifts remained at the same level as the general trend.

Volunteers of Group 1 exhibited increased LF/HF ratios (intensity of low-frequency to high-frequency oscillations) decreased (with the significance of the differences $p = 0.07$) SDNN (ms), increased MA (%), and increased ($p < 0.05$) VEI (c.u.). All of these indicators reflect a shift in the autonomic balance towards predominant activity of the sympathetic division.

The indicators measured in the volunteers of Group 2 exhibited an opposite trend: the LF/HF ratios decreased, SDNN (ms) increased, MA (%) decreased and VEI (cu). decreased substantially ($p < 0.05$). This in turn, means that the autonomic balance is shifted towards predominant activity of the parasympathetic division of the ANS.

The indicators for which the statistical significance p is not given exhibit only a slight trend in this direction. The numerical values of all the described parameters are given in Table 1 (top numbers in the cells of the table).

The average value of an individual minute did not change in the entire sample after exposure to blue light. However, the two groups exhibited opposite variation trends. The change in the duration of the subjective minute after exposure to blue light can apparently be linked to predominant activity of sympathetic or parasympathetic division of the ANS at the beginning and end of the experiment. Group 1 (vegetative balance shifted toward predominant activity of the sympathetic division of the ANS after light exposure) exhibited a trend towards shorter subjective minutes, by 10 s on average (Table 2). The duration of the subjective minute remained virtually unchanged in the second group (predominant activity of the parasympathetic division of the ANS after light exposure) after light exposure. Notably, first group included all participants with above

Table 2

Variation of subjective minute length in Groups 1 and 2 before and after light exposure

Indicator	Parameter value	
	Group 1	Group 2
Age, years	22.00 ±1.60	22.30±2.12
Neroticism level, c.u.	14.00±3.67 13.80±4.04	9.40±2.49
Introversion/Extraversion level, c.u.	14.60±4.12 15.50±3.30	15.70±2.53
Length of subjective minute, s		
before exposure	65.80±16.96 60.80 ±15.04	60.60±9.63 65.10±8.63
after exposure	55.30±8.14 64.60±8.40	61.80±7.68 65.50±11.97

Notes 1. Top and bottom numbers in table cells correspond to exposure of subjects to blue and white light, respectively. A single value is given for coinciding numbers. 2. Group 1 consisted of two males and nine females, Group 2 of four males and three females (the data in Tables 1 and 2 correspond to the same groups).

average levels of neuroticism. It follows from these data that females were more sensitive to exposure, also exhibiting a tendency to higher levels of neuroticism (13.25 ± 3.21 versus 9.33 ± 2.78). The groups had only minor differences in extraversion/introversion.

The experiment was repeated with the same subjects with blue light replaced by white daylight. The subjects were divided into the same two groups. No noticeable changes in the vegetative balanced were observed at the end of the experiment, compared to the beginning (see Table 1, bottom numbers in the cells).

Analysis confirmed that the background indicators measured were stable. No statistically significant differences could be found between the selected HRV parameters of the subjects before light exposure between the first and repeated experiments.

No significant changes could be observed in the length of subjective minute after exposure to daylight in either the 1st or Group 2 (Table 2, bottom numbers in the cells).

The data obtained indicate that blue light had a pronounced stimulating effect at least for some of the subjects (Group 1), shifting the vegetative balance towards predominant sympathetic division of the ANS. This group exhibited a marked decrease in the duration of an individual minute (by 20.8%). This is consistent with the available data, describing increased function of the cerebral cortex [6] and increased levels of wakefulness [5, 8] upon exposure to blue light (~440–485 nm) through ganglion-specific parasympathetic effect of monochromatic blue light for this group, but also no stimulating effect combined with natural deterioration in the functional state of the subjects by the end of the experiment due to fatigue or monotony. Accepting this explanation, we can then logically assume that the stimulating effect of blue monochromatic light on Group 1 could be more pronounced than the experimental data indicate, since it helped overcome possible deterioration of the functional state of photosensitive retinal cells and suprachiasmatic nuclei of the hypothalamus. Our data also confirm that lighting characteristics can affect the parameters of heart rate variation [17, 18]. However, no significant changes could be observed in the average pulse rate as a result of exposure to blue light. This means that our data on variations in the duration of an individual minute in Group 1 cannot be explained by the hypothesis that the pulse rate serves as a possible internal "pacemaker" that sets the subjective speed of time [15, 16]. It can be assumed based on these data that some other physiological process acts as a natural internal "pacemaker", changing depending on the type of vegetative regulation. Blue light had no such effect on Group 2 of subjects. On the contrary, vegetative balance partially shifted toward predominant parasympathetic division of the ANS during the experiment. This result can be explained not only by the specific parasympathetic effect of monochromatic blue light for this group, but also by absence of stimulating effect combined with natural deterioration of the subjects' functional state by the end of the experiment due to fatigue or monotony. Accepting this explanation, we can then logically assume that the stimulating effect of blue monochromatic light on Group 1 could be more pronounced in Group 1 than experimental data indicate, since it helped overcome possible deterioration in the functional state.

Mixed results can also be explained by other factors that were not taken into account in this experiment, in particular, subjective emotional attitudes to blue light. Color preferences of adults depend both on the energy characteristics of the color and on the informational component of the color exposure. A preference towards three colors, blue, green and red, was found in adults [28]. Many people associate blue, the color of the sea and the sky, with feelings of tranquility, so the difference in response may be related different systems, cortical and subcortical, and the type of rearrangement of the activity of ANS divisions to their balance. A notable study [29] found that the type of vegetative regulation largely determines the body's response to exposure. The parameters of cardiac and cognitive functions for normotonic and sympathetic types shifted in the opposite direction after mental exertion (solving problems for 30 minutes) compared with the parasympathetic type. Further studies may experimentally confirm these hypotheses.

Conclusion

We have studied the effect of different lighting modes on individual perception of short time intervals. In particular, we have considered the effect of blue light, presumably through ganglionic melanopsin-containing retinal cells, on circadian rhythms governed by a functional system of the brain, an internal pacemaker. While multiple attempts to trace the effect of different endogenous biorhythms on perception of time were made earlier, the role of these biorhythms still remains largely unclear.

The data obtained indicate that the effect of light exposure on subjective perception of time duration is linked to an individual's initial state and personality characteristics: the level of neuroticism and the ratio of sympathetic-parasympathetic balance. These parameters determine the direction of vegetative shifts; in view of this, we found two groups with different types of response to blue light. No changes were observed if blue light was replaced with white daylight, which confirms that the specific region of the spectrum of visible (~460–485 nm) has a particularly strong effect. Blue light stimulated predominant activity the sympathetic division of the ANS in eleven out of eighteen people. The same subjects showed a tendency towards shorter subjective minutes after exposure to light. The shift in the vegetative balance in the other seven was in the opposite direction without changes in measuring the minute interval.

Blue light was not found to have a statistically significant effect on time perception in the overall sample. Some of the subjects (Group 1) exhibited a tendency towards shorter subjective minutes (by about 10 s) after exposure to blue light and a shift in the vegetative balance towards predominant activity of the sympathetic division of the ANS. This group included all subjects with a high level of neuroticism. A smaller part of the volunteers (Group 2) exhibited no changed in the duration of the subjective minute after exposure to blue light, while the vegetative balance shifted towards predominant activity of the parasympathetic division of the ANS. These effects were not observed upon exposure to white light with the same duration and intensity.

Key findings and conclusions

1. We have experimentally proved for the first time that exposure of human subjects to blue light leads to significant changes in vegetative balance. For example, the total power of the spectrum and the vegetative equilibrium index VEI changed by 45% in magnitude on average, compared with the background values.

2. Different orientations of the changes in vegetative balance are associated with different types of vegetative response. The activity of the parasympathetic division of ANS in highly neurotic subjects shifted towards the sympathetic division after exposure to blue light. An opposite situation was observed in subjects with low levels of neuroticism.

3. Increased cortical tone and increased levels of wakefulness exhibited by some of the subjects are consistent with the data given in literature on the effect of the blue component of the visible spectrum (~440–485 nm) through photosensitive retinal ganglion cells and suprachiasmatic nuclei of the hypothalamus.

4. The experimental data obtained confirm that exposure to blue light may affect heart rate variability; additionally, we have found that the 440–485 nm region of the visible spectrum has a particularly pronounced effect (see 3).

5. The experimental data confirm that restrictions should be imposed on night lighting (in particular, phosphor LEDs emitting cold white light with a strong blue peak in the range of 446–477 nm) [24], with a substantial fraction of wavelengths below 540 nm. The reason for these restrictions is that such light is highly bioactive [30].

Replacing 460 nm light causing "light pollution" of the environment [31] with 490 nm light, also adding 635 nm light, seems to be the most reasonable solution for LED sources. The important function of the 635 nm light source is in compensating for the deficiency in red light [32].

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