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A multichannel LED-based lighting approach to improve color discrimination for low vision people

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Abstract

The population of low vision people increases continuously with the acceleration of aging society. As reported by the World Health Organization (WHO), most of this population is over the age of 50 years and 81% were not concerned by any visual problem before. A visual deficiency can dramatically affect the quality of life and challenge the preservation of a safe independent existence.

This study presents a LED-based lighting approach to assist people facing an age-related visual impairment. The research procedure is based on a psychophysical experiment consisting in the ordering of standard color samples. Volunteers wearing low vision simulation goggles performed such an ordering under different illumination conditions produced by a 24-channel multispectral lighting system. A filtering technique using color rendering indices coupled with color measurements allowed to objectively determine the lighting conditions providing the best scores in terms of color discrimination.

Experimental results demonstrated that white light obtained by a special mixing of three selected channels can improve the color perception of low vision people in comparison to white LEDs nowadays available on the market for general lighting. Even if additional studies are required to go further, these first results give hope for the design of smart lighting devices that might adapt to the visual needs of the visually impaired.

Introduction

The number of people over the age of 65 years will double by 2050 [63]. Such an aging trend may cause many social and health problems. It is for example one of the main factors of visual impairments [61, 65] which are likely to triple in the next 10 years according to the last estimates [7].

According to the International Classification of Diseases 11th Revision published in 2018 by the World Health Organization (WHO), a visual acuity worse than 3/60 defines "blindness" [66]. Even though there is no standard international definition, in most scientific papers and professional studies, "low vision" is used to refer to visual impairments resulting in visual acuity between 6/18 to 3/60, as shown in Figure 1 [14, 38].

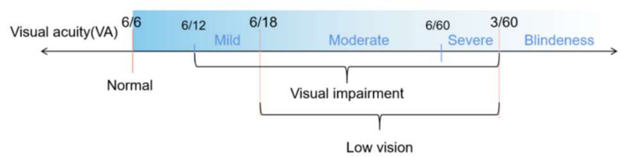


Figure 1. Range of visual acuities referring to "low vision"

At least 2.2 billion people worldwide are suffering from a visual deficiency. A majority of them are over the age of 50 years and are referred as low vision people [66]. As clearly shown in Figure 2, visual disorders increase sharply with age though the age-standardized prevalence of blindness and severe visual impairment has declined in recent decades.

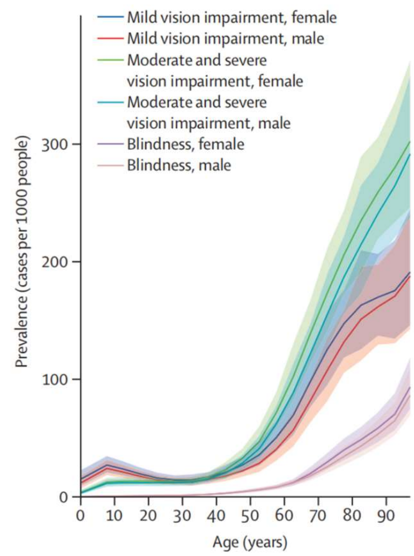


Figure 2. Prevalence of vision impairment in 2020 [8]

The predictable aging tendency and the enormous group of low vision people in the world not only pose a huge financial burden for the entire society but also affect the lives of individuals. In addition to the physical limitations that affect their daily activity and productivity, psychological problems, social isolation, and reduced participation in society also have an impact, which can severely affect the quality of life [45, 55, 56, 60]. Moreover, it can be impossible to maintain independence in a safe manner which is a predominant concern of older adults [36].

Therefore, it becomes both an ethical responsibility and a public health imperative to urgently assist visually impaired people in their everyday life. This study is in line with such a challenging goal. It investigates how the Spectral Power Distribution (SPD) provided by a multichannel LED lighting system could be optimized to improve the color discrimination for low vision people. The underlying idea is to use light to facilitate object detection and recognition in low vision situations to assist visually impaired people in their daily activities. The approach is completely new and provides a break in regards to the existing visual aids by simplifying the vision rehabilitation, the mobility and the socioeconomic independence of the population living with vision impairment.

Related works and proposed approach

A variety of assistive approaches for the visually impaired have been proposed in the last decade. They can be divided into two families with regard to the type of feedback they provide. A first family corresponds to the assistance methods with non-visual feedback which means that information is transformed and provided to the user in another form than visual, such as sound or vibration. These aids mainly help people with severe visual impairments and blindness, as they have little or no residual vision. A second family corresponds to the visual feedback assistance methods that can enhance visual information. These techniques are especially helpful for people who have a residual vision still functional.

Non-visual feedback assistance

Users with severe visual deficiencies need additional cues to avoid obstacles or to collect object information. Sensor-based devices can for example help people to evaluate the distance of obstacles.

Sensor-based smart canes

Canes are commonly used by visually impaired people as a primary mobility aid that can be especially useful outdoors. A traditional cane can help low vision people to detect short distance obstacles and ground irregularities. However, canes are insufficient when potential collisions are on the user's side or above the user's waistline.

Various electronics-embedded smart canes have been launched to reduce these limitations. Most Electronic Travel Aids (ETA) use different sensors, such as ultrasonic and infrared sensors, to evaluate distances in order to improve spatial perception [30]. Some handheld devices retain the shape of a cane that integrates the controller, micromotor, battery and sensors [5, 23, 31, 46]. Modified versions may have more functions by adding external components such as wheels and tactile indicators [32, 53, 57].

However, the large size and the limited detection area may cause inconvenience when used in real life [62]. In addition, most of the above ETA present a major drawback: except from the distance of the obstacle, they cannot provide the size, movement status and other information [27]. Moreover, those devices require users to scan the walkway continuously to find their path.

Camera-based assistant devices

With the high speed development of image processing and computer technologies, cameras can be introduced into the ETA devices to provide additional information on obstacles. Usually one or several digital cameras are coupled to compute and process visual information, next to provide feedback to users [30]. The feedback can be vibration [2, 69], electro-tactile [40] or acoustic information, including audio signal [1, 4, 42] and stereo sound [34, 68]. Some systems can also perform object classification or recognition based on the captured image information and provide various feedback to the user [2, 43]. In addition, some aids with incorporated Global Positioning System (GPS) can provide landmarks for better obstacle avoidance and navigation function [16, 33, 41].

Visual feedback assistance

Visual feedback assistance can be proposed to visually impaired people who are still able to leverage their residual vision. This kind of assistance is generally based on vision enhancement techniques.

Augmented Reality glasses

Augmented Reality (AR) is a subset of Mixed Reality (MR) which connects the real environment and the virtual world [44]. With an AR head-mounted set, an user can see virtual objects integrated with the real world. Thanks to the real-time interaction characteristic of AR [3], there is an opportunity to utilize an AR headset to assist visually impaired people [11]. There are various ways to improve vision through a Head Mounted Device (HMD) as, for example, by using magnification [58, 59], edge enhancement [22, 29], contrast enhancement [17], or by combining different functions such as brightness and/or color adjustment [25, 70].

Most of these approaches can benefit to low vision people thanks to an increasing of their visual performance. However, there are unfortunately still some shortcomings.

Unlike the human eye, which can accommodate with the control of the thickness of its own lens by changing the stretching and contraction of the ciliary muscle, AR systems can only help either near or distance vision [24].

In addition, users need to spend time to learn how to manipulate these devices and how to adjust them. It is also important to keep in mind that older adults make up a large proportion of the visually impaired population [66]. Thus, difficulties and motivation of the elderly to learn how to use a new digital device has clearly to be considered [49]. The research of Culham *et al*. [15] concluded that older patients would be less likely to benefit from HMD because of their relatively low familiarity with technology. Morover, adaptability is one of the most important considerations when evaluating a device [21]. Since most HMDs are relatively heavy, this may decrease users' willingness to use them [50].

Although some studies use commercial HMDs (that are already on the market [29, 58, 59]), such devices are still expensive and not affordable for many people [28, 54]. The lower use of these HMDs would indirectly affect social acceptance [39].

Lighting assistant devices

Unlike a wearable device like HMD, a less bulky method is to use custom lighting. It is necessary to adapt and to tailor light features because lighting needs of the visually impaired people differ from those of the normally sighted [51].

Many recent studies have demonstrated that the illuminance and the color temperature can affect the visual performance of low vision people [19, 26, 64]. It has also been shown that their quality of life can be improved by adapting lighting conditions [6, 10].

Sa-Ngadsup *et al*. [52] proposed a lighting edge enhancement method for independent navigation of visually impaired people. A psychophysical experiment on autonomous mobility was conducted. Three distinct types of visual impairments were considered in the experiment. Results showed that the proposed lighting system has the potential to benefit people who suffer from tunnel vision and central scotoma.

A recent work of Katemake *et al*. [35] involves three sub-experiments. In complement to the illuminance level, the Correlated Color Temperature (CCT) and edge enhancement, a third sub-experiment focused on color contrast enhancement. This work demonstrated that manipulating the light spectrum to increase color contrast can satisfactorily improve mobility of cataract patients. Such a result allows us to hypothesize that adjusting the SPD of the light could be an approach to facilitate visual perception of people with visual impairments and to improve their daily mobility and independence, especially in an indoor environment.

Unlike the other traditional visual assistive methods, such as smart canes or some recent solutions based on Augmented Reality (AR) glasses, the lighting-based approach offers many advantages as a visual aid:

- the world representation of low vision people is not changed,
- the field-of-view is unlimited,
- no device has to be worn which preserves natural movements,
- both hands are free to perform more easily daily activities,
- the lighting conditions can be adapted to the visual environment as well as to the visual deficiency, reducing by the way the rehabilitation constraints.

Moreover, the residual vision is still stimulated, which is highly recommended by all professionals working in the field of low vision. By exploiting the color capabilities and the tuning range of LED-based lighting systems, important elements are available to develop a low vision aid which can be personalized and set up for different visual impairments.

Experimental protocol

Color is known to be involved in object detection and identification [9, 18]. The greater the color difference, the greater the likelihood that both normally sighted and visually impaired people will be able to discriminate objects in a real scene. Color differences can be enhanced by changing light SPD. Tunable multichannel LED devices present the advantage of being able to flexibly adjust the SPD by varying the intensity of the individual channels. Moreover, the light features can be adapted to the specific requirements of visual needs of visually impaired people [13].

A set of experiments targeting a specific type of visual impairment - central loss of vision - was devised. A central loss of vision is one of the main symptoms of AMD (Age-related Macular Degeneration). A 24-channel LED lighting system was used to optimize the mixed light spectrum and to increase color contrast in order to improve in terms of color discrimination the visual performance of people suffering from a visual impairment.

The proposed experiment was organized in two phases designed to address two connected questions: “What is the ideal LED light mixing for color discrimination?” and “How does the optimized LED light mixture is effective for color differentiation?”. Figure 3 depicts the general flowchart of the experimental protocol.

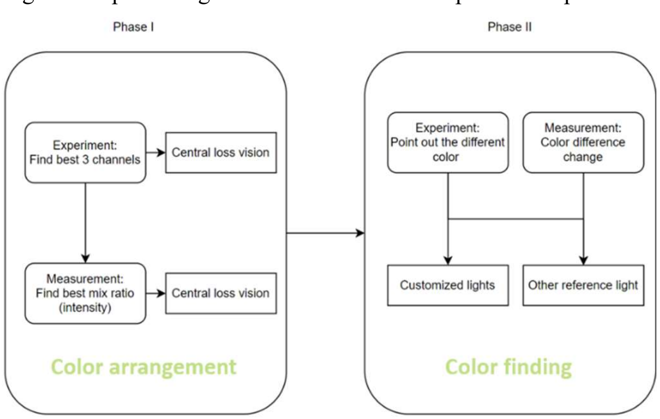


Figure 3. General flowchart of the experimental protocol

Phase I

There are two primary parameters to set up in order to design an ideal light LED mixture: selecting the channels and adjusting their respective intensities.

Assuming that it should be used by low vision people as a daily illuminator, the expected optimized light should be white. Due to the narrow spectrum of LEDs, more than two channels are then required to generate white light from a color mixing approach [47].

On the market, multichannel white LEDs are generally based on three types of junctions that emit red, green and blue lights. It is the result of a selection that strikes a balance between cost, color rendering and luminous efficiency. However, there is no standard specification for the peak wavelength, Full Width at Half Maximum (FWHM), etc. of the three channels of lights.

Relatedly, the number of channels was limited to 3 in this pilot experiment. The goal was to identify three new channels that could improve the color discrimination performance of individuals with specific visual impairments.

Apparatus and experiment setup

The lighting system used in this experiment is a 24-channel LED lighting system from Telelumen company (United States). It includes both visible and invisible channels, ranging from Ultraviolet (UV) to Infrared (IR). The SPD of every channel of the lighting unit is shown in Figure 5.

Not all channels were appropriate for the experiment. For example, as UV radiation may provide a fluorescent effect and be harmful to human eyes if overexposed, UV channels were not used. Two IR channels were also rejected as they are not involved in color perception. In addition, the illuminance on the experimental area was an essential parameter. Figure 4 shows an overview of the experimental setup. The main observation area was a 45cm diameter circle located on the horizontal surface of a table. This area was uniformly illuminated by a diffuse light producing an illuminance of 500lux to respect the minimum level recommended by European standards [37]. Thirteen channels of the lighting unit met these constraints and were thus selected.

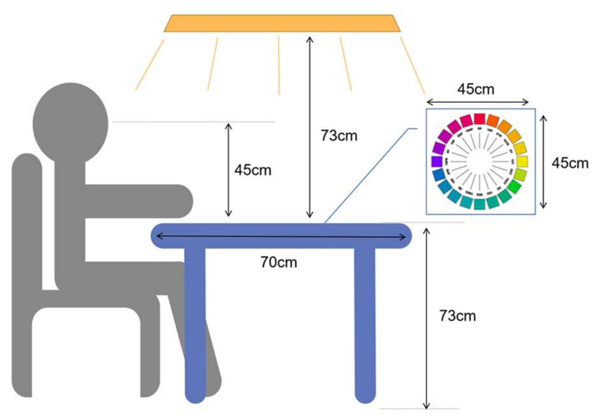


Figure 4. Experiment setup

The experiment was carried out in a dark room with black walls, black floor and furnished with a neutral grey table. There were two windows with black opaque curtains blocking the light from outside to ensure that only the experimental LED light was used for observation. The average illuminance in the dark room was lower than 1lux.

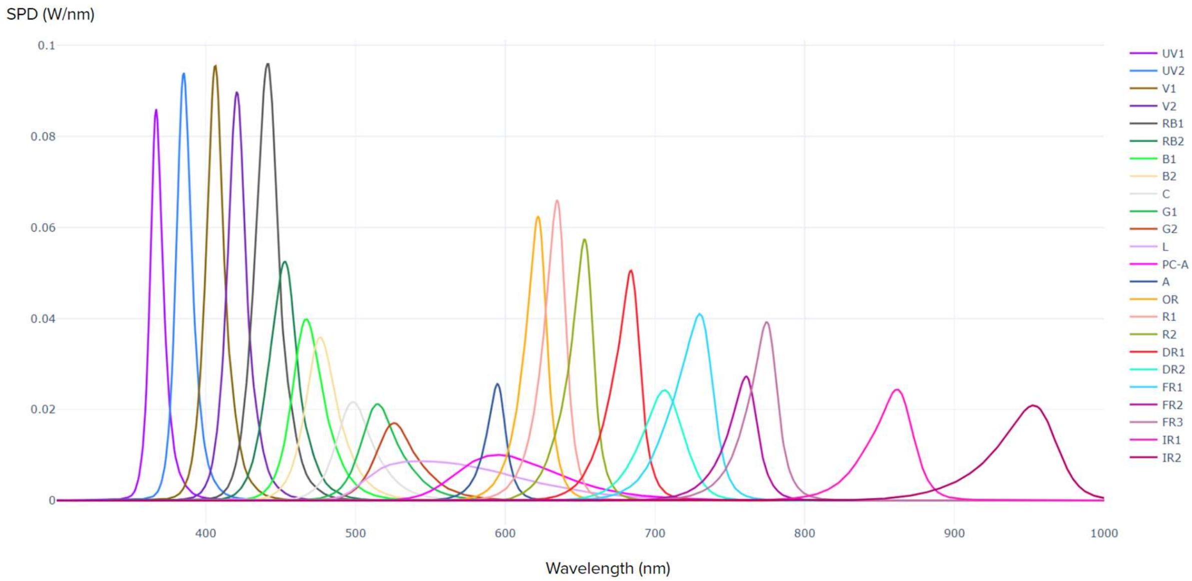


Figure 5. Spectral power distributions of the 24 channels of the LED lighting unit used in the experiment

Participants and experiment procedure

The psychophysical experiment of phase I consisted in performing an arrangement of 20 color samples using each of the 13 selected light channels that were switched on one after the other. After analyzing the color arrangement results obtained from a panel of observers, the next stage consisted in selecting groups of three channels that produced white light when combined together and that had a maximum "color discrimination range".

Sixteen naïve volunteers (5 females, 11 males) from 10 nationalities with ages ranging from 22 to 42 years participated in this psychophysical experiment. Before performing the proposed visual task, participants were invited to complete the Farnsworth-Munsell dichotomous D-15 test to be sure that all of them had no colorblindness. All volunteers had also normal or corrected-to-normal visual acuity.

Before the experiment began, each participant was assigned a central scotoma simulation goggle (from Fork in the Road, United States) with a Visual Acuity (VA) of 6/60 and was assigned 1-2 minutes to adjust. All the volunteers were asked to wear these goggles for the duration of the experiment.

Figure 6 shows the 20 selected color samples from the Munsell color system, all with an identical chroma of 6 and a value of 6, but different hues. All color samples were 3×3cm squares with matt finish. Among these 20 hues, 5 primary hues (5R, 5Y, 5G, 5B and 5P) were used as reference samples put in fixed positions. These positions are labelled with black dots in Figure 6. Participants were asked to arrange the other 15 samples relatively to the 5 reference samples. To help the observers, little dot markers were placed on the table to remind where to place the color samples. Volunteers were also informed that the reference color samples could not be moved, that they had to sort out all the samples at their disposal, and that it was only possible to place 3 colors between each pair of reference samples.

There was no time limit for the task but participants received a reminder if they spent more than 8 minutes for an arrangement. After an observer completed the arrangement, the lighting system switched to a same 6500K daylight setting. Moreover, each color sample was encoded with a number from 1 to 20 clockwise from 10R 6/6 in order to record more easily and more efficiently the sorting results. For the sake of clarity, these numbers appear here in Figure 6 but they were on the back of the samples during the experiment to avoid participants seeing them during manipulations. Each color arrangement was recorded as the order of the sample numbers.

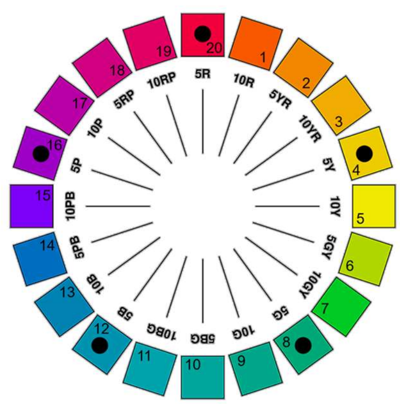


Figure 6. The 20 hues from the Munsell color system (value 6 / chroma 6) used in phase I of the psychophysical experiment

Since 13 channels were selected, the color arrangement task was repeated 13 times in total for each volunteer. Considering that lengthy trials would affect the reliability of the results and cause fatigue to the observers, the experiment was split into two sessions of approximately 45 minutes each. The configuration and the protocol of each session remained the same.

Data acquisition and analysis

The outcome of the arrangement tasks employed the similar scoring method as the Farnsworth-Munsell 100-Hue Test which is calculated by the sum of differences of adjacent numbers [20]. The higher the error score, the worse the color discrimination. Conversely, the lower the error score, the better the color discrimination. As there were individual differences between participants when they performed the arrangements, each observation score was normalized before summing up the data collected under each channel. This ensures a similar weight to each observation and it decreases the impact of extreme values.

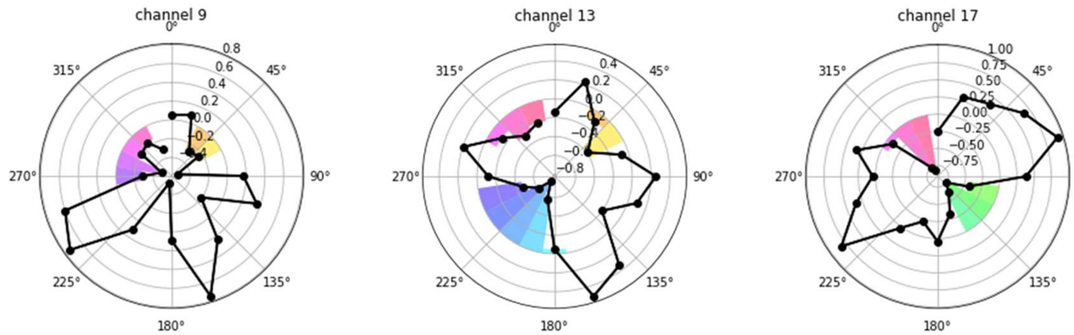
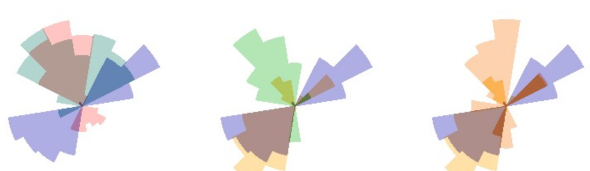


Figure 7. Examples of color arrangement scores under different lighting conditions displayed in a hue-chroma diagram with polar coordinates

Figure 7 shows examples of results for 3 different channels. Plotting rules are the same as those used in the Farnsworth-Munsell 100-Hue Test. Color samples used in the experiment are displayed in a hue-chroma diagram with polar coordinates. Solid lines with dots represent the average score for the mentioned channel. Sectors displayed in false colors highlight low error scores indicating that color discrimination was good in that range of hues under the current illumination. The "pass" threshold that determines whether or not the color discrimination was accurate was set to zero and the "pass range" was defined such as the current and neighboring errors were all below the threshold. Therefore, the "pass range" indicates the hue range of good color discrimination of each channel.

By collecting the absolute values of each channel's "pass range" and merging them together, the whole "pass range" of the 286 distinct possible combinations ($_{13}C_3$) can be computed. The sector's area reflects how good the score is because it is inversely connected to the error values. Then, to select the most appropriate combination(s), the mixture(s) with a wider range and a larger "pass range" might be able to offer a good color discrimination. Another crucial criterion is that the selected three channels must be able to produce near-white light, i.e. the color of light should be near the Planckian locus. From such criteria, 3 distinct combinations were selected. They correspond to the combination of channels 6-10-13, 6-11-16, and 6-12-16 which are shown in Figure 8.



a. b. c.

Figure 8. The 3 combinations of channels derived from the results of the color arrangement test. a. channels 6, 10 and 13; b. channels 6, 11 and 16; c. channels 6, 12 and 16

Determination of mix ratio

Following the selection of channels, their respective intensities need to be determined. Numerous metrics may be used but, in the context of low vision, three main characteristics have to be considered: a high color rendering fidelity, a wide color gamut area and a low D_{uv}. A high color rendering fidelity means that the lighting allows the colors to appear in a similar way to what natural light would do. A high color gamut indicates that the lighting can increase color saturation which can improve color contrasts. A low D_{uv} means that the lighting color coordinates are close to the Planckian locus making it suitable for daily use.

In a first stage, the intensities of the three selected channels were adjusted from 0.1 to 1 in increments of 0.1 which results in 10×10×10 = 1000 different configurations. These 1000 lighting configurations were played sequentially and a spectroradiometer Spectraval 1511 (from JETI, Germany) was used to measure a collection of data including the Color Rendering Index (CRI), the color gamut index (Rg), the Color Quality Scale (CQS), the D_{uv} and the CIE 2017 color fidelity index. In this coarse adjustment stage, the objective was to filter out invalid lights. For that, the CRI value is an essential and straightforward indicator. If the light has no CRI or if the CRI value is too low, it is not suitable for the target application.

On the basis of the set of measures, all lighting configurations without CRI values or with a CRI lower than 30 were rejected. In addition, all lighting configurations having a Rg < 100 were also rejected because the color gamut index better reflects the observer's performance on the Farnsworth-Munsell 100 Hue test than the CRI [48]. Then, remaining lights were classified in a ranking list according to their CQS values.

In a second stage, the intensity value range of each channel was narrowed down from the top 30 values of the ranking list. With this restricted intensity range, a new increment was set to 0.05 in order to refine the first measures. The same measurement process as the one used for the coarse adjustment step was performed.

There are no existing relation for scoring different lightings or standard to determine the most appropriate light features in the context of low vision. To avoid mononumerosis, such a relation should have a wide range of relevant and representative parameters. As previously stated, the color rendering, the color gamut area and the D_{uv} are the three most important parameters in the framework of this study. Then, relation (1) defines a scoring method with a weight of 50% for color fidelity, 50% for color gamut area, and a penalty for high D_{uv}.

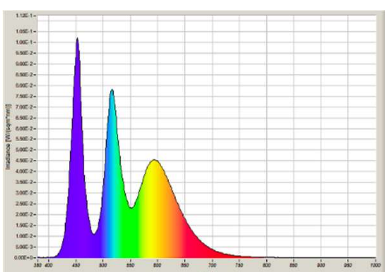
$$\text{Score} = 0.3\times Q_a + 0.5\times R_g + 0.1\times R_f + 0.1 \times \text{CIE2017 } R_f - 100\times D_{uv} \quad (1)$$

The 50% of color fidelity comes from the definitions of CQS, TM30-18 color fidelity index and CIE 2017 color fidelity index. The CRI is not included in this relation because CIE Technical Report 177:2007 [12] argues that the CRI is inapplicable for predicting the color rendering rank order of light sources when white LEDs are considered.

Three lighting configurations having the 3 highest scores derived from relation (1) were finally selected. In the following, *L1*, *L2* and *L3* refer specifically to these 3 optimized lights. Table 1 presents the main features of the 3 selected LED light mixtures when Figure 9 shows their respective SPDs. Each of the 3 selected combinations of 3 channels meet at least two of the three criteria: high color fidelity index, high color gamut area and low D_{uv}.

Table 1: Characteristics of the selected combinations of 3 channels

	L1	*L2*	*L3*
Channels	6 – 10 – 13	6 – 11 – 16	6 – 12 – 16
Intensity	0.3 – 0.6 – 0.7	0.25 – 0.9 – 0.45	0.225 – 0.675 – 0.36
CCT	6707K	5279K	3077K
D_{uv}	0.0020	-0.0016	-0.292
TM-30-18 R_g	104	127	121
CRI	93	43	75
CIE R_f	90	67	80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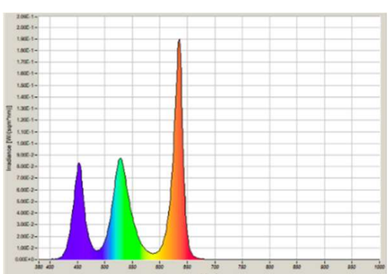
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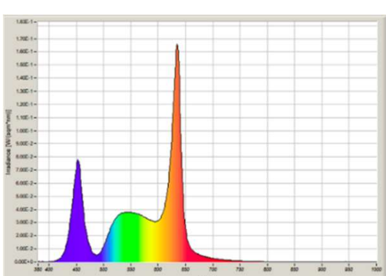
c.

Figure 9. Spectral power distributions of lights L1 (a), L2 (b) and L3 (c)

Phase II

Phase II of the experimental protocol aims to validate the lighting combinations *L1*, *L2* and *L3* selected in phase I. The validation process was based both on a second psychophysical experiment and on color difference measurements. The goal was to check if the selected combinations of light were able to improve color discrimination in order to visually assist patients with central scotoma (see Figure 3).

Apparatus and experiment setup

In addition to *L1*, *L2* and *L3* provided by the 24-channel LED lighting system from Telelumen, a white LED unit (LFL-360-SW from CCS, Japan) was used as a reference. This lighting unit is a rectangular LED panel that emits diffuse white light distributed uniformly. It is manufactured with phosphor converted white LEDs similar as those commonly used for indoor lighting. The illuminance of the lighting system was adjusted to the same value as the 3 other lights. In the following, *LW* specifically refers to this white LED device.

The second psychophysical experiment was conducted in the same place as the one of phase I. Observation conditions remained unchanged as well as the illuminance of all the lights set up to 500lux which corresponds to the recommended standard for office areas according to the European Commission's Premium Light Pro project [37].

Participants and experiment procedure

This experiment involved 15 volunteers (11 males and 4 females) from 10 different nationalities with an average age of 24 ± 3 years. All participants had normal or corrected-to-normal VA and had no color blindness. During the experiment, observers wear the same central scotoma simulation goggles (from Fork in the Road, United States) with VA of 6/60 as those used in phase I.

Eight panels composed of 24 color samples from the Natural Color System (NCS) were used. Each panel was a 260×260mm square with a neutral grey frame. Color samples having a same size of 30×30mm were organized on a 5×5 grid. There were 23 samples with the same color, 1 test sample with a different color and no color sample at the center. Figure 10 depicts the structure of each panel (the test sample is marked with a blue hexagonal star). The color difference between the reference samples and the test sample was chosen to be not too large nor too small. More precisely, the range of CIEDE2000 values was between 1.5 and 3.5.

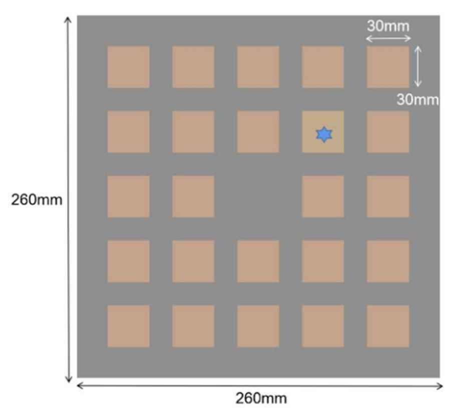

Figure 10. Structure of experimental panels. The blue star is here to identify the test color sample

Figure 11 shows the selection of the color samples for the 8 experimental panels. Reference colors were the four primary colors and four inter-colors of the NCS. Test colors were chosen relatively to the hue proximity of the reference colors. Sample B50G was an exception since the color difference between nearby colors and the reference was insufficient. Reference and test colors had the same saturation and lightness which were close to the chroma and to the value of the Munsell color system samples used in phase I.

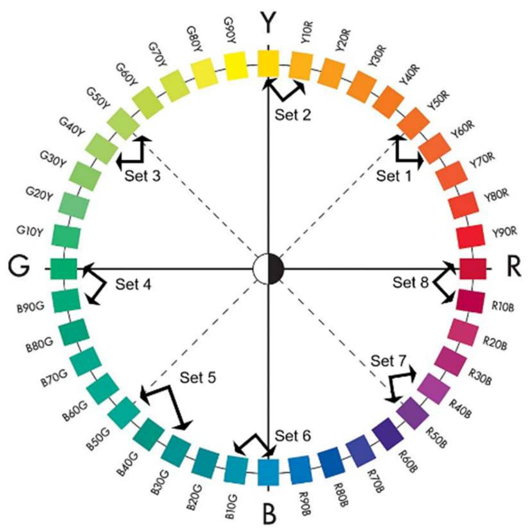

Figure 11. Color sample selection from the Natural Color System (NCS)

During the experiment, participants were given one minute to adapt to the current light. They were then instructed to identify as quickly as possible the patch having a different color from the others. Panels were presented in a random orientation and in a random order. Identification time was recorded for each panel under each lighting conditions. If a participant identified the correct test color sample, the result was recorded as "True" and the associate time was also noted. If an observer chose an incorrect sample or was unable to select any sample within 90 seconds, the result was recorded as "False". Participants were unaware of the accuracy of their responses until the experiment was entirely completed.

This identification session was repeated four times in a random order under *L1*, *L2*, *L3* and *LW*. The duration of the total experiment for one participant was 35 minutes on average. At the end of the experiment, observers were also interviewed about their subjective perception, visual feelings and preferences for each light.

In addition to the psychophysical experiment, color differences (CIEDDE2000) under the different lighting conditions were measured. Measurements were performed in a room with a background illumination less than 1lux. All the light combinations were set up to provide the same luminance of 500cd.m^{-2}. A Spectraval 1511 spectroradiometer (from JETI, Germany) was used at the same viewing angle as the observer to measure the XYZ values. The CIEDE2000 color differences were then calculated with MATLAB Colour Engineering Toolbox.

Results

Success rates derived from the responses of the 15 participants who observed the 8 panels under 4 different lighting conditions are presented in Table 2. Values correspond to the number of correct identifications followed by the correct rate in brackets.

Table 2: Success rates under the four lighting conditions

Panel	*L1*	*L2*	*L3*	*LW*	overall
set1	**9 (60.00%)**	8 (53.33%)	**9 (60.00%)**	3 (20.00%)	29 (48.33%)
set2	**15 (100.00%)**	**15 (100.00%)**	14 (93.33%)	14 (93.33%)	58 (96.67%)
set3	9 (60.00%)	**15 (100.00%)**	**15 (100.00%)**	12 (80.00%)	51 (85.00%)
set4	8 (53.33%)	4 (26.67%)	2 (13.33%)	**7 (46.67%)**	21 (35.00%)
set5	6 (40.00%)	**11 (73.33%)**	5 (33.33%)	6 (40.00%)	28 (46.67%)
set6	**14 (93.33%)**	**14 (93.33%)**	14 (93.33%)	10(66.67%)	52 (86.67%)
set7	13 (86.67%)	**15 (100.00%)**	**15 (100.00%)**	**15 (100.00%)**	58 (96.67%)
set8	**3 (20.00%)**	2 (13.33%)	2 (13.33%)	2 (13.33%)	9 (15.00%)
Sum	77 (64.17%)	**84 (70.00%)**	76 (63.33%)	69(57.50%)	306 (63.75%)

It clearly appears that *L2* has the highest score while *LW* has the lowest one. The success rates of the other two lights are similar. Results also show that the number of correct identifications can be quite different for a same panel. For instance, 11 observers correctly identified the test color sample of panel 5 under *L2* when only 5 participants were able to see it under *L3*. The overall correct rates range from 15% to more than 95%. Such a wide range can be partly explained by color differences between the test and the reference samples that were not identical for all panels (see Table 3).

Completion time is another important parameter in this kind of psychophysical experiment. For correct identifications, a shorter response time indicates that the participant was able to distinguish the test sample at a glance. A longer response time is associated with a slower and more detailed observation as well as with a greater uncertainty. To verify this, a two-way independent Analysis of Variance (ANOVA) was performed. Figure 12 shows box plots of the completion times for the correct identifications. Most of the responses were given within 30 seconds, except for very few extreme values. Substantial disparities between the panels under the different lighting conditions can also be observed.

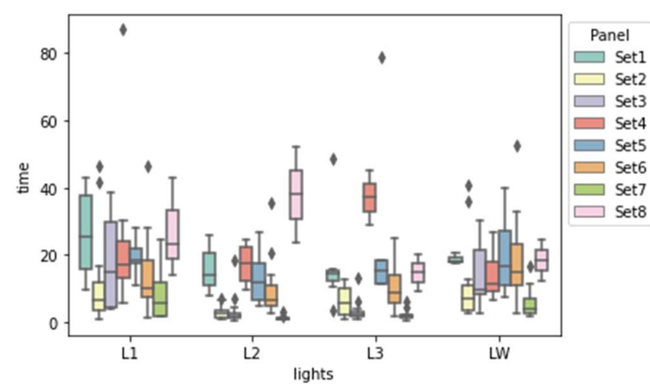

Figure 12. ANOVA of response times (in seconds) for the 8 sets of panels under the 4 lighting conditions L1, L2, L3 and LW

Table 3 presents the CIEDE2000 color differences measured between the test and the reference samples of each panel under the 4 lighting conditions. These color differences are also given for illuminant D65. The highest color differences are displayed in a bold font. Values in brackets correspond to the differences between the CIEDE2000 values obtained with illuminant D65 and those measured under the real experimental light combinations. Positive values indicate that the color differences increase and vice versa.

According to the measures, each of the four lighting conditions induced a higher color difference with regard to D65 for at least one panel. In addition, *L2* provided the largest number of maximum color differences. This LED light combination enhanced color differences for panels 5, 6 and 7, which is consistent with the results of the psychophysical experiment.

Table 3: Color differences measured between the test and the reference samples under the four lighting conditions compared to illuminant D65

Panel	D65	*L1*	*L2*	*L3*	*LW*
Set1	2.7946	2.6953(-0.0993)	2.2883(-0.5063)	2.7493(-0.0453)	**2.9639**(+0.1692)
Set2	2.9986	3.4887(+0.4901)	**4.6879**(+1.6893)	2.6384(-0.3602)	2.5359(-0.4627)
Set3	3.2805	3.1282(-0.1523)	**6.0754**(+2.7949)	5.2157(+1.9352)	3.7810(+0.5005)
Set4	2.4633	**2.4238**(-0.0395)	2.0382(-0.4251)	2.3747(-0.0886)	2.3946(-0.0687)
Set5	2.5414	2.3497(-0.1917)	**2.4877**(-0.0537)	1.8975(-0.6439)	1.9417(-0.5997)
Set6	3.6206	3.8480(+0.2274)	**4.2142**(+0.5936)	3.3777(-0.2429)	3.2127(-0.4079)
Set7	3.9066	3.4724(-0.4342)	**6.7867**(+2.8801)	6.2823(+2.3757)	3.3993(-0.5073)
Set8	1.6197	1.6628(+0.0431)	1.6903 (+0.0706)	**1.7297**(+0.1101)	1.5729 (-0.0468)

Figure 13 summarizes in a pie chart the participants' lighting preferences derived from their personal interviews after completing the experiment of phase II. More than 65% of the volunteers preferred *L1* and *L2*. The most common reason given by the observers was the colors of the light and of the samples appeared natural. Only one participant expressed a preference for *LW* and two for *L3*. It is important to note that there does not appear to be a correlation between the illumination preferences and the correctness of the color identification. However, we can suppose that the smoothness of the experiment could influence the final observer's preference to some extent.

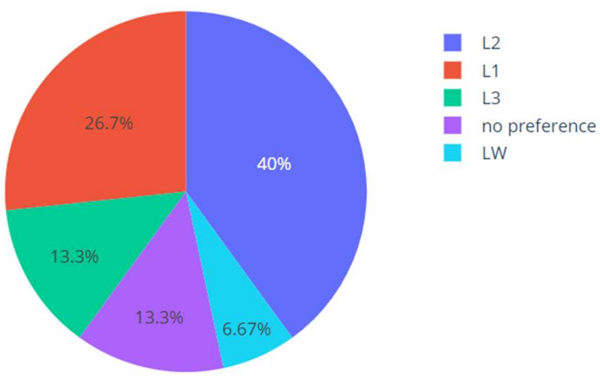

Figure 13. Lighting preferences from participants

Discussion

The proposed study explored the effect of different LED light combinations on color discrimination in the particular context of central scotoma (central loss of vision). The underlying idea was to investigate how the use of light can facilitate the object detection and recognition in low vision situations with the goal to assist visually impaired people in their daily acclivities.

First results derived from the pilot psychophysical experiments described in this paper demonstrate that the adaptation of the SPD to the visual needs of low vision people can improve their abilities to differentiate colors. A multichannel, narrow band, high color gamut index and low D_{uv} light would seem to be recommended in the case of a central loss of vision (see Table 1 and Figure 9). Such characteristics are far from those of the white LEDs commonly used in general lighting (see Figure 14).

The three light combinations *L1*, *L2* and *L3* selected during phase I of the experiment have color coordinates close to the Planckian locus (i.e. they are visually perceived as white light). Each of them meets two of the three criteria: high color rendering index, high color gamut area and low D_{uv}. More precisely, *L1* has a high fidelity index and a low D_{uv},. *L2* has a high gamut index and a low D_{uv}. *L3* has relatively high color gamut and fidelity indices but also a high D_{uv}. Figure 15 presents the TM-30-18 color vector graphics of these three light combinations.

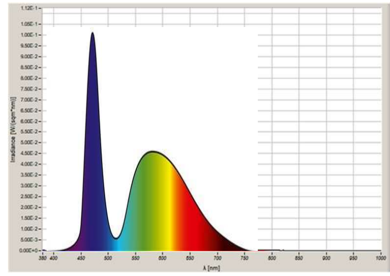

Figure 14. Spectral power distribution of the reference light LW that was a conventional phosphor converted white LED unit

As assumed during the selection of the 3 best candidates among all the LED light combinations, Figure 15 suggests that an oriented expansion of the color gamut area is a key factor in enhancing color contrasts. By oversaturating colors in hue ranges on either side of an axis, *L2* outperforms *L1*, which has a minimal expansion of its gamut area, and *L3*, which has a more or less uniformly averaged expansion of its gamut area in all color ranges.

In addition, *L1* and *L3* both contain a non-narrow band and they achieve equivalent outcomes during phase II of the experiment but not as significant as *L2*. This may indicate that narrow bands induce a greater capacity to improve color discrimination by unbalancing the hue range ratio. Such an observation is consistent with the above comments on the expansion of the color gamut area. In subsequent studies, it would be interesting to integrate this factor in the selection of LED light combinations.

One limitation in phase II of the experiment was that there were only 8 sets and that the color differences between test and reference samples were not constant for all panels (see Table 3). Even though the samples were chosen as the most representative hues from the entire hue circle of NCS, they cannot reveal accurate color discrimination abilities over the whole color range (see Figure 11).

The measured CIEDE2000 color difference between adjacent hue samples in the NCS album was not uniform, resulting in varying levels of difficulty for each hue pair. Especially in the near-purple region, color differences were more noticeable than in the other hue ranges. This would be a real asset to be able to work with color pairs having the same color difference. The experimental evaluation of the lighting capabilities to enhance color contrasts should then be more accurate.

There were no restrictions on the arrangement method in phase I of the experiment. Participants were observed using a variety of techniques, such as color grouping, one-by-one comparison, or even creating a "waiting list". Although no direct influence on the experimental results were noticed, the chosen method impacts the total duration of the experiment which in turn affects the volunteers' patience. Even though the color arrangement was split into two sessions, certain errors due to fatigue cannot be ruled out.

User experience is of great importance in lighting design for low vision people. The after-experiment interview revealed that majority of participants prefers *L2* and *L1* which are both providing a cold white light.

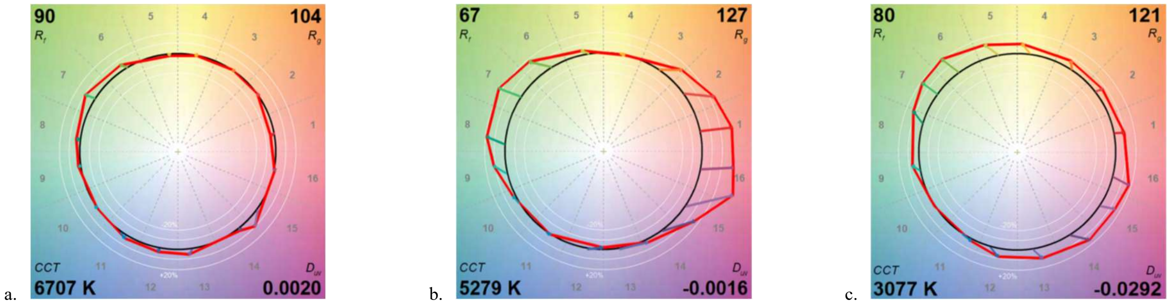

Figure 15. TM-30-18 color vector graphics of the 3 selected lights: L1 (a), L2 (b) and L3 (c)

First results related to central scotoma show that special light mixtures derived from 3 channels can efficiently enhance color differences and can improve color discrimination in comparison to "standard" white LEDs.

To go further in this direction, new experiments need to be carried out in order to investigate how many channels should be used and how to optimize the light mixing as well as the relative power of the selected channels. Other visual impairments such as tunnel vision or blur vision have also to be considered.

LEDs offer a great potential for adjusting the characteristics of light according to particular visual needs because of their capabilities with respect to the control of the emitted light intensity, the driving flexibility and the multiple spectral mixtures that can be obtained over the entire visible range. The approach is completely new and provides a break from the existing visual aids. It aims to simplify the vision rehabilitation, the mobility and the socioeconomic independence of the population living with vision impairment.

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