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ORIGINAL ARTICLE

Innovative and non-invasive method for the diagnosis of dyschromatopsia and the re-education of the eyes

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Abstract

Objective Dyschromatopsia is a pathology that afflicts many people even if, in most cases, they are not aware of it. The pathology, in fact, is not disabling in everyday life even if it is limiting from some points of view. Once diagnosed, dyschromatopsia is generally not investigated further: it is not known exactly how it manifests itself and with what extent. Furthermore, since it is a genetic pathology, it is "condemned" not to be resolvable. Biological neural networks have shown the capability to readapt their structure in order to overcome sensory malfunctions or neuronal damage. We propose a diagnostic algorithm capable of qualitatively and quantitatively assessing the degree of visual impairment due to the presence of congenital or acquired dyschromatopsia. The algorithm can also be easily integrated for its possible therapeutic use.

Methods The application of a novel approach based on an innovative algorithm for the diagnosis of dyschromatopsia and plastic reeducation training of the eye is proposed.

Results Our algorithm provides an accurate measure of the degree of dyschromatopsia severity in patients quickly and noninvasively. In addition, it can be used for a reeducational training process.

Conclusions Dyschromatopsia is an increasingly common disease in the world. The method we developed can diagnose dyschromatopsia. The algorithm also develops a metric scale for recognizing the degree of severity. The algorithm can be used independently by specilized and non-specilized people. In addition, the algorithm can be integrated with Machine Learning techniques to create a customized eye retrainer based on the plasticity and adaptability of neural tissue.

Keywords Neurological disease · Diagnostic · Dyschromatopsia · Image processing · Color processing

Introduction

Sight is one of the five senses through which we know the world around us. In particular, together with touch, it constitutes the means of perception par excellence in the newborn. The association of shapes with objects and their consistency begins to take place precisely in this phase of life. In particular, the chromatic sense constitutes one of the three fundamental components of sight and, in addition to developing progressively with age, it can be educated (Fish et al. 2021).

Dyschromatopsia is a deficiency in the perception of one or more colors. In the most severe stages, it manifests itself with the inability to observe the entire color scale taking the name of achromatopsia. Generally, when diagnosed, it refers to the dyschromatopsia of genetic origin, transmitted on the maternal line even though it is the male sex that manifests it. However, there is a second form of dyschromatopsia that can be acquired over the course of life. The disease arises from a malfunction of the cells that must recognize colors at precise wavelengths. In our eye, these receptors are called cones and are of three types depending on the wavelength to which they are sensitive: red band (from 549 to 570 nm), green band (from 522 to 539 nm) and blue band (from 114 to 424 nm).

In general congenital color blindness is due to a genetic mutation afflicting the X chromosome. Once inherited, it general affects both eyes (Salducci and Deandri 2020).

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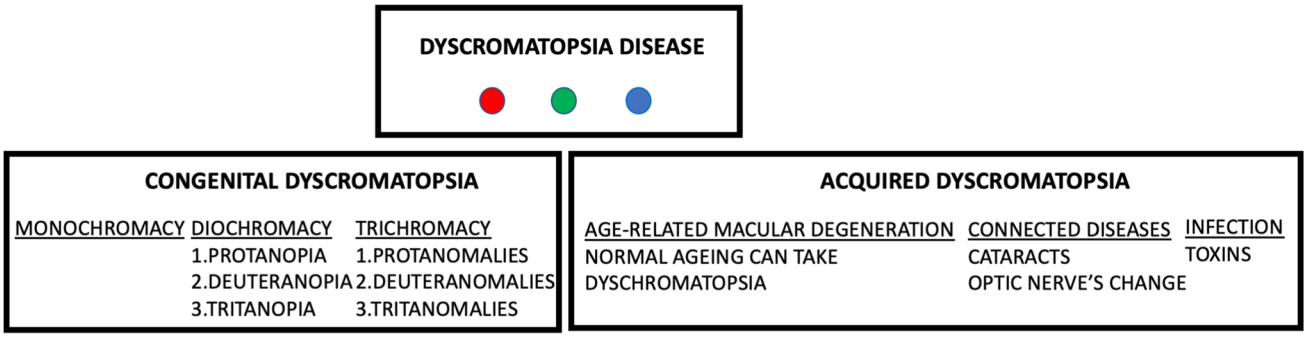

Fig. 1 Descriptive scheme of the disease of dyschromatopsia in the forms in which it can occur

Congenital dyschromatopsias are classified on the basis of the identifiable colors as reported in Fig. 1. However, when the disease is not congenital but acquired as a result of inflammation, there are some cases in which it is monolateral. Dyschromatopsia acquisition causes are the most varied and range from ocular discomfort close to aging. Genetic dyschromatopsia can manifest itself in three different forms depending on the activated cones:

- Monochromacy: only one color can be recognized.
- Dichromacy: a group of photoreceptors is not present in the eye. In pronatopia, the photoreceptors of red are missing, those of green are missing in deuteranopia and those of blue are missing in tritanopia.
- Trichromacy: in this case, all the photoreceptors are present but some functions are altered. This variant of the pathology is the most widespread and is divided into three different possible manifestations. It is called *protonomaly* the loss of red–green vision due to poor functioning of the cones sensitive to red. The *deuteranomalies* occurs if there is a loss of green vision due to a shift in the functioning of the cones sensitive to green. Finally, the tritanomalies is when there is the loss of the blue–green spectrum due to a shift in the cones that identify the colour blue.

Dyschromatopsia is considered a marginal pathology, which does not affect people's quality of life. Yet it reduces people's chromatic vision, in a more or less severe way, effectively precluding knowledge of some aspects of reality. These considerations are obviously more limiting in congenital dyschromatopsia rather than in that derived from inflammation, because it causes limitations in learning and development.

A study conducted in 1994 in Liguria (Italy) shows that students with dyschromatopsia defects have considerable learning difficulties on teaching methods based on the nature of colors (Grassivaro Gallo et al. 1998). Dyschromatopsia can also be limiting from the point of view of practicable professions. It can cause difficulties in clinical operation and lead to error (da Silveira Cespedes et al. 2021); when the disease is severe, it can be a reason for exclusion from all those professions that require a flight license, such as airline pilots or astronauts (https://www.concorsiaeronautica.it/visus-concorsi-aeronautica/).

Three main types of tests are currently used for the diagnosis of dyschromatopsia. The Farnsworth test is characterized by discs of different colors. The test consists of putting them in order of color and hue. In a qualitative (not numerical) way, this test allows to measure the degree of dyschromatopsia. The Ishihara test consists of pseudochromatic plates (they seem characterized by a single color), realized by many colored dots, whose position in density determines particular figures to be recognized. Also, in this case, the test provides a qualitative measure of the degree of dyschromatoposia only.

The Hardy Rand and Rittler (HRR) Standard Pseudoisochromatic Test 4th Edition uses pseudoisochromatic plates like the Ishihara tables. The first four plates are used for a small training phase, in which it is explained to the patient how the test works. The following six plates they are fundamental for the recognition of the disease and the level (Huna-Baron et al. 2013). Passing these images, the subjects are considered with normal view. The subsequent 14 plates are the diagnostic series and provide diagnostic (Foote et al. 2014).

Here, a new method of investigating the disease of dyschromatopsia is being investigated. The objective of the proposed algorithm is twofold: to identify the severity of the disease and provide for a re-education of the brain mappings by exploiting its characteristic self-organizing plasticity (Ianero et al. 2021; Bile et al. 2022).

The human brain is a system capable of self-organizing according to needs. When an organ of the crocus is injured, the neural mapping is morphologically reorganized to compensate for any degradation or imbalance (Kandel 2017). This characteristic dynamism is exploited in many situations to cure some problems and solve dysfunctions. In Duffau (2006), the author reviews the mechanisms that can lead to brain remodeling and how it occurs. As a

result of damage to the peripheral nerves, for example the patient may partially or totally lose motor ability; among the strategies (Navarro 2009) used, there are those that aim at modulating central nervous system reorganization with the amplification of positive adaptive changes. In Taub (2004), behavioral models and some physical constraints are used to bring about drastic changes in the structure and function of the brain in order to achieve rehabilitation in the use of a monkey's arm. Clinical hospitalization after central nervous system injury is attributable to mechanisms of functional compensation and neuroplasticity (Curt et al. 2008).

In this paper, an innovative algorithm for diagnosis and re-education is introduced: the method is based a progressive filtering of the densities of colors present on the Ishihara plates to accompany the eyes in identifying the correct form, originally not visible.

Method

The algorithm presented in this manuscript is able to quantify a precise detection of the degree of visual dyschromatopsia deficiency. The proposed algorithm is non-invasive and can be managed independently by any user in possession of a computer or a smartphone. At the same time as this work, we are in fact working on an interface that can be exported in the form of an app running on all smarthphone platforms. At the end of the diagnosis, the user was given a questionnaire to evaluate the judgment on the applicability of the test. The results will be analyzed in the Results section.

Our group is currently working on an integration of the diagnosis algorithm presented with a machine learning system which, according to the degree of deficiency, develops a personalized re-education plan. This paper aims to present only some common features of this algorithm extension. All results will be collected and analyzed later.

The algorithm

The algorithm has been implemented in the MATLAB 2020 environment (MATLAB 2020).

First, an Ishihara table is presented to the patient, specific to the type of color mink deficiency possessed. If the patient is unable to give the correct answer, or if he declares that he does not see anything or if he reports an incorrect answer, a table filtering process is carried out. Before going into detail, the color management system used in the MATLAB environment will be illustrated through the Image Processing Toolbox.

The RGB color space is characterized by three fundamental colors, red (R), green (G) and blue (B), from which, through their combination, any color can be obtained. Each element of the triad [R, G, B] $\in R^3$ is represented by 256 discrete values, ranging from 0 (absent) to 255. Therefore, the triad build a cube of $(2^8)^3$ values (Fig. 2a), with 2^8 for side. The use of the RGB color space, for the algorithm development, is justified given the functional similarity with the eye cones representing biological "sensors" (Roorda and Williams 1999). Due to this structural proximity, methods based on the use of RGB color space management, to test the level of color blindness (Utama et al. 2016) and to allow a temporary correction of the defect, have recently been proposed (Utama et al. 2017; Ohkubo et al. 2010; Liu et al. 2017; Yu et al. 2016). An RGB digital image is formed by an *m x n x 3* matrix, i.e. from three superimposed two-dimensional matrices, as shown in the Fig. 2b. Each layer represents one of the three basic colors of the space. The final image is the combination of the pixels that make up each layer: the color of each image pixel is the sum of

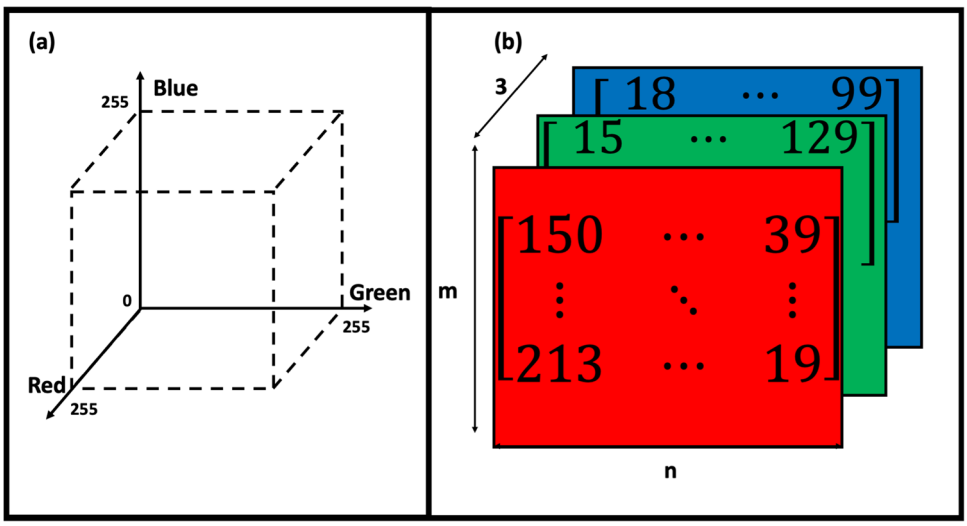

Fig. 2 (a) Representation of color cube and (b) digital structure of an RGB image, divided into three two-dimensional matrices then superimposed with values that move in a range between 0 and 255; each matrix represents a component of the fundamental RGB triad

the values corresponding to the pixel in the three matrices. Through the management of each layer, it is possible to adjust the contribution of red, green and blue to the final result. When there are multiple densities of color, also characterized by different shades, as in the case of the Ishihara plates, it is possible to selectively act on the colors to reveal the arrangement of one color density rather than another.

Based on this principle, the proposed algorithm identifies the target color density of the Ishihara test and then filters the detected color component by iterations. The result is a progressive enhancement of the contours of the target color spheres.

The procedure takes place in continuous dialogue with the user, adapting more to the characteristics of the patient and thus achieving an optimal test result.

Therefore, at each iteration, the patient is asked to digit the number seen in the administered image test. Each step involves a filtering that makes the target color density more evident.

Until the answer becomes correct, a new filtering process is performed which corresponds to the use of a new value of the alpha parameter. The efficiency of the filter operation is indicated through an α parameter that is 255 for the original image and decreases as the action of color filter increases. The goal of the filter system is to show the shape of the target color within the density of non-target colors, which are not affected. Gradually, the target is desaturated; therefore, the trend for the alpha parameter is $\alpha \in [0, 255]$. In particular, if $\alpha \rightarrow 0$ the patient has severe dyschromatopsia, while if $alpha = 255$ then the patient is healthy. During the testing phase, the algorithm stops when the target is recognized. The patient has α level dyschromatopsia. The flowchart of the testing algorithm is reported in Fig. 3. Once that the severity of the disease has been identified, the same algorithm can be used to proceed with a re-education path to the vision of color densities exploiting the plasticity of the brain (Fig. 4) .

By switching the color density very slowly, as shown in Fig. 5, it is possible to obtain an adaptation of the view to the identification of the forms, numerical or not, present in the proposed tables. The patient is gradually led to identify the densities of color associated with precise figures within the Ishihara plates. The re-education consists in the administration of Ishihara tables at different difficulties which are progressively filtered, favoring the guided recognition of color densities. Each re-education exercise consists of two structural moments. The first is to guide the patient in identifying the target. At the end of each training week, a new, unfiltered Ishihara board is proposed and any improvements compared to the previous week are observed and recorded. Re-educational training needs to be done on a daily basis and takes 10 min a day.

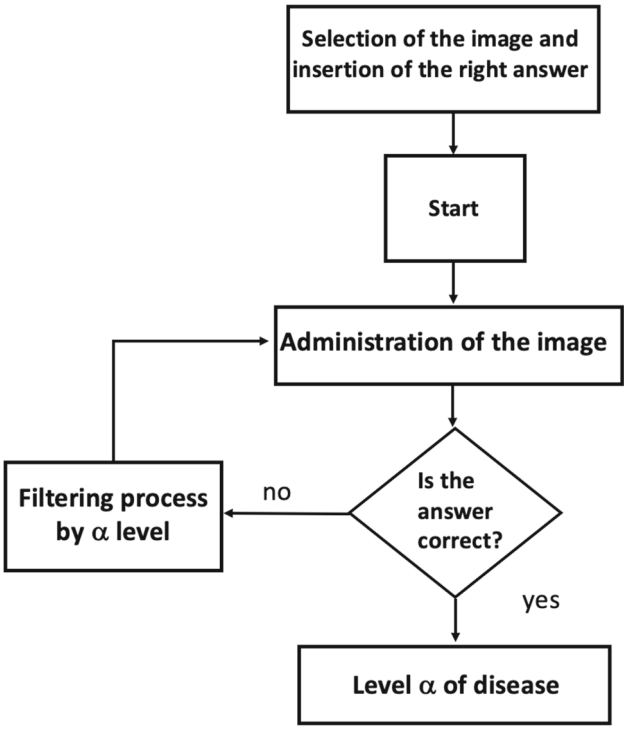

Fig. 3 Shows the logical flow of the testing algorithm. After the administration of an Ishihara table, the program interfaces with the patient who is required to respond with what he sees. Whenever an incorrect answer is given, a customized filtering is carried out based on the density of colors present. When the patient recognizes the target or the filtering is complete, the program stops and a value is assigned to the test carried out corresponding to the filtering intensity α

The algorithm is characterized by a user-friendly interface. This introduces a significant advantage in the re-education process. In fact, the presence of a specialist is not necessary, but each patient is able to proceed in autonomy. In this way, the daily routine of exercising is favored.

Results

To evaluate the validity of the testing algorithm from the user's point of view, a short questionnaire was developed with the aim of testing the possibility of using the algorithm for very large screening campaigns by exploiting its speed of response and non-invasiveness of the technique.

The questionnaire was administered to 50 users, of whom only 18 (36% of the total) showed color vision deficiency linked to dyschromatopsia, of varying severity. In general, almost all of those who are afflicted show a serious deficiency.

The questions in the questionnaire are 6 and have been articulated as follows. For each question, the possible

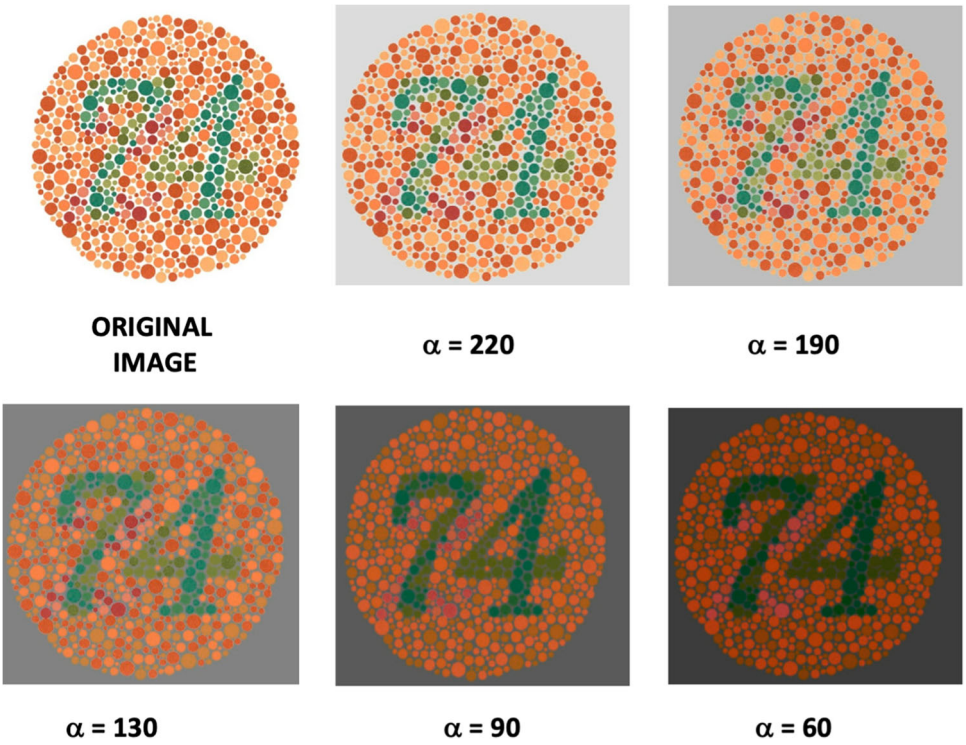

Fig. 4 Production of the recursive filtering process at the base of the algorithm for the detection of the level of dyschromatopsia and for the re-education in the recognition of color shades. In this test, the disease about distinction green-red is analyzed. From left to right are the original image and, in succession, the filtered images. People with dyschromatopsia cannot recognize any of the figures in the first table. Depending on the severity of the disease, as filtering progresses, the patient first recognizes the hidden pattern

answers are yes or no. The relative percentages are also shown.

- *Do you think it is useful to carry out a screening campaign at least once in your life to know your condition with respect to dyschromatopsia?*
  100% of users responded positively
- *Were you a subject afflicted by dyschromatopsia?*
  Most of the tested users (64%) proved sane in the test.
- *If so, did you know you are prone to dyschromatopsia?*
  Of the 18 patients with color blindess, 67% said they were unaware of their condition.

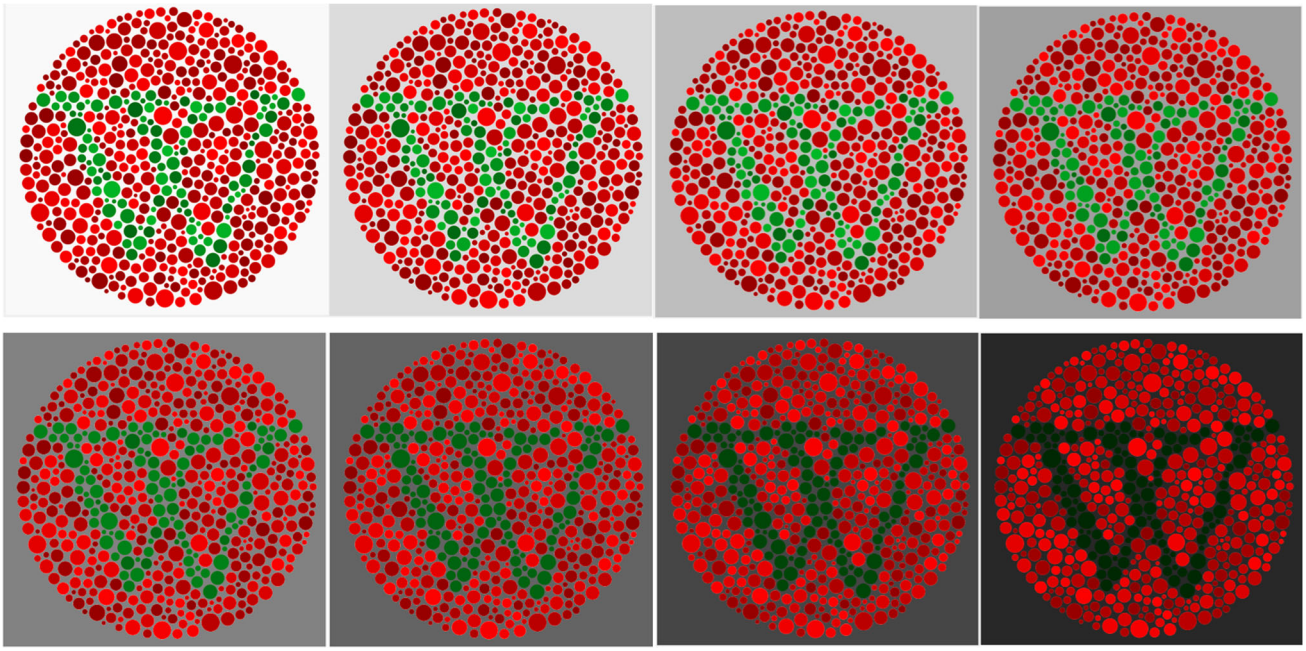

Fig. 5 From left to right: filtering sequence on color densities starting from the original table for the re-education process of the eye through the development of a new neural mapping

- *Would you prefer a more user-friendly interface?*
  90 % of patients said they preferred a more user friendly interface.
- *If an app is made available to you on your phone, do you plan to use this test for yourself and your acquaintances?*
  100% of respondents proved to be in favor.

Discussion

The aim of this study was to evaluate a new method as a diagnostic test for color vision that can be subsequently integrated through machine learning to create therapeutic software. This technique provides a platform to first find out how severe the degree of dyschromatopsia is and, based on the value of the alpha test, provides a consecutive learning algorithm to re-educate the neural network of the eye and improve the visual conception of the brain in terms of reliability, feasibility and reproducibility of the trained network.

The proposed alpha test for color vision is a rapid and reliable test allowing diagnosing any type of dyschromatopsia, whether inherited or acquired, with a protan, deutan or tritan axis of confusion and allows quantifying the severity of the chromatic deficiency. The above-mentioned three types of congenital color deficiency have their own specific color confusion characteristics. The colors along these confusion lines may look the same to the color-deficient person. For dichromats and severe anomalous trichromats, colors that are far apart on the confusion lines are confused, while mild and moderate anomalous trichromats only confuse colors that are closer together on the confusion lines. The alpha standard examination for the diagnosis of dyschromatopsia remains the anomaloscope. The proposed test allows accurately and reproducibly qualifying and quantifying all types of dyschromatopsia, and differentiating with certainty dichromatism from anomalous trichromatism. Moreover, the cost and/or the lack of availability of the test limit its use in daily clinical practice, our platform can overpass this limitation and can provide the possibility of everyday access through the realization of the app base facilities and make early-stage diagnosis possible.

In our validity study, Ishihara's pseudoisochromatic cards are used to screen color-blind patients. We chose this test among the numerous pseudoisochromatic plate application test because for mass screening of congenital dyschromatopsia, it seems to be the most suitable due to its sensitivity and its ease of use and interpretation.

Once the alpha test provided the degree of dyschromatopsia, based on the machine learning techniques, the algorithm will suggest training sets to re-educate the neural network of the brain. Reinforcement learning techniques will redistribute the synaptic density of the eye neural network and will modify the density of synapses in the favor of the visual conception of the brain. Indeed, it is a simple, easy to perform, and open diagnostic test that efficiently differentiates normal subjects from dyschromatic subjects (protan, deutan and tritan deficiencies).

Conclusion

Dyschromatopsia is a disease that affects more and more people around the world and can have a genetic origin or one derived from inflammation. In both cases, as revealed by numerous studies, it alters the vision of reality and the perception of colors, thus limiting from the point of view of learning, knowledge and from a professional point of view. Over time, numerous tests have been developed to understand the degree of severity. Recent works have developed testing techniques using technology and only recently has tools been developed to find a remedy.

This paper proposes an algorithm that can be used both to understand the level of severity of the disease in an easy and non-invasive way. Moreover the algorithm can be integrated with machine learning techniques to build a customized re-educator of the eye based on the plasticity and adaptability of the neural tissue. This has proven to be the basis for rehabilitation from numerous pathologies or injuries.

One of the advantages of the algorithm is the possibility of being used in full autonomy by patients who can understand their level of dyschromatopsia.

The proposed work represents the theoretical part of a study that is currently in progress from an experimental point of view. Although the first tests are providing positive results, the use on a greater number of patients is being studied to understand its effectiveness and understand if it is a local or permanent benefit over time.

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Declarations

Competing interests The authors declare no competing interests.

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