Color vision deficiencies and camouflage: a comparative study between normal and CVD observers

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Abstract: There is a belief that observers with color vision deficiencies (CVD) perform better in detecting camouflaged objects than normal observers. Some studies have concluded contradictory findings when studying the performance of normal and CVD observers in the camouflage detection tasks in different conditions. This work presents a literature review on this topic, dividing it into three different and contradictory types of results: better performance for CVD, for normal observers, or same performance. Besides, two psychophysical experiments have been designed and carried out in a calibrated computer monitor on both normal and CVD human observers to measure the searching times of the different types of observers needed to find camouflaged stimuli in two different types of stimuli. Results show the trend that, in our experimental conditions, normal observers need shorter searching times than CVD observers in finding camouflaged stimuli both in images of natural scenes and in images with synthetic stimuli.

1. Introduction

The prevalence of color vision deficiencies (CVD) is around 8% in men and 0.5% in women [1,2]. People with CVD (called CVD observers), find difficulties in their daily lives such as: acknowledging the bad conservation state of some food, realizing when the other person is blushing, differentiating among players of different teams in sports, etc. [1]. Usually, these handicaps lead to disadvantages when compared to the activity of observers with normal color vision (called normal observers in this work). Nonetheless, recent studies have found that the impairment is relatively small when analyzing how much dichromats are disadvantaged in discriminating colors drawn from natural scenes [3]. Back in the 20th century, during World War II (WWII), the belief that CVD observers could detect camouflaged enemy units easier than normal observers was widely accepted. It appears that both parties developed military strategies using CVD soldiers for this task, believing that they could save a higher number of lives and military units on the battlefield [4]. Unfortunately, none of these facts are historically accredited.

In this framework, we are dealing with visual camouflage, which, in our context, we define it as the ability of an individual or an object to reach an appearance that is similar to that of its surroundings. This way, it can blend in, making it difficult or impossible for observers to visually detect it. This is not a global definition of camouflage, yet it is applicable for our study.

It has been during the last 20 or 30 years that researchers have carried out experiments on primates and humans to support or refute the hypothesis of the advantage of CVD observers for detecting camouflage [5,6]. Some works in the literature support the hypothesis (see subsection 2.1), while others, not only refute it, but also assert that CVD observers are at a disadvantage over normal observers in this sense (see subsection 2.2). Finally, some studies also conclude that both CVD and normal observers perform the same in detecting camouflage (see subsection 2.3).

On this issue, there is an important difference to consider between anomalous trichromats and dichromats: since the anomalous trichromats have one of the cone spectral responsivities displaced with respect to the range of peak positions corresponding to normal observers, then they do not always accept the normal observers color matchings. The cone spectral responsivities of dichromats are the same as in normal observers, but they are missing one of the responsivities. Hence, dichromats always accept the matchings that normal observers do [7]. Given this difference between anomalous trichromats and dichromats, it follows that in principle, there is no reason why dichromats could be at an advantage with respect to normal observers for perceiving camouflaged objects. If two colors appear the same (as in camouflage scenes) for a normal observer, they will also appear the same for a dichromat; being not always true the opposite [8]. However, this would not be the case for anomalous trichromats, and so this group of subjects could potentially perceive as different colors that appear equal for normal observers, and this could facilitate the detection of camouflaged objects, at least theoretically.

The following sections are organized as follows. Section 2. presents a literature review on previous experiments performed in human and primate observers, both CVD and with normal color vision, dividing the references found in 3 different groups. This division is made according to whether they conclude an outperformance of CVD observers, normal observers, or a draw between them in the task of camouflage breaking. Section 3. explains how the two experiments were designed and performed. Section 4. shows the results obtained in the experiments, as well as a discussion about those results. Section 5. draws the final conclusions of the experiments.

2.   State of the art

2.1.   CVD observers perform better

This subsection shows in chronological order those articles found defending the better performance of dichromats and anomalous trichromats over normal observers at detecting camouflage.

In [9], Morgan et al. showed that dichromats were able to outperform normal observers in finding stimuli under a camouflage pattern. The first part of the experiment consisted in finding a region containing small horizontal segments within a stimulus of vertical segments, all of them of the same color. In the second part, the same experiment was performed, but including a random red and green color camouflage pattern. They found that, even if for the non-camouflage condition, all observers performed in a similar way, under the camouflage pattern, both protanopes and deuteranopes performed better, finding the target region faster than normal observers, but only if the camouflage patterns were red and green. In this experiment, 16 normal observers and 7 dichromats (2 protanopes and 5 deuteranopes) participated.

Later, Saito et al. [5], performed experiments on 14 primates (6 dichromats, 1 anomalous trichromat and 7 normal trichromats). They showed red and green circular stimuli containing geometrical figures inside (triangle, circle, diamond and square). The subjects were rewarded when they found the circle figures. The searching times were measured. The circular stimuli could be solid red, solid green or red-green camouflage pattern. They found that dichromats and anomalous trichromats primates were faster and had less errors than normal trichromats. After this, the same authors repeated this experiment with 24 human observers (12 with normal color vision and 12 deutans, not distinguishing between dichromats or anomalous trichromats) [6]. Results showed that longer searching times were needed for normal trichromats in the red-green camouflage pattern stimuli. It is worthy to mention that, so far, the three works described studied the camouflage conditions using only red and green colors with normal versus red-green CVD observers.

The same experiment was replicated by Widayati et al. in [10] with 6 primates (2 with normal color vision, 2 protanomalous trichromats and 2 dichromats). They found the same results than the works by Saito et al. [5,6]. However, when the design of the circular plates was changed and the geometrical shapes to find were displayed on red color over green background (the way

Ishihara tests [11] does with numbers and trajectories), they found that dichromats got more errors compared to both normal and anomalous trichromats. In this case, the task was just to find where the plate with a geometrical shape was in a two-alternative choice (the other one had no shape on it, only background color). They concluded that protanomalous trichromats had the same ability as dichromats in camouflage conditions and the same ability as normal trichromats in red shape over green background conditions.

In addition, Smith et al. [12], also studied the ability of CVD 41 primates (12 normal trichromats and 24 dichromats and 5 unknown) to find camouflaged stimuli. This time the stimuli consisted of insects with different camouflage patterns (mimicking natural colors, leaves, tree barks and total green color). They found out that normal trichromats found more prey, but dichromats found a higher proportion of camouflaged insects.

2.2. Normal observers perform better

In [13], Caine et al. did experiments with 14 dichromat and normal trichromat primates. They hid colored cereals between natural grass and green-dyed wood shavings. The cereals were dyed in orange color in one experiment and green in another one. Results showed that there was no difference in performance when the cereals were green in color on a green background. However, normal trichromats performed better than dichromats finding orange cereals on a green background.

Later, Pessoa et al. [14], did an experiment with 40 human observers (20 normal trichromats and 20 CVD observers), displaying images on a computer monitor. They were grouped in sets of 4 pictures, and only in one of them there was a camouflaged animal that they had to find. Results showed that normal trichromats were significantly faster than dichromats in detecting the camouflaged animal.

Six years later, Troscianko et al. [15], carried out online experiments with human observers. The observers could participate as normal color vision subjects or as simulated CVD dichromats. Again, sets of 4 images were presented on a screen. Only in one of them there was a camouflaged bird for one of the experiments, or an egg for the other experiment. Observers had to find the camouflaged object as fast as possible. In both experiments, four different variables were studied separately by altering the stimuli conditions. The first variable tested was the object-background texture difference. The second variable was the object's luminance. The third variable was the objects' size, and the fourth variable was the background luminance. In all conditions (bird or egg) and for all variables, normal observers were faster at finding the camouflaged object than simulated CVD observers.

After this, Fennel et al. [16], performed similar experiments with human observers as in [15]. They presented natural scenes (wood and desert) in a monitor and included differently colored camouflaged objects that observers had to find. In the experiment, normal observers participated as normal color vision subjects or as simulated dichromats. Results showed that normal observers were faster finding the camouflaged objects than simulated dichromats. Besides, they classified those colors that were more difficult to detect for both types of observers.

To finish this section, Moraes et al. [17], repeated the same experiment as in [15,16], now choosing three different natural scenarios with camouflaged animals (meadow, savannah, and wood). 39 primate observers participated (19 dichromats and 20 normal trichromats). Results showed that normal observers were faster than CVD observers finding hidden animals of reddish color in woods and savannah scenarios, and grey-colored animals in wood scenarios.

2.3. Normal and CVD observers perform the same

This subsection shows in chronological order those articles found which do not conclude any advantage for normal or CVD observers in detecting camouflaged stimuli.

In [18], Caine et al. performed an experiment which was similar to that presented in [13]. 15 primates participated (5 normal trichromats and 10 protanope dichromats). This time they included more variants in the background where they hid the colored cereals (pine shavings, grass, or soil). Results showed that none of the observer's types (dichromats or normal trichromats) performed significantly faster in finding the colored cereals.

Later, Melin et al. [19], evaluated how dichromat and normal trichromat monkeys performed in finding insects. 34 primates participated in this experiment (27 dichromats and 7 normal trichromats).The experimental conditions were divided in three categories. In the first one, insects were placed with no vegetation at all on top. In the second one, they were partially covered by vegetation. In the third one, they were completely covered by vegetation. As a result, they observed that dichromats were more efficient detecting hidden insects, especially in low light conditions. However, normal trichromats detected a higher number of insects in general, though less of them camouflaged. These results suggested that dichromatic vision is important upon detection, but, since the insect captures were not completed, they could not conclude that dichromats were more efficient breaking the camouflage.

One year later [20], the same authors studied the differences in feeding patterns between dichromat and normal trichromat primates. 33 primates participated in this study (26 dichromats and 7 normal trichromats). The experiment consisted in measuring the searching time for fruits and insects. The fruits were divided into two groups. The first group was cryptic fruits (those which are green even after maturation). The second group was composed of striking, red colored fruits. Regarding the insects, they were divided into insects over the surface and camouflaged insects. They found that age was a key factor in the searching times. Hence, they only accounted for the results in adult primates. Consequently, they found that only dichromat females spent more time searching for food. The rest of the results did not show any different performance between dichromats or trichromats.

Later, these authors [21], conducted one more experiment with 14 dichromat and 10 normal trichromat primates. This time they had to search for figs. Some of them become red when mature, and others stay always green (even after maturation). Results showed that dichromats found a higher number of figs, but they were not faster at finding them.

2.4. Overall summary of the state of the art

This state-of-the-art review presents contradictory conclusions when comparing the different studies in humans and primates. Among the possible reasons for these discrepancies, we could mention the different experimental conditions (controlled or laboratory framework, uncontrolled viewing conditions, natural scenes, artificial stimuli, etc.), the different groups of observers studied (human, primates, dichromats, trichromats, simulated CVD observers, etc.), the different tasks performed by the observers in the experiments, etc. Thereupon, we cannot conclude whether CVD observers could present or not an advantage in detecting camouflaged stimuli. Nonetheless, two main ideas can be extracted from the literature. On the one hand, when the experiments were performed showing artificially looking stimuli (like geometrical figures hidden in plates), it seems that CVD observers performed better than normal observers. On the other hand, when the experiments were performed in natural conditions or showing natural looking stimuli as animals hiding in natural landscapes, CVD observers performed worse than normal observers. None of the studies so far tested both kinds of stimuli using the same set of observers.

For this reason, this work tries to focus on studying these different conditions in human observers. Two different experiments, measuring the searching time, based on the ones found in the literature have been designed. One of them shows camouflaged stimuli in natural landscapes. The other one synthetic colored patterns stimuli with geometrical shapes. The details about both experiments are explained in the following section.

The main novelties presented in this work are the following: the experiments have been carried out by normal observers and real CVD observers, not by normal observers working with CVD simulations of images. In the group of CVD observers, both dichromats and anomalous trichromats have been considered, and also both protans and deutans. The same group of observers have performed the two experiments. In the second experiment (synthetic stimuli), more sets of colors have been included, and not only combinations of red and green as found in the literature. All subjects did the experiments in the same calibrated PC monitor and under controlled viewing conditions.

3. Methods

Two psychophysical experiments were carried out with both CVD observers and observers with normal color vision. In both experiments, a color calibrated 15.6 inches LED digital monitor was used. The monitor was calibrated using the Eye One Display 2 colorimeter (Xrite, USA). The monitor was always working with maximum luminance setting and the experimental conditions were always of indoors lighting, consisting in natural daylight (through the window). The luminance of the maximum white was 603.6 cd/m^2. The illumination conditions were characterized using a spectroradiometer model PR-745 (Photo Research, USA) measuring over a standard white reference tile (Sphere Optics, Germany). The luminance ranged from $186cd/m^2$ to $272cd/m^2$, and the CCT from $5100K$ to $5572K$. Maximum luminance settings in most monitors may have a sub-optimal behavior in terms of gamma function. Nonetheless this is not a key factor for these experiments. The key factor was to have all observers performing the experiments under the same controlled viewing conditions. The maximum luminance ensured normally visible images on the screen for all observers in the naturally illuminated surrounding. The monitor's surface was matte, so no specular reflections were present on the screen. Chromatic adaptation is a key factor when dealing the color perception. The viewing conditions of the experiment were designed in such a way that observers were completely adapted to normal screen viewing conditions. All observers were working in the same conditions. The workflow followed in both experiments was the same. After a brief example shown to the observers to explain what the task was about, and a 2 minutes adaptation period on a gray screen, the experiments started. A set of stimuli was presented on the screen. The observers were asked to identify a specific stimulus among them. Once they found it, they had to press a key. After the keypress the stimuli disappeared, and a central black cross over a gray background was presented. The cross was introduced to control the fixation point of the observer before a new set of stimuli was presented. It was placed in the middle point of every stimulus present in each set of stimuli. This way, whatever the searching strategy of each observer was, the start position was always the same central point. The time between the presentation of the stimuli and the key press was measured for all instances. There was a limit time of 20 seconds. After this time, if the observer did not find the target stimulus, the attempt was considered as a wrong answer. During the presentation of the black central cross on screen, the time was not measured, and the observers were asked where the target stimulus was. Once the observers answered and were ready for the next set of stimuli, they pressed a key again and the new set of stimuli appeared on screen. Figure 1 shows a workflow of the two experiments. The details of each experiment and the requested tasks are explained in the following subsections 3.1 and 3.2.

3.1. Experiment 1 (scenes stimuli)

This experiment was designed using images of natural scenes. Working in ideal conditions, it would be good to have the opportunity to create real natural scenes including camouflaged soldiers, so that all observers could perform the experiment there under the same natural conditions. If we could go into such a variety of real-world scenes and measure colors point-wise in all of them, we would find a gamut which is much wider than that of the same scenes represented in a
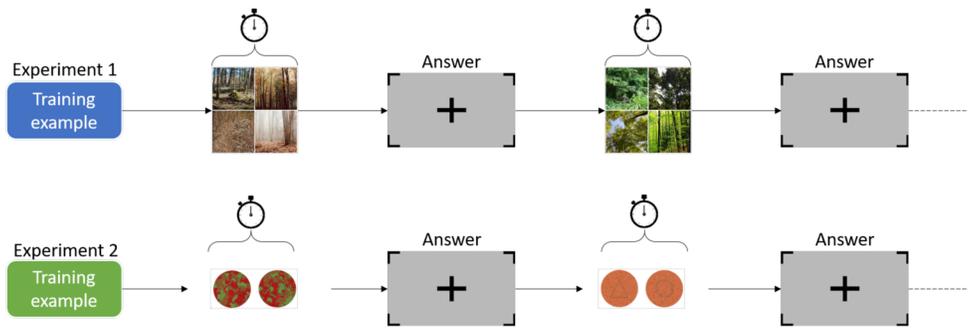
Fig. 1. Workflow of the two experiments performed. The timers indicate when the searching time was measured.

monitor. Actually, the color of each point of a real-world scene, depends on many uncontrolled factors that change constantly with time: position of the sun or other illuminants, inter-reflections, moving objects, shadows, climate conditions (cloudy skies, haze, fog, rain, etc.). Hence even if it would be possible to completely characterize the color of a real scene, it would probably change in few minutes. For this reason, we chose to display color images of these natural scenes. This way, we could ensure that all observers were looking at the same scenes with the same colors, and that they were scenes including real-world information that could be familiar for them (trees, plants, forest, etc.). Each set of stimuli consisted of 4 images (two on the top and two on the bottom as shown in two example sets in Fig. 2). Among these 4 images, only one of them contained a soldier camouflaged with the surroundings (highlighted with a red ellipse in Fig. 2). The observers' task was to locate the image containing the soldier and then press a key. During the resting stages they had to tell where the soldier was (top-left, top-right, bottom-left, or bottom-right). The answers were annotated to quantify the number of errors and ensure that the observer was really detecting it. The maximum searching time allowed was 20 seconds. After that time the trial was considered an error. A total of 20 sets of stimuli were shown during this experiment. Each of the four images had a screen size of 75 x 75 mm, and the observers were placed at 40 cm from the screen. Hence, each image subtended a visual angle of 10.6^o.

Fig. 2. Example of two sets of stimuli shown during experiment 1. The camouflaged soldiers are highlighted with a red ellipse in both cases.

3.2. Experiment 2 (synthetic stimuli)

This experiment was designed by creating synthetic stimuli. The design of these stimuli was based on the Ishihara plates [11], although there were significant differences from them. They consist of circular plates filled with a background of tiling patterns of different colors (as shown in Fig. 3). The tiling texture is included to give them a less synthetic appearance. Note that there are edges in the tiling, but this is not a drawback for the purpose of this experiment. Inside each plate, there is a geometrical object which can be either a circle, a square, a triangle or a diamond. These stimuli are inspired in the experiments carried out in [5,6]. However, the design has been modified since in [5,6], the difference between background and object was a texture change, while in our design the difference was a hue + chroma shift (keeping the luminance). This was done trying to avoid the possibility of the observers to detect the camouflaged shapes just due to a notorious texture difference, even if they cannot distinguish between different colors.
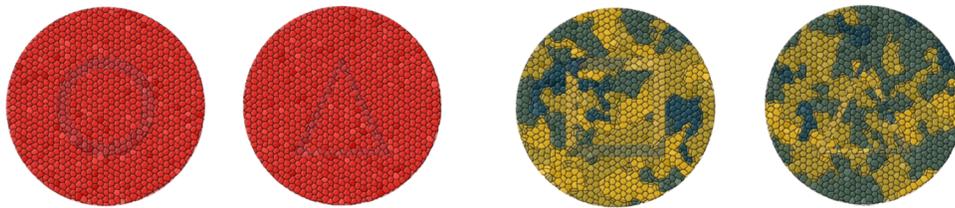
Fig. 3. Example of two sets of synthetic stimuli. Left: red solid pattern (circle and triangle). Right: yellow-blue camouflage pattern (square and triangle).

Two kinds of patterns were designed for the stimuli: solid patterns and camouflage patterns.

- Solid patterns: a single color was used among yellow, blue, red, green, magenta, and orange. Table 1 shows the L^*, a^*, and b^* color coordinates for both background and object for each color used. The maximum white of the monitor was used as reference white. These colors were selected from colors used in the Ishihara plates. Figure 3 left shows an example of a red solid pattern. The tiling pattern included some little shading from the main color just to give the plates a more natural appearance.

- Camouflage patterns: two colors were used in each stimulus with random shapes which are typical from camouflage military clothes. The color combinations were blue-yellow, red-green, magenta-orange and green-green with different green colors. Figure 3 right shows an example of a yellow-blue camouflage pattern. GIMP software was used for the design of the targets. The two main colors used in the camouflaged patterns were selected (see Table 1), and GIMP refilled the camouflage pattern with intermediate colors.

In each set of stimuli, two stimuli were shown side by side. Both had the same color pattern but contained different objects. The observers were asked to find the one containing the diamond and press a key. During the resting stages they had to tell where the diamond was. Three different answers were possible: left, right or not present. This third possibility was included since, otherwise, if the diamond was always present in one of the two stimuli, the observer could just look at one of them and answer according to whether it was or not the diamond, reducing the response time. Including the not-present possibility, the observer should look at both stimuli and identify the object present in each of them.

The screen size of each stimulus was 10 cm diameter, and the observers were placed at a distance of 40 cm from the screen. Hence, each image subtended a visual angle of 14.25^o. A total of 50 sets of stimuli were created. Each set consist in a combination of two of the possible geometrical shapes: for instance square and triangle. For each of the 10 different color patterns (solid color or camouflage pattern), 5 sets were created.

Table 1. CIELAB color coordinates of the color patterns used in experiment 2 as well as for the RGB primaries of the monitor and the maximum white, minimum black and gray adaptation field.

Color	Yellow		Blue		Red		Green		Magenta		Orange	
	Back	Front	Back	Front	Back	Front	Back	Front	Back	Front	Back	Front
L*	80.7	79.6	51.6	46.7	38.2	35.9	67.9	71.4	36.8	47.5	62.1	65.4
a*	-1.4	3.1	1.0	-0.8	52.1	44.4	-8.6	-5.7	35.4	37.5	20.2	26.4
b*	56.9	66.1	-5.1	-9.6	43.1	30.8	25.1	24.3	2.5	0.7	33.7	40.9

	R primary	G primary	B primary	White	Black	Gray
L*	53.5	82.7	48.7	100.0	3.0	78.3
a*	55.3	-56.0	33.9	0.0	1.0	3.2
b*	55.4	85.7	-81.5	0.0	-3.0	-3.7

3.3. Observers

In this study, 43 volunteer observers have participated. They received clear information and instructions so that they were completely informed about all aspects of the experiment. The age range of the observers was 19 to 55 years (mean = 31), of which 12 of them were females and 31 were males. All subjects gave their informed consent for inclusion before they participated in the study. The study was conducted in accordance with the Declaration of Helsinki, and the protocol was approved by the Ethics Committee of the University of Granada ($2378/CEIH/2021$).

Before the experiments, three different color vision tests were conducted to diagnose the type of color vision of each subject. These tests were: a digital version of the Ishihara test, a digital anomaloscope, and a digital version of the D15 sorting test [22]. These tests were performed in the same calibrated monitor where the experiments were done. The use of digital versions of color vision diagnosis tests is not new. Their suitability has been reported in different works [23,24]. Psychophysical tests work fine in distinguishing protan-like observers from deutan-like. It is though more complex to diagnose an observer as dichromat or anomalous trichromat. It has been reported that there is no single test that can diagnose it 100% accurately by itself [25]. Rather, it is more convenient to use different tests. Moreover, Davidoff et al. conclude that genetic tests correlate well with the anomaloscope test [26], and Jagle et al. estate that the anomaloscope is suitable for distinguishing protan from deutan and dichromats from trichromats [27]. In our case, we performed these three tests, which agreed in the resulting diagnosis for all observers.

22 observers (51.16%) had normal color vision and 21 (48.84%) had some type of CVD. Among the CVD observers, 19 were males and 2 were females. 8 subjects (18.6%) were protanopes, 4 (9.3%) were protanomalous trichromats, 6 (13.95%) were deuteranopes, and 3 (6.98%) were deuteranomalous trichromats according to the tests. Figure 4 shows the number of each type of observers.

When analyzing the results, the observers were divided into 6 different categories: normal trichromats, anomalous trichromats (protanomalous + deuteranomalous), dichromats (protanopes + deuteranopes), protans (protanomalous + protanopes), deutans (deuteranomalous + deuteranopes), and CVD (protans + deutans). Thus, each CVD observer belongs to 3 different categories at the same time, as show Fig. 4.
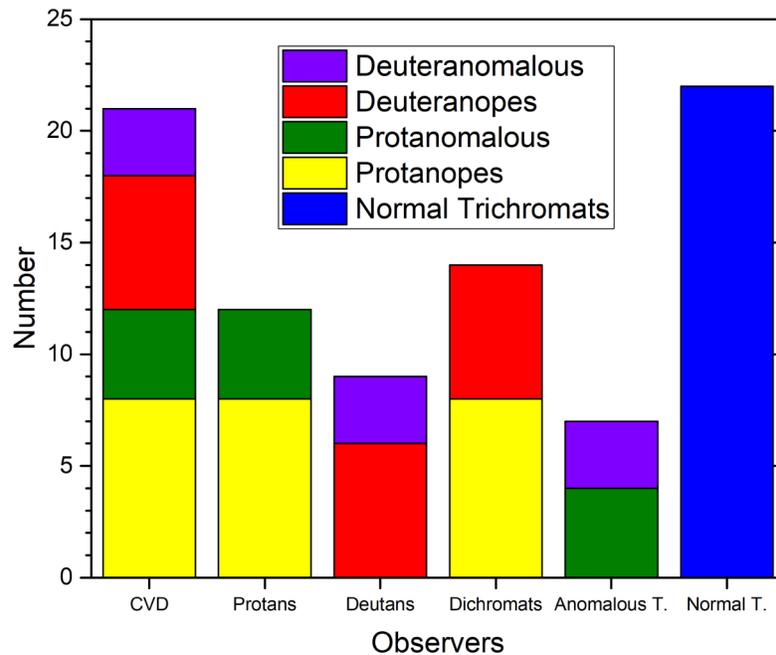
Fig. 4. Number of observers in 6 different categories: normal trichromats, anomalous trichromats, dichromats, protans, deutans, and CVD.

4. Results and discussion

Figure 5 shows the mean searching times in both experiments for each type of observer, as well as their standard deviations (as error bars). All mean and standard deviation values have been calculated across all sets of stimuli for each experiment and across all observers of each type.
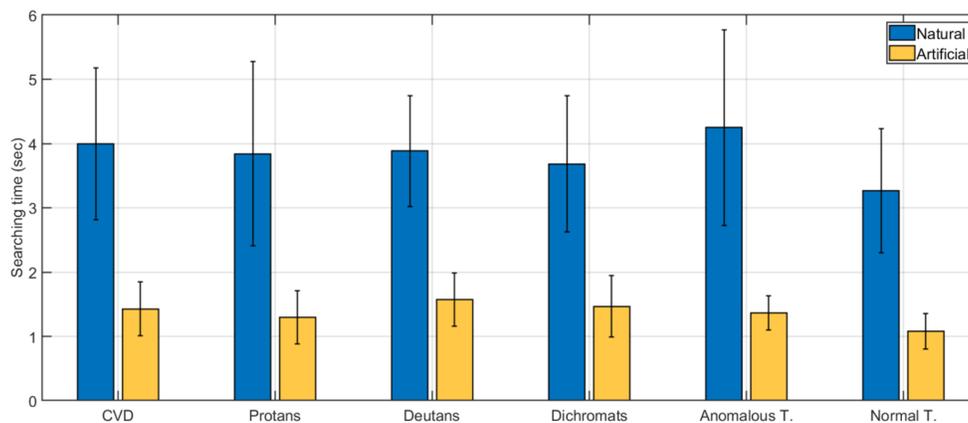
Fig. 5. Mean and standard deviation of searching times for each type of observer in both experiments.

As we can see in Fig. 5, average searching times (ST) for experiment 2 (synthetic stimuli) were shorter (64% shorter in average) than those of experiment 1 (natural scenes). This is expected since, among other reasons, in the first case, each set of stimuli contained 4 images, while in the second case, there were only two plates. Besides, according to observers' opinion, the task

was easier in general for experiment 2, even disregarding the different number of stimuli per set. A t-test analysis shows that this difference between natural scenes and synthetic stimuli is statistically significant ($p<0001$), and the effect's size is large according to Cohen's criteria [28,29], and the probability that our experiments will reject a null hypothesis is large ($d>1$ and $1 - \beta = 1$).

Besides, for both experiments, the shortest ST were found for the observers with normal color vision: normal trichromats. In experiment 1 (natural scenes), normal observers were on average 18.28% faster than CVD observers, and in experiment 2 (synthetic stimuli), normal observers were on average 24.43% faster. Analyzing these results by means of a t-test, we found that, for experiment 2, differences between normal and CVD observers are statistically significant ($p = 0.003$). We can accept these differences considering that the effect size is $d = 0.92$ and the power of the t-test is $1 - \beta = 0.829$. In the case of the natural scenes experiment, p value is (0.047), although we cannot really consider this difference as significant because the effect size is medium-low ($d = 0.533$) and the power is low ($1 - \beta = 0.391$).

Within the CVD group, observers with L-cone anomalies (protans) were faster than observers with M-cone anomalies (deutans). The differences were 1.08% in experiment 1 (natural scenes) and 17.45% in experiment 2 (synthetic stimuli). According to the statistical analysis with the t-test, these differences were found not to be statistically significant in any of the experiments ($p = 0.468$ and $p = 0.116$). Moreover, for the natural experiment, CVD dichromats were 13.26% faster than CVD trichromats, but for the artificial experiment CVD trichromats were 7.06% faster than CVD dichromats. In both cases, the t-test analysis showed a non-statistically significant difference ($p = 0.480$ and $p = 0.169$ respectively). Comparing the ST of normal observers with those of the different types of CVD observers, we found that the largest difference was that with anomalous trichromats in experiment 1 (natural scenes), against whom normal observers were 23.12% faster. This difference was found not to be statistically significant in the t-test analysis ($p = 0.063$). In experiment 2 (synthetic stimuli), the largest difference was with deutans (both anomalous trichromats and dichromats), against whom normal observers were 31.34% faster. The t-test analysis showed that this difference was statistically significant ($p = 0.006$, $d = 1.41$, and $1 - \beta = 0.998$).

Regarding the percentage of the number of errors made by observers in each task (experiment 1 and 2), Fig. 6 shows the mean and standard deviation values across all stimuli sets and all observers of each type in both experiments. As Fig. 6 shows, in experiment 1 there is small variability between percentage of errors for the different types of observers, being the maximum value for the anomalous trichromats (5.71% error on average) and the minimum value for normal observers (5.23% error on average). The mean percentage of errors across all types of observers was 5.48% with a standard deviation of 0.18%. In experiment 2, the minimum mean percentage of error was found for the anomalous trichromats, who had no errors at all, followed by protans (0.67%) and normal (0.91%) observers. The group with the highest mean percentage of errors was deutans with 2.22%. Across all types of observers, the mean percentage of errors was 1.2%, with a standard deviation of 0.87%. As a remarkable difference between observers with different type of cones affected, deutans had more than 3 times the number of errors than protans in experiment 2.

Though not statistically significant, these results are very close to support the hypotheses made in [13–17], that normal trichromats perform better in finding camouflaged stimuli in natural conditions. On the other hand, these results would refute the hypothesis that CVD observers could have an advantage in the battlefield localizing camouflaged stimuli. The apparently small ST differences found, could not be decisive in battle circumstances. When the camouflaged stimuli are generated ad-hoc using confusion colors for CVD observers, they perform worse than normal observers. The ST analysis in the comparison across experiments shows that experiment 1 (natural scenes) was a task remarkably more difficult than experiment 2 (synthetic stimuli).
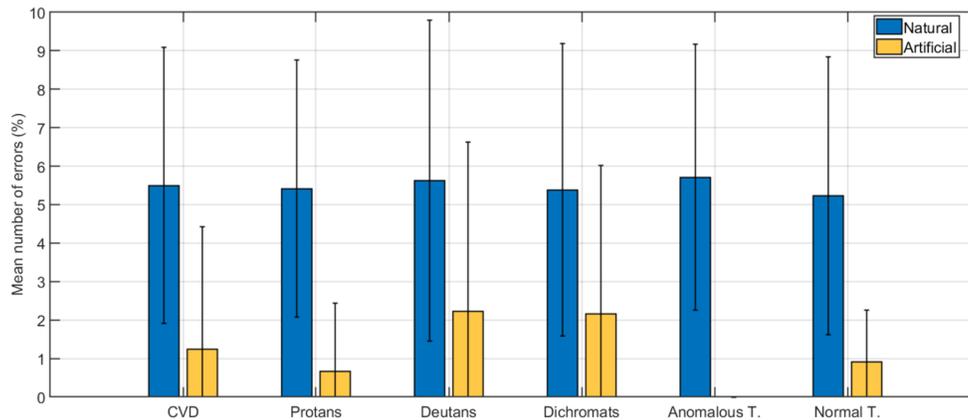
Fig. 6. Mean and standard deviation of percentage of errors made by each type of observer across all sets of stimuli in each experiment.

The error analysis is also consistent with this hypothesis because all subjects had a higher mean number of errors for experiment 1. The scenes used in experiment 2 do not offer much of a challenge for any type of observers, but the fact that they are synthetic patterns generated using confusion colors as a base makes more difficult for CVD subjects to use clues that they have developed during their visual experience with natural scenes.

This might explain the fact that, even if the differences found between normal and CVD observers were not statistically significant for experiment 1, probably due to population size (although the normal subjects still tend to perform better), for experiment 2, the normal observers could outperform the CVD subjects more clearly because for them the task was much easier than experiment 1 (natural scenes), while for the CVD observers this task was not as easy, both due to the selected colors and the fact that the stimuli were not natural scenes.

The trend found for the dichromats to be slower and make more mistakes in experiment 2 also seems to be correlated with the reduced color discrimination capacities in this group of observers, that would be more sensitive to colors placed in confusion lines than anomalous trichromats and normal observers. Also, given a fixed color contrast for an artificially generated pattern around a confusion color, it is expected that the dichromats will find harder to distinguish the object from the background than anomalous trichromats or normal observers.

Having a deeper look into the results of experiment 2, we could divide the analysis in different color patterns of the stimuli. Figure 7 shows the mean ST for the different types of observers and each color/camouflage pattern used in this experiment. Each mean value has been calculated across all observers of each type and all sets of stimuli of each color/camouflage pattern.

Grouping all observers, Table 2 shows the mean (and standard deviation) values of ST across all observers for each color/camouflage pattern of experiment 2.

Table 2. Mean and standard deviation of searching times across all observers for each color/camouflage pattern of experiment 2.

Pattern	Yellow	Blue	Red	Green	Orange	Magenta	Y-B	R-G	M-O	G-G
Mean (s)	1.85	1.46	1.08	1.57	1.18	1.01	1.4	1.74	1.24	1.19
Std (s)	0.24	0.15	0.06	0.43	0.13	0.06	0.16	0.42	0.1	0.12

Grouping all color patterns used in experiment 2, Table 3 shows the mean (and standard deviation) of ST across all color/camouflage patterns used in experiment 2 for each type of observer.
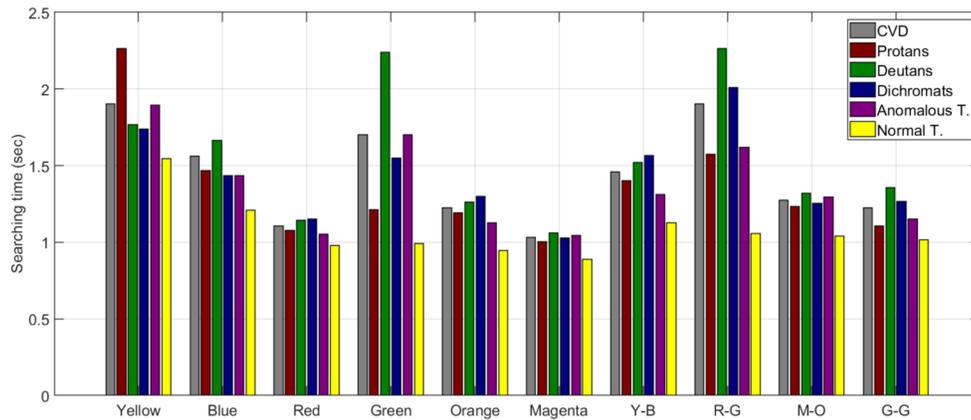
Fig. 7. Mean searching times for each color/camouflage pattern and each type of observer.

Table 3. Mean and standard deviation of searching times across all color patterns used in experiment 2 for each type of observer.

Type	CVD	Protans	Deutans	Dichromats	Anomalous T.	Normal T.
Mean (s)	1.44	1.35	1.56	1.43	1.36	1.08
Std (s)	0.32	0.37	0.42	0.29	0.29	0.19

As pointed out in Fig. 7 and Table 2, for all different color patterns, normal observers were the fastest compared to any other group of observers. On average, deutans were the slowest group, although not in all color patterns. Analyzing the type of cone affected in CVD observers, protans were faster on average than deutans, although not in all the color patterns, since deutans were faster than protans in the solid yellow pattern.

When comparing anomalous trichromats and dichromats, the former were faster on average than dichromats, although having a look at the individual color patterns, dichromats were faster for yellow, blue, green, magenta, and M-O patterns.

It is worthy to mention that, on average for all observers, the most difficult patterns were the solid yellow followed by the R-G camouflage and the solid green patterns. This was unexpected since it would be more intuitive to think that the most difficult pattern should be a camouflage pattern instead of a solid color pattern. Table 4 shows the mean ST for solid color vs camouflage patterns for each type of observer.

Table 4. Mean ST across all solid color/camouflage patterns used in experiment 2 for each type of observer. Bold highlights the fastest case for each observer type.

Observer	CVD	Protans	Deutans	Dichromats	Anomalous T.	Normal T.
Solid color (s)	**1.42**	1.37	**1.52**	**1.37**	1.38	1.09
Camouflage (s)	1.47	**1.32**	1.62	1.52	**1.34**	**1.06**

As we can see in Fig. 7, the longest mean ST of the experiment was found for deutans in the R-G camouflage pattern. Thus, we have performed a CVD simulation using the model proposed in [30] for a specific case as an example. The sRGB simulation is shown in Fig. 8.

As Fig. 8 shows, it seems that indeed, deuteranope observers could find more difficulties to identify the hidden triangle shape compared to normal or protanope observers, which could be the reason why they took in average the longest ST in this camouflage pattern.
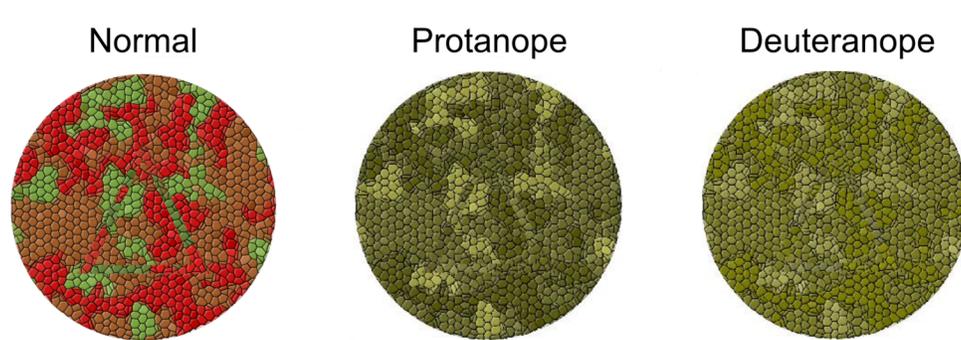
Fig. 8. sRGB simulation of one of the red-green camouflage pattern samples as seen by normal, and the two types of dichromat observers.

5. Conclusions

This work presented a state-of-the-art review in the topic of the ability of normal and CVD observers detecting camouflaged stimuli. Given the contradictory conclusions found in this review, two psychophysical experiments were designed, implemented, and performed with normal and real CVD (dichromats and anomalous trichromats) human observers. Searching times were measured for the same group of observers in two experiments: using natural scenes and synthetic stimuli. Besides, in the synthetic stimuli experiment, additional color patterns were included compared with the traditional red-green ones used in previous works.

Results show that, under our experimental conditions, normal trichromat observers performed better in both experiments (finding statistically significant differences in experiment 2). In none of the cases, any type of CVD observers performed better than normal observers.

In the natural scenes experiment, results agree with those found in the those works concluding that normal observers perform better than CVD observers [13–17].

However, in the synthetic stimuli experiment, our results disagree with those found in some references of the literature [5,6,9]. In our study, normal trichromat observers are faster finding the camouflaged stimuli for all types of color patterns (solid and camouflage), including the red-green camouflage pattern. This opposite conclusion could be due the fact that, in our experiment, the difference between the geometrical shapes and the background consisted in a small hue + chroma shift, while in the experiments found in the literature with similar stimuli, the difference was mainly a texture shift [5,6], for which the CVD observers might be privileged with respect to the normal observers, because they are used to take advantage of other clues to detect objects against their background. The base colors were selected from confusion colors in our case, and this can influence the difficulty of the task as well for CVD subjects, although the results indicate that they are able to perform the detection with very few mistakes.

Our conclusion is that the differences found between normal an CVD observers are only statistically significant under restrictive conditions. It is true that in all the cases normal color vision observers performed better in finding camouflaged stimuli. In natural scenes presented in a display, the differences found seem to be so small that we cannot be sure if they are sufficient to be considered. In general, experiment 2 was designed using colors that are confusing for red-green CVD observers. On the other hand, Stimuli in experiment 1 consist of complex images, which are usually more difficult scenarios for CVD observers to interpret the elements present on the scene based on its color content.

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Data availability. Data underlying the results presented in this paper are available in Dataset 1 [31]. See Supplement 1 for supporting content.

Supplemental document. See Supplement 1 for supporting content.

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