DESIGNING A WAVELENGTH SPECIFIC COLOR PERCEPTION TEST FOR JUST NOTICEABLE DIFFERENCE IN COLOR DOMAIN

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CERTIFICATE

This is to certify that the thesis entitled “**DESIGNING A WAVELENGTH SPECIFIC COLOR PERCEPTION TEST FOR JUST NOTICEABLE DIFFERENCE IN COLOR DOMAIN**” being submitted to the National Institute of Technology, Rourkela by **Mr. Siddharth Muduli** for the award of the degree of **B.Tech** in **Bio Medical Engineering** is a record of bonafide research work carried out by him under my supervision and guidance. His work has reached the standard fulfilling the requirements and regulations for the degree. To the best of my information, the work incorporated in this thesis has not been submitted in part or full to any other University or Institute for the award of any degree or diploma.

Date: Dr. Sirsendu Sekhar Ray

Place: Department of Bio - Medical Engineering

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Date: (Siddharth Muduli)

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ABSTRACT

To the human vision, there exists in color images a certain amount of perceptual redundancy since the human visual system (HVS) has limited sensitivity in discriminating color signals of small differences. Such colors of small differences are called **Just Noticeable different** colors.

A test has been designed to check for such near wavelength colors that does not seem different to a normal human eye. The test is solely based upon the perception of human eye towards different wavelengths in the visible spectrum. The test consists of a central color of certain wavelength which was surrounded equidistantly by colors having wavelengths, not differing much from the central color. In the test the subjects had to choose the colors that looked similar to the central color. As the color perception varies from individual to individual, this test when conducted over a large population having a healthy vision varying in age, gender and ethnicity can yield a generalized color perception by a normal human eye.

The objectives of test were to find out the just noticeable different colors among a given set of colors having wavelengths that are just few nanometers different from each other and to get a generalized color perception for a human eye. When data of a very large sample space is statistically analyzed, we get reliable information that can be used to diagnose defects in the color vision.

Contents

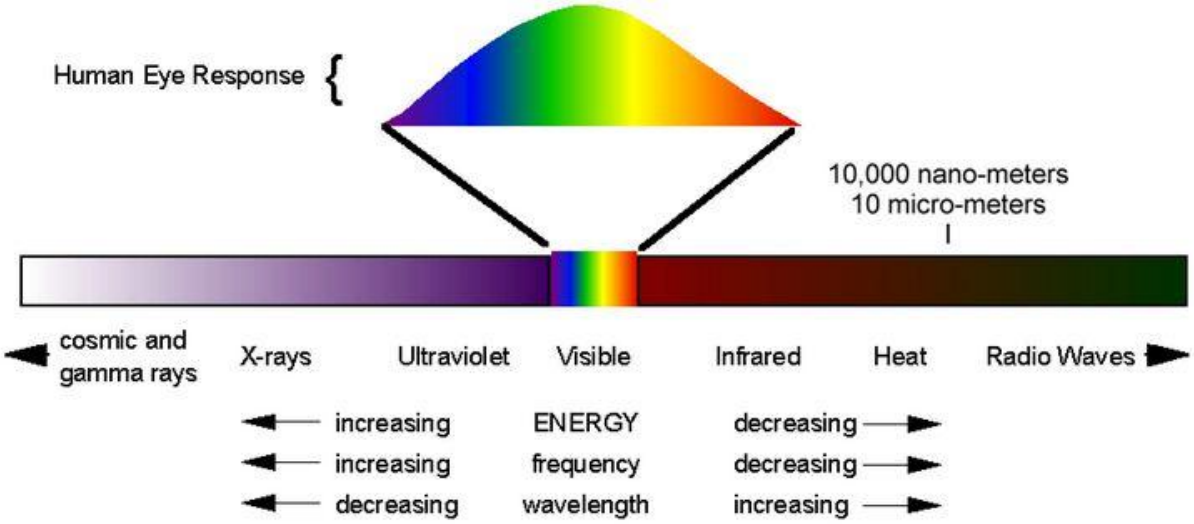
CHAPTER 1: INTRODUCTION

Of all the attributes, color adds beauty to an object and is an important part of our visual experience which is useful for powerful visual processing. Human visual system is a very complex one. Human eye perceives color as a distribution of wavelengths of light entering into the eye. This spectral distribution function impinges on the retina of the eye and is absorbed by the cones which in turn sends signals to the brain. Though many alternative models have been fabricated to mimic the human visual system, very few were based upon the wavelengths of light, perceived as color by human eye.

Here we have attempted a color vision and perception study over a population of generalized individuals solely based upon different wavelengths of entire visible spectrum.

1.1 THE VISIBLE SPECTRUM OF LIGHT

Light enters the eye as spectrum of colors, distributed by wavelength. A typical human eye will respond to wavelengths from about 380 to 780 nm.



1.2 VISUAL RECEPTORS

A photoreceptor cell is a specialized type of neuron cell which is found in the retina and is capable of photo-transduction.

The retina of every organisms contains mainly two kinds of photo receptors, rods and cones. The human retina contains as many as 120 million rod cells and 6 million cone cells. Rods are extremely sensitive whereas cones are not. Rods can get activated by even 6 photons. Therefore, the visual perception at very low light intensities is mainly due to rod cells.

Cone cells provide the eye’s color sensitivity. These cells can be divided into three types based upon the range of the wavelengths by which they are activated. They are “Red” cones (64%), “Green cones” (32%) and “blue cones” (4%).

1.3 COLOR VISION

The phenomenon of colour is a direct result of electromagnetic waves or energy interacting with an object and the inferences obtained by the observer . Color vision is the ability of any organism to distinguish among the objects based upon the wavelength or frequency of the light that is emitted transmitted or reflected by the object. The retina of every organisms contains mainly two kinds of photo receptors, rods and cones. The human retina contains as many as 120 million rod cells and 6 million cone cells. Rods are extremely sensitive whereas cones are not. Rods can get activated by even 6 photons. Therefore, the visual perception at very low light intensities is mainly due to rod cells.

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1.4 CONCEPTS OF COLOR

For the color perceived by the human eye, there are three different concepts:

a) ***Color psychology****:* This represents the emotion stimulated in the brain by a color. If a particular wavelength is characterized as green, it is green because it is what the person has been taught. The perception of the color green may be vary for different individuals. Thus, because of the effect of the color or wavelength has on an individual, differences are observed in the color perception among different individuals.

b) ***Colour physiology****:* This represents the different physiological effects produced on the human eye by different wavelengths. Thus as a result of this a psychological perception of the wavelength or the color is produced. Being an excellent optical device, a human eye is able to recognize narrow regions of the visible light range.

c) ***Physical colour****:* The color can be mathematically defined as numbers according to the wavelength and intensity of light by the means of measurement appliances. This color is also important in terms of Spectrophotographic methods and measurements.

1.5 COLOR VISION THEORIES

Out of many theories, two major theories stand out and explain research on color vision: the *trichromatic* theory also known as the Young-Helmholtz theory, and the *opponent-process* theory. Both theories complement each other and explain processes that operate at different levels of the visual system.

The *trichromatic theory* of color vision or the Young-Helmholtz theory assumes the existence of three kinds of photoreceptors called as the cone cells; S-type, M-type and L-type that have different spectral sensitivities. These photoreceptors produce signals or responses which are sent to the central nervous system and perceived as color sensations[1].

Also known as the *Young-Helmholtz three-component theory*, it is based on the analysis of the response required to trigger color sensations and provides satisfactory explanation for additive color matching. Unfortunately, the *Young-Helmholtz* theory fails to explain some issues relating to perception of colors, such as the opponent nature of visual after images, as well as why some colors cannot perceived together while others (*e.g.*, green and yellow, green and blue, red and yellow, and red and blue) are easily found [2].

All these shortcomings can be satisfactorily explained by Hering's *opponent-color theory*, which assumes the existence of six basic colors i.e. white, black, red, green, yellow, and blue.

Hering said, photo pigments absorbs light but, the signals from the cones and rods are processed by human visual system in an antagonistic manner. Instead of having six separate channels, the visual system uses only three opposing channels: white versus black (*WS*), red versus green (*RG*), and yellow versus blue (*YB*). While same amounts of black and white produce a gray sensation, equal amounts of red and green cancel to zero. Similarly, same amounts of yellow and blue also cancel out. Zero, here means that the spectral response functions for the opponent channels nullifies at the points where opponent colors take equal values.

Response of one color belonging to an opponent channel is antagonistic to that of the other color i.e. there is no bluish – yellow or reddish – green.

As we see considering separately, neither of the theories satisfactorily explains many color vision phenomena of importance. The trichromatic theory explains color vision phenomena at the photoreceptor level; the opponent-process theory explains color vision phenomena according to how photoreceptors are neutrally interconnected .

By combining both the theories, however, they could explain and predict many color vision phenomena involving color matching, color discrimination, color appearance, and chromatic adaptation, among others, for both normal color vision and color vision deficient observers[1].

According to Von Kries, the trichromatic theory should be valid at the photoreceptor level, but the resulting signals needs to be further processed in a later stage in accordance with the opponent-color theory[3].

This is called *stage theory* or *zone theory*. It provides the most logical models for color vision among humans. Besides the two-stage theory suggested by Von Kries, other two- and three-stage theories of color vision have been proposed, including M¨uller three-stage theory. A discussion of some of these theories can be found in [3].

To the human vision, there exists in color images a certain amount of perceptual redundancy since the human visual system (HVS) has limited sensitivity in discriminating color signals of small differences. Such colors of small differences are called **Just Noticeable different** colors.

In the following test, such near wavelength colors has been checked that does not seem to be different to a normal human eye.

Moreover the color perception of a single color varies from individual to individual, more or less. A generalized idea can be drawn if we have the results of color perception of a huge population having normal vision .

As stated earlier , this test is solely based upon the wavelength of light and its perception by normal human eye. The test consists of a central color of certain wavelength which was surrounded equidistantly by colors having wavelengths, not differing much from the central color. In the test the subjects had to choose the colors that looked similar to the central color.

The main objectives of the test is to check for the just noticeable different colors among the nearly different wavelengths and to obtain a generalized normal human color perception.

Conclusive and reliable results can be found when the results of the test of a large sample of individuals, say 1000 or more, is statistically analyzed. These results could be highly useful in the early diagnosis of several eye defects such as cataracts or could even be useful in diagnosing color blindness.

This test can also diagnose Age related Macular Degeneration (AMD) at an early stage when color perception is lost due to the loss of functionality of normally formed photoreceptor cone cells, which are most dense on macula.

CHAPTER 2 : LITREATURE REVIEW

2.1 FACTORS AFFECTING HUMAN COLOR PERCEPTION

The color of a fovea centered object may appear different *if seen peripherally*. In the far periphery, a person would not be able to tell the object's color immediately, but would know the object was there - a function of rods versus cones. As the object got closer and the person started to perceive its color, he/she may not have perceived the correct color. It may happen that the color of the objects seemed to change many times until the correct color was sensed during the remainder of its trek across the visual field towards the fovea (Kinney, 1979).

According to the paper published by Capt Eileen Ancman on color perception limitations, subjects wrongly identified the color of a peripherally located, 1.3" circle displayed on a CRT 5% of the time if it was blue, 63% of the time if red, and 62% of the time if green. Blue could not be seen further than 83.1" off of the fovea along the x-axis.Red had to be closer than 76.3" and green nearer than 74.3" before the subjects reported seeing the colors. These average color field dimensions changed with differing subject psychological states due to the observed "visual field narrowing" (i.e. reduction of the subject's peripheral field of view) in both the relaxed and stressed states. A significant degree of visual field narrowing was noted for the relaxed state (8%) with a trend noted for the stressed state (2%).[4]

According to the *spatial color distribution* in the image domain human visual system can show different color perception sensitivity [5], [6]. Human visual system is very sensitive to the color distortion in the homogeneous regions that are composed of pixels having coherent colors. Sensitivity to the distortion in the distinctive or prominent areas that concentrate great attention of human visual system is also significant. Approaches have been put forward to consider such properties not only for image quantization but also for segmentation of image.[7], [8]. Algorithms an approaches based upon based upon clustering and histogram tried to separate feature space that is derived from a color image for image quantization. During a clustering stage the color space to represent the differences between color vectors are precisely and carefully selected.

The *size of the object* influences the appearance of the color of the object as it dramatically changes the color perception with the size of the object being viewed. Evaluating different colorings on the object of same size is a good practice for experimentation of the effective use of color for visualization because it minimizes the number of variables being studied. Viewing of the color physically changes it to one which is a blend of the foreground and background colors. Even the lights between the adjacent pixels can mix. Such blending and mixing process is spatially sampled and integrated as the human eyes scan the display. This effect is called *Spreading*.[9]

Textures are common distinguishing features used in segmentation and characterization of images texture influences the observer's ability to perceive color differences[10].

A color may appear different depending on its relation to *adjacent colors*, popularly known as Bezold effect. It happens when small areas of color are interspersed. An assimilation effect called the von Bezold spreading effect, similar to spatial color mixing, is achieved.

2.2 JUST NOTICEABLE DIFFERENCE (JND).

Just noticeable difference, though originated from the psychological background, has a strong mathematics supporting it definition. The Difference Threshold (or "Just Noticeable Difference") is the minimum amount by which stimulus intensity must be changed in order to produce a noticeable variation in sensory experience.

Ernst Weber, a 19th century experimental psychologist, observed that the size of the difference threshold appeared to be lawfully related to initial stimulus magnitude. This relationship, known as Weber's Law, can be expressed as:

$$\frac{\Delta \mathrm{I}}{\mathrm{I}} = \mathrm{k}$$

Where ΔI represents the difference threshold, I represents the initial stimulus intensity and k signifies the proportions on the left side of the equation remains constant despite variations in the I term.

Mathematically, if we denote I as the gray scale depth representation which consists of, say n pixels and c is its center pixel. Then the centre pixel, c is just noticeable if and only if,

$$\left| \frac{\mathcal{I}_c - | \frac{1}{n-1} \sum_{j \neq c} \mathcal{I}_j}{\frac{1}{n-1} \sum_{j \neq c} \mathcal{I}_j} \right| \geq \delta,$$

Where j = 1,2,3,…..,n, and Ij is the pixel value for the jth pixel and δ is the JND value, which is normally small.

The human visual system cannot sense the visual alert under a certain threshold which is called the just-noticeable difference threshold. This physiological and psychophysical phenomena is useful in image and video compression, quality evolution, and watermarking [1–3], etc.

The JND color model in RGB space based on limitations of human vision perception as proposed in [11]. According to [12] a normal human eye can perceive at the most 17,000 colors at maximum intensity without saturating the human eye. In other words, if the huge color space is sampled in only 17,000 colors, a performance matching close to human vision at normal illumination may be obtained. A human eye can discriminate between two colors if they are at least one 'just noticeable difference (JND)' away from each other. The term 'JND' has been qualitatively used as a color difference unit [13].

The red axis has been quantized in 24 levels and the blue and green axes are quantized in 26 and 28 levels [11]. Using this sampling notion and the concept of 'just noticeable difference' the complete RGB space is mapped on to a new color space Jr, Jg, Jb where Jr, Jg and Jb are three orthogonal axes which represent the Just Noticeable Differences on the respective R,G and B axes. The values of J on each of the color axes vary in the range (0,24), (0,26) or (0,28) respectively for red, blue and green colors.

The human visual system (HVS) is a multichannel system, two channels can be assumed to exist in the HVS, which deliver luminance adaption factor and texture masking factor. The Luminance adaption factor refers to the masking effect of HVS towards background luminance. The texture regions can tolerate much noise. Because they have abundant redundancy . The disorder degree and spatial masking of the texture are estimate the texture masking effect. This deduces JND threshold that coincides with the Human Visual System. Finally, the luminance adaptation factor and texture masking factor are combined nonlinearly. It has been proved through various experiments that the improved model has a better visual effect than models proposed before.

Additionally contrast masking (CM) on edge and textured regions needs to be distinguished as distortions on edges are easier to be noticed than that on textured regions. Therefore, efficient estimation of the CM on edge and textured regions is an important issue for accurate JND (Just Noticeable Difference) estimation. contrast masking refers to the masking effect of HVS towards the spatial activities in the neighborhood.

In Chou and Li's model [14], the JND threshold of the background luminance is deduced from the Weber's law. And the texture masking effect is estimated by the maximum signal among the four edge detectors. Finally, the bigger value between the two masks is chosen as the JND threshold.

In Chou *et al.*'s model [15], CM is estimated with the maximum signal from four edge detectors with 45 degrees apart.

In Chiu *et al.*'s model [16], CM is determined by the maximum luminance difference of the central pixel and its neighbors in horizontal and vertical directions.

The JND threshold is defined as a weighted sum of luminance adaptation threshold and texture masking threshold.

Yang *et al*. [17] modified Chou et al.'s model by detected edge pixels (by Canny detector [18] with a threshold) and suppressed the CM on the detected regions. In Chou *et al*.'s models, CM on textured region is under-estimated since they treated texture as the same as edge. In general, Yang *et al*.'s model outperforms Chou *et al*.'s models since edge and texture are distinguished by edge detection. Edges are distinguished from the texture regions to avoid over estimating of their JND thresholds, since the HVS is sensitive to edges However, for some images (especially the image with lots of texture), the performance of Yang *et al*.'s model can be worse than that of the Chou et al.'s model due to the inaccuracy of edge detector

To solve the above mentioned drawback in the existing models, an enhanced image domain JND estimator is devised by Liu *et al* [19] with a new model for CM. CM on edge and textured region is to be estimated separately, and the separation can be done by image structure-texture decomposition based upon the total variation model. Liu *et al* concluded that edge and texture are better distinguished by using the said image decomposition model; a more accurate CM model, therefore, a better JND model to mimic the masking effect of the HVS.

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In Wu *et al*'s [20] model, two major factors, luminance adaptation and texture masking, are chosen to estimate the JND threshold disorder of the texture, is added to estimate the texture masking for computing a much precise JND threshold of the texture region The two factors, luminance adaptation and texture masking, affect the visibility threshold in the HVS in a cooperative manner. In the flat regions, the luminance adaptation is dominating whereas the texture masking effect is primary in the texture regions. The JND threshold of each pixel is a nonlinear combination of the two factors.

2.3 COLOR PERCEPTION TESTS

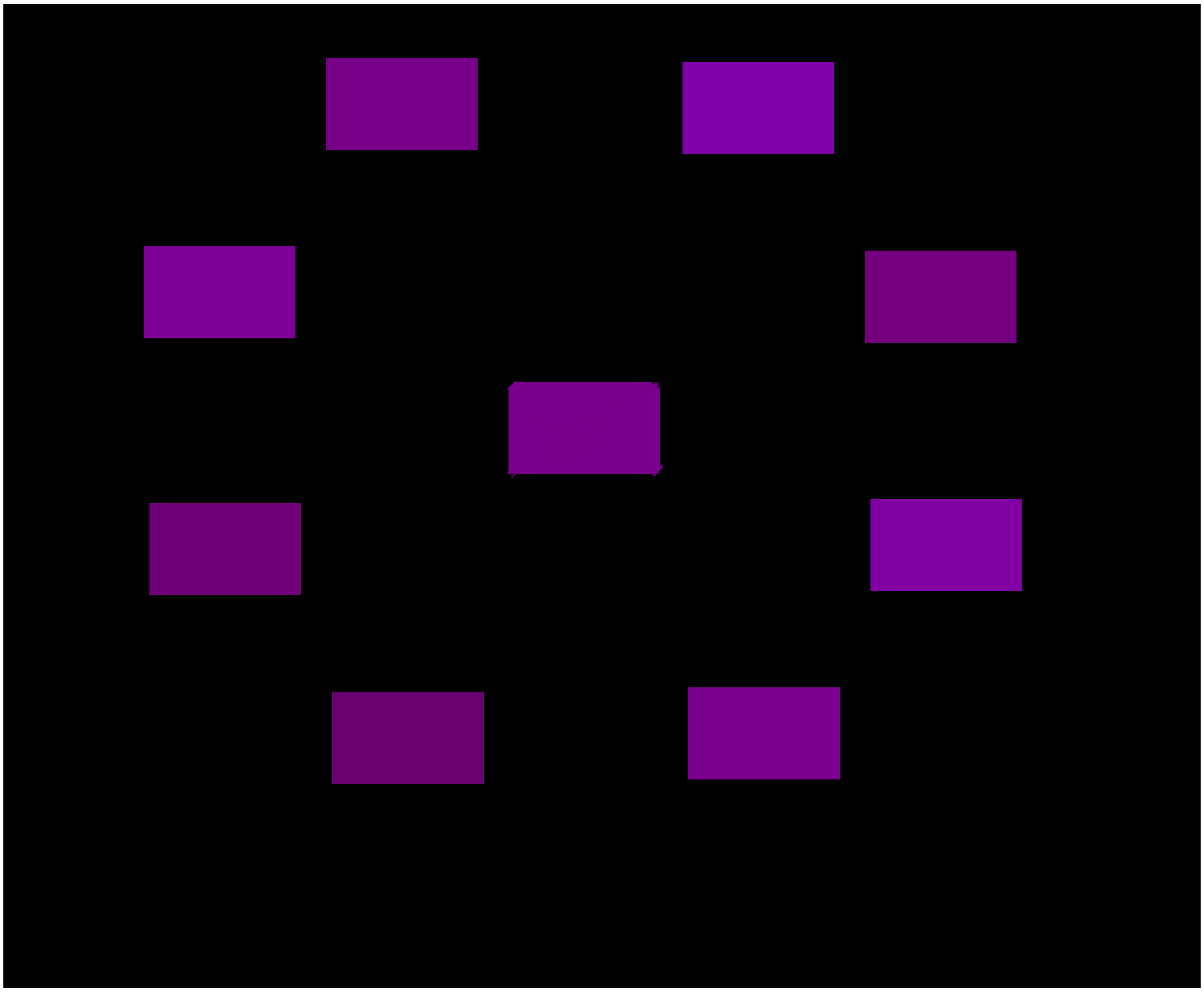
Pseudoisochromatic (PIC) plates are example of color camouflage. The object and background of the test design are colored spots or patches of randomly aligned size and luminance [21]. This particular properties provide size and luminance noise, so only color information can be used by individual to detect the latent object. The colors of the background and test spots are aligned along the dichromate confusion lines, with variations of luminance and chromatic saturation.

The dotted pictures are often referred to as *Ishihara plates*, Within each pattern, a number is present. It was named after its designer, Dr. Shinobu Ishihara, who first published his tests in 1917. The test is intended to determine the type of color vision defect, protanopia or deuteranopia and the severity of it.

Anomaloscope as the name suggests is an apparatus used to diagnose anomalies of color perception in which one half of a field of color is matched by mixing two other colors. one-half of a circular field which is illuminated with yellow with a mixture of green and red in the other half. The yellow half can be varied in brightness, while the other half may be varied continuously from red to green. A certain combination of the red and green mixture is considered normal, and variations from that mixture indicate anomalous colour vision. With this instrument one can distinguish between a protanope and a protanomal and between a deuteranope and a deuteranomal. Some anomaloscopes also test for blue-yellow colour vision deficiencies, e.g. Pickford-Nicholson anomaloscope.

CHAPTER 3 : MATERIALS AND METHODS

The test consisted of twenty slides having the central wavelengths from 390 nm to 770 nm with an interval of twenty nanometers i.e. 390 nm, 410 nm, 430 nm, …. Upto 770 nm. The layout of the test is given underneath.



The central rectangular box is of the color having wavelength from 390 nm, 410 nm, 430 nm and so on upto 770 nm. The eight remaining boxes are of colors having wavelengths +7 nm, +5 nm, +3 nm, +1 nm, -1 nm, -3 nm, -5 nm, -7 nm with respect to the wavelength of the central wavelength. Thus the test consisted of twenty such slides having central wavelengths ranging from 390 nm to 770 nm hence covering the whole visible range of color spectrum.

The subjects are required to highlight the colors or boxes that look similar (color wise) with the central color box for all the twenty slides.

The test has to be conducted in a dark room to avoid any interference from other light sources and chromatic adaptation.

The background color of the slides was chosen to be black in color to avoid color addition due to “after image” of the surrounding colors.

The subjects need to keep their head still throughout the test and it needs to be in parallel with the projection screen to avoid any parallax. A specially designed table-chair system where the position of the table could be changed horizontally and vertically with respect to the chair.

Borders were avoided around the rectangles to overcome the Bezold efeect.

The subjects are then have to take the test again, but this time highlighting the color boxes that are dissimilar to the central box after a brief interval of time at least 15 minutes. The dissimilarity test ensures ruling out of any erroneous observations that might have occurred in the similarity test.

The data so obtained are then recorded.

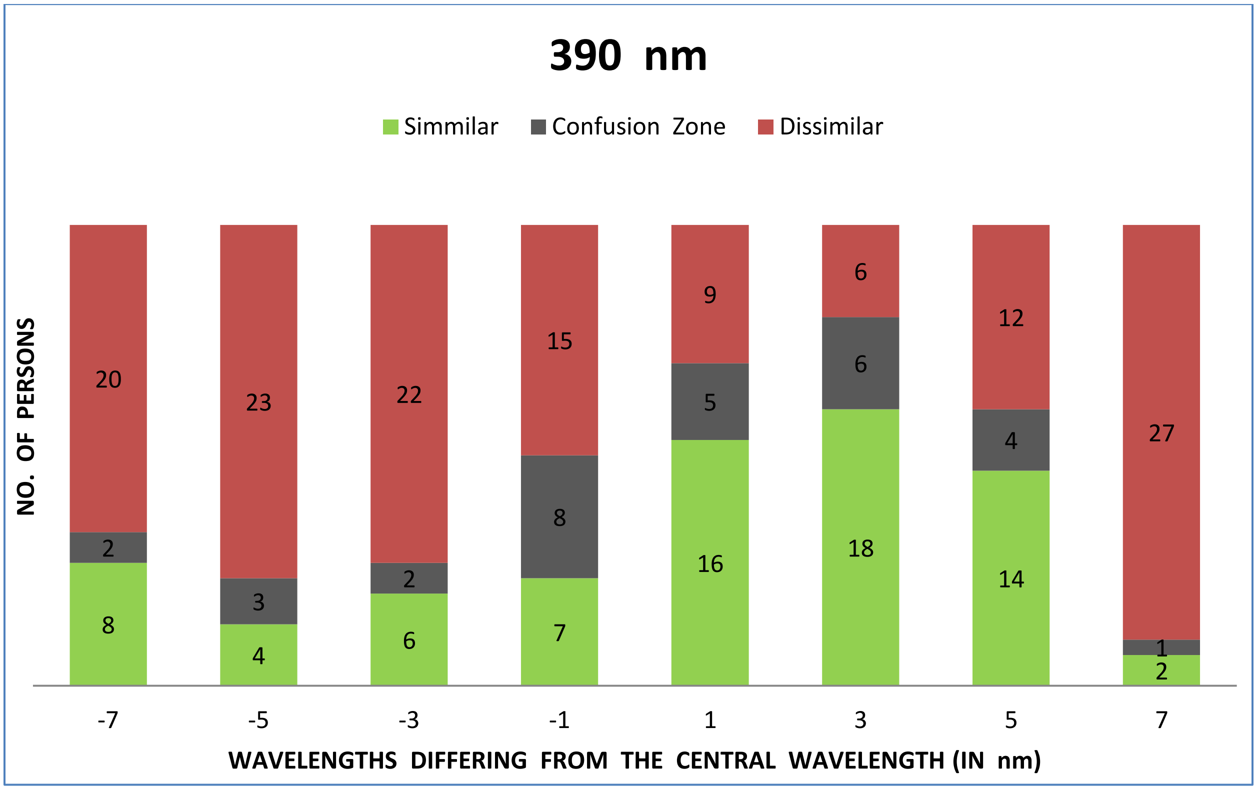
The test was conducted over a population of 30 subjects varying in age group and gender.

Graphs were plotted for each central wavelengths in which the frequencies of the remaining wavelengths are plotted.

CHAPTER 4 : RESULTS AND DISSCUSSIONS

4.1) Results for each central wavelengths :-

a) For central wavelength = 390 nm

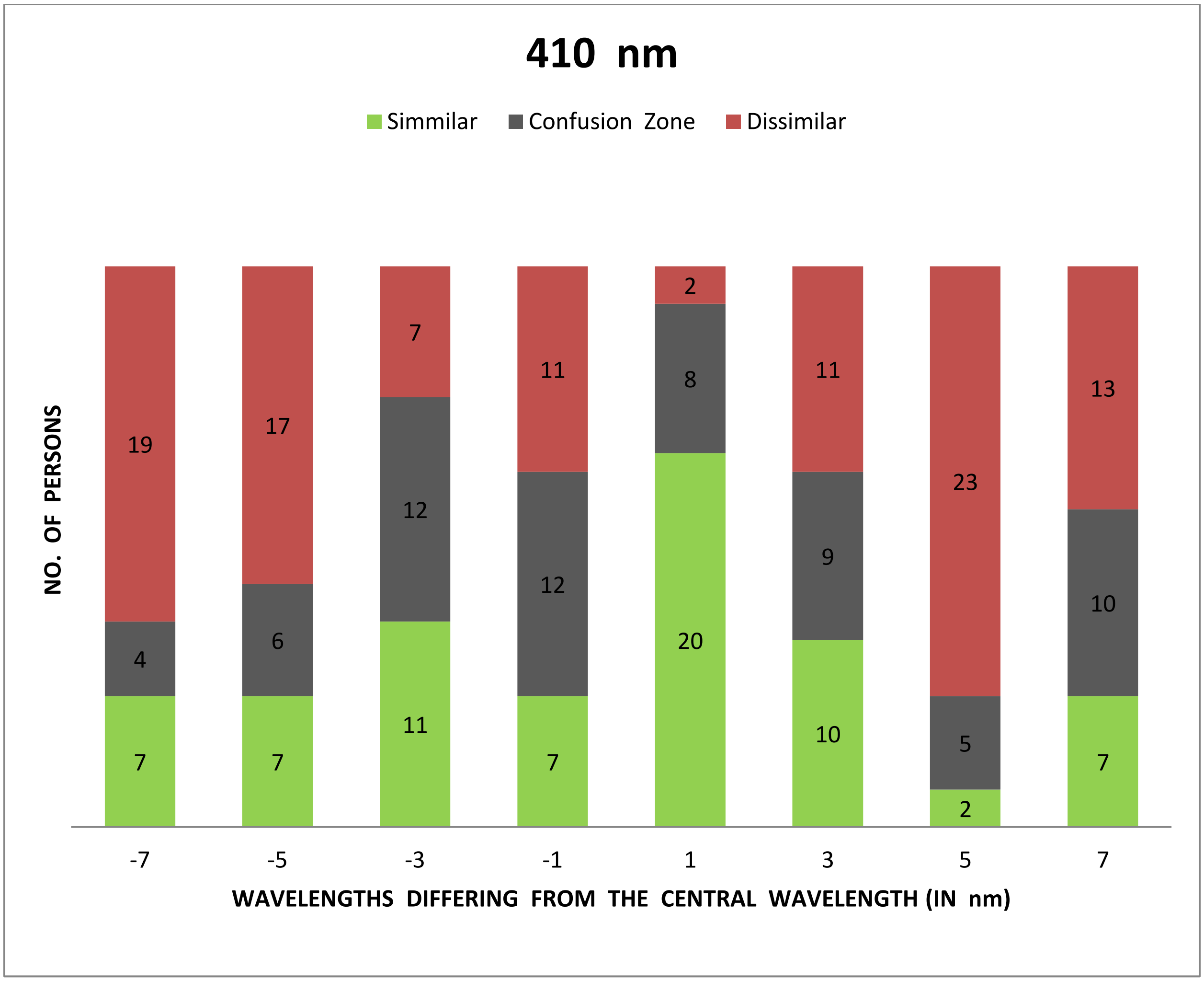


From the graph it is clear that the mode for the similar test is 393 nm with a frequency of 18 whereas for the dissimilar test is 397 nm with a frequency of 27.

The mean for the similar test was calculated to be 391.26 nm.

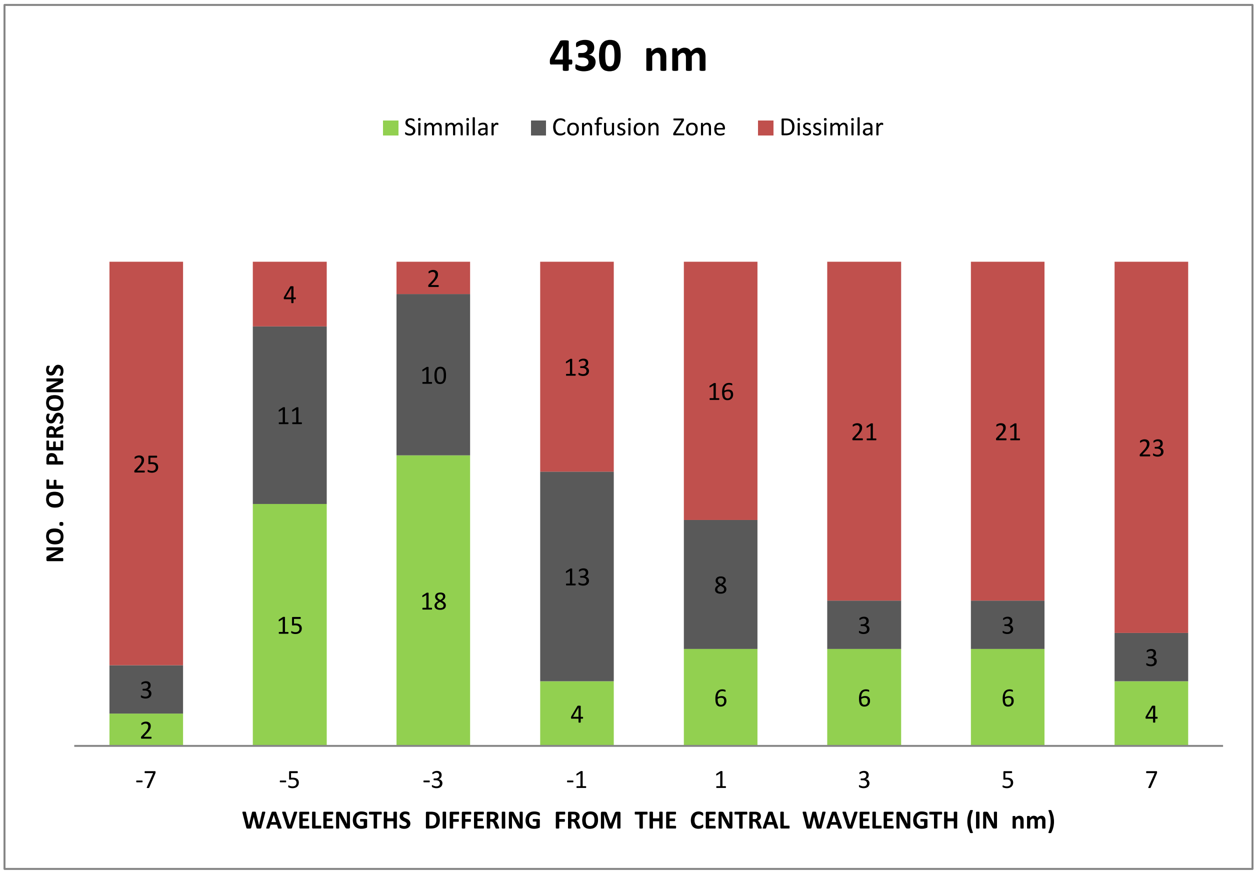
The most resembling colors for 390 nm are found to be in the positive side of 390 nm which are 391 nm, 393 nm, 395 nm. Thus the mean value was shifted towards the positive end.

b) For central wavelength = 410 nm



From the graph it is clear that the mode for the similar test is 411 nm with a frequency of 20 whereas for the dissimilar test is 415 nm with a frequency of 23. Strikingly the immediate negative wavelengths i.e 409 nm, 407 nm are confused most times.

c) For central wavelength = 430 nm

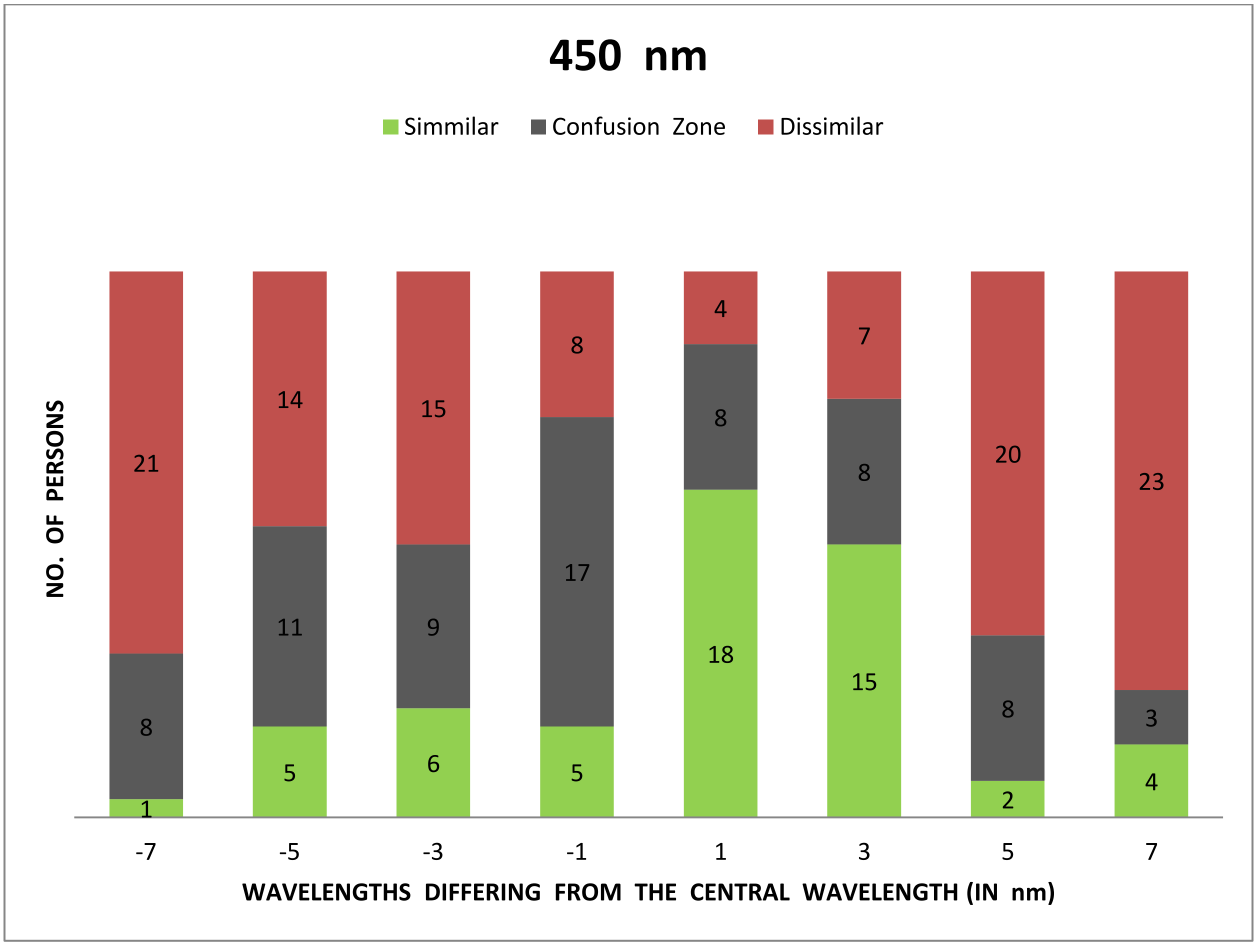


From the graph we know that the mode for the similar test is 427 nm with a frequency of 18 whereas for the dissimilar test is 493 nm with a frequency of 25.

The mean for the similar test was calculated to be 428.93 nm. The wavelengths that resembled the most with λ = 430 nm are found to be in the negative side.

The most similar ones are the most confused wavelengths as well and have been picked as dissimilar for the least number of times.

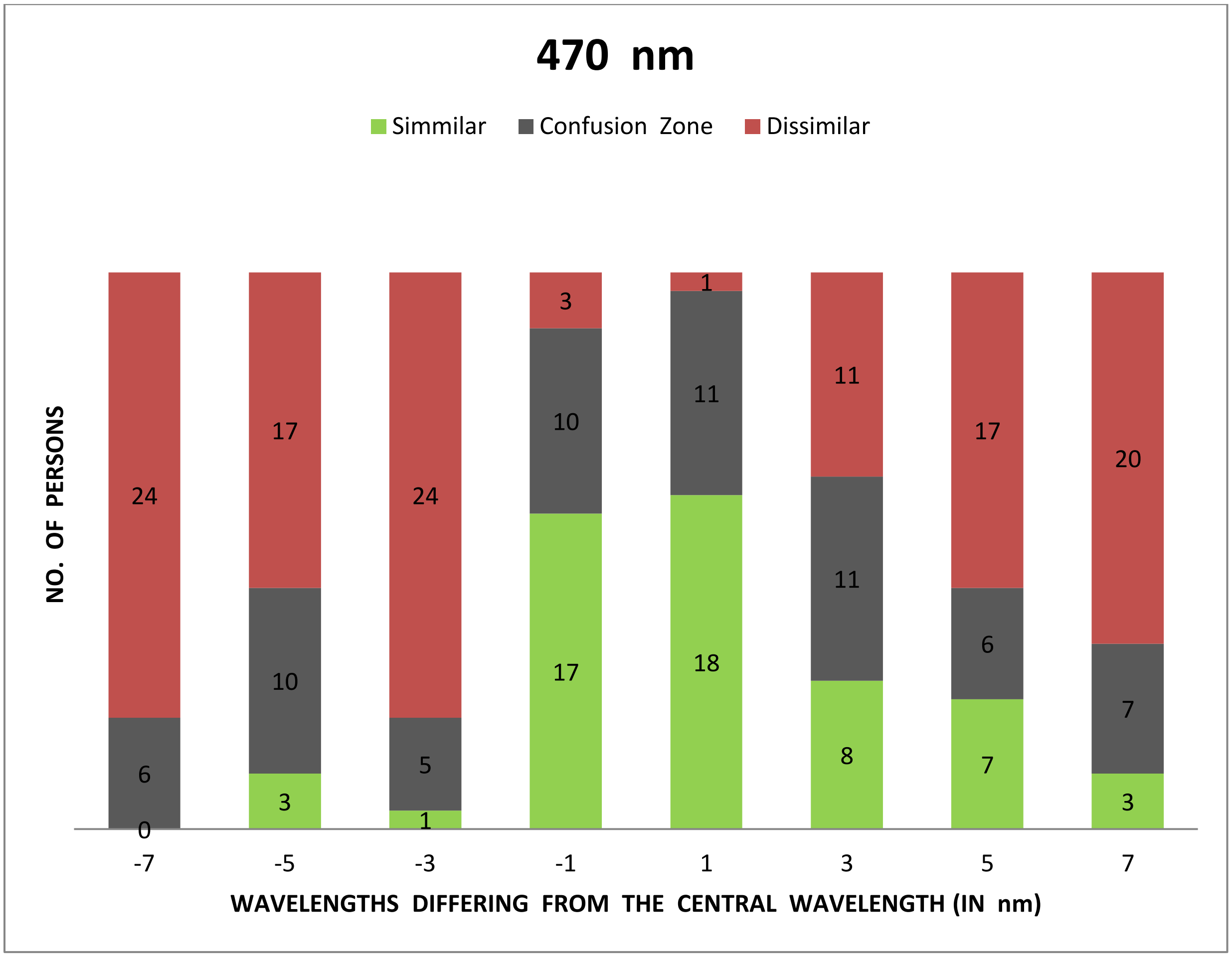
d) For central wavelength = 450 nm



This is the most confused color when compared with its near wavelengths especially in the negative side. From the graph it can be concluded that the mode for the similar test is 451 nm with a frequency of 18 whereas for the dissimilar test is 457 nm with a frequency of 23.

The mean for the similar test was calculated to be 450.82 nm.

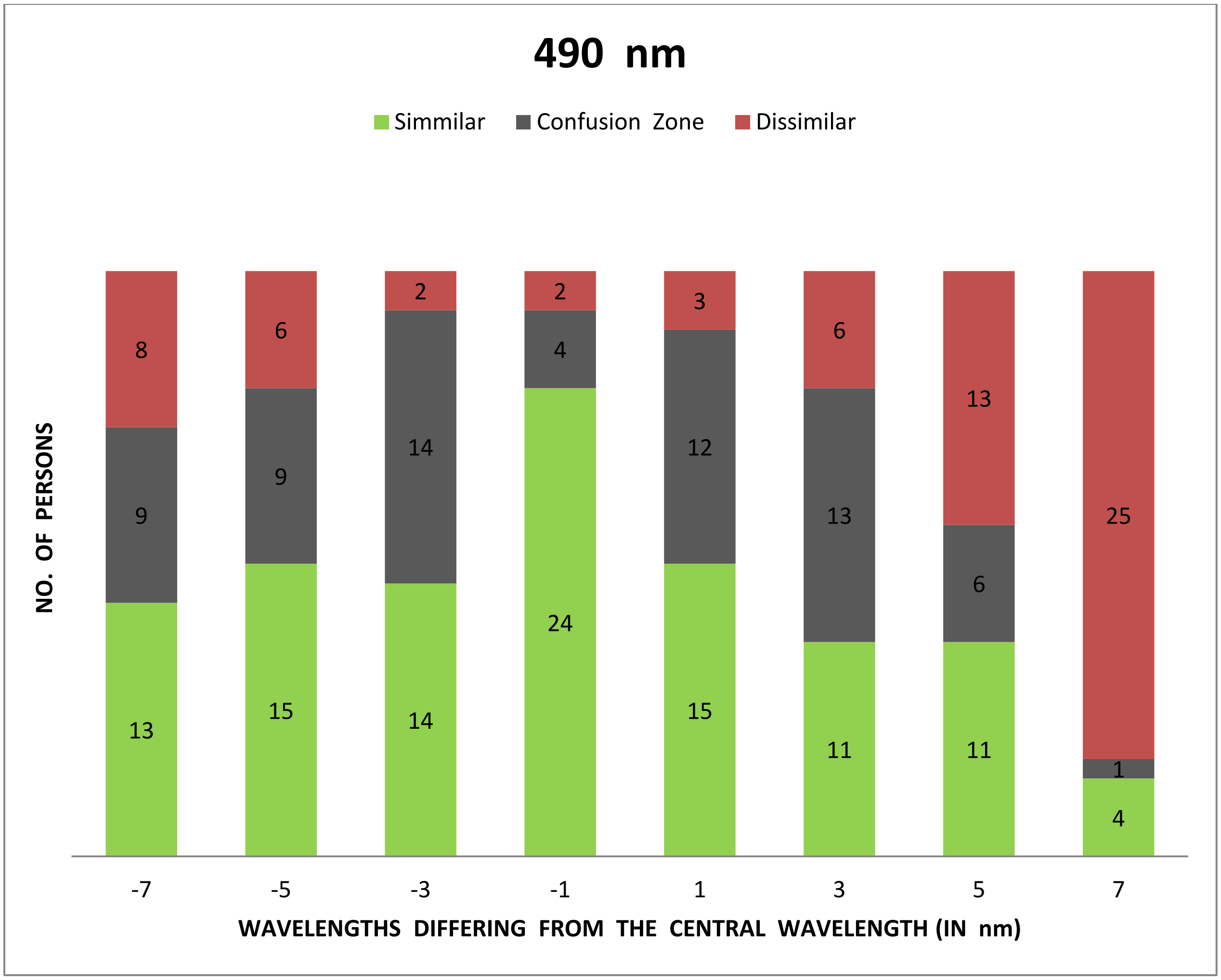
e) For central wavelength = 470 nm



From the graph it is clear that the mode for the similar test is 471 nm with a frequency of 18 whereas for the dissimilar test is 463 nm and 467 nm with a frequency of 24. The immediate neighbors of the central wavelength are the most alike colors with a high confusing frequency as well.

The mean for the similar test was calculated to be 471.1 nm.

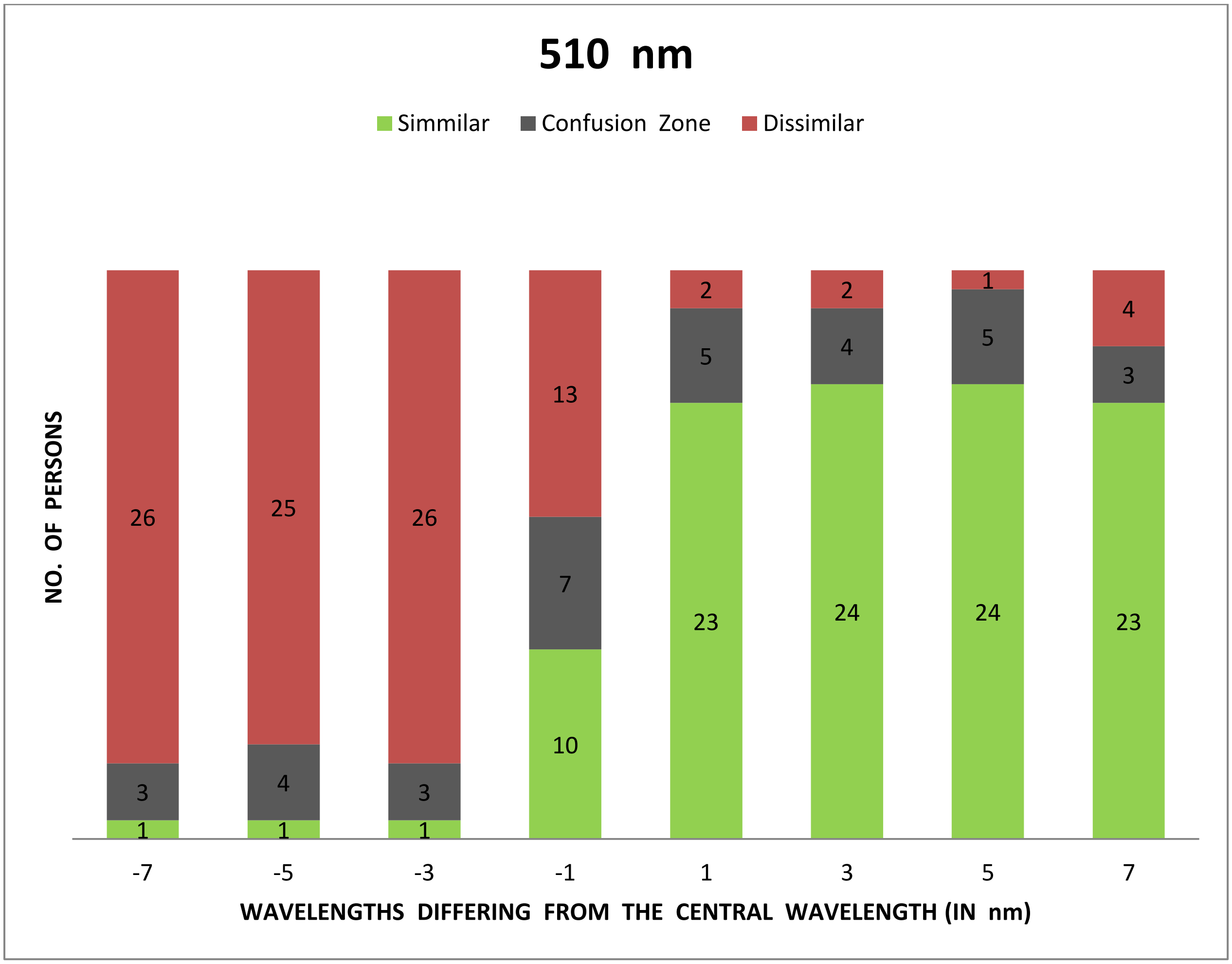
f) For central wavelength = 490 nm



From the graph it is clear that the mode for the similar test is 489 nm with a frequency of 24 whereas for the dissimilar test is 497 nm with a frequency of 27. Except the maximum and minimum frequencies rest all wavelengths have almost the same frequencies .

The mean for the similar test was calculated to be 491.26 nm

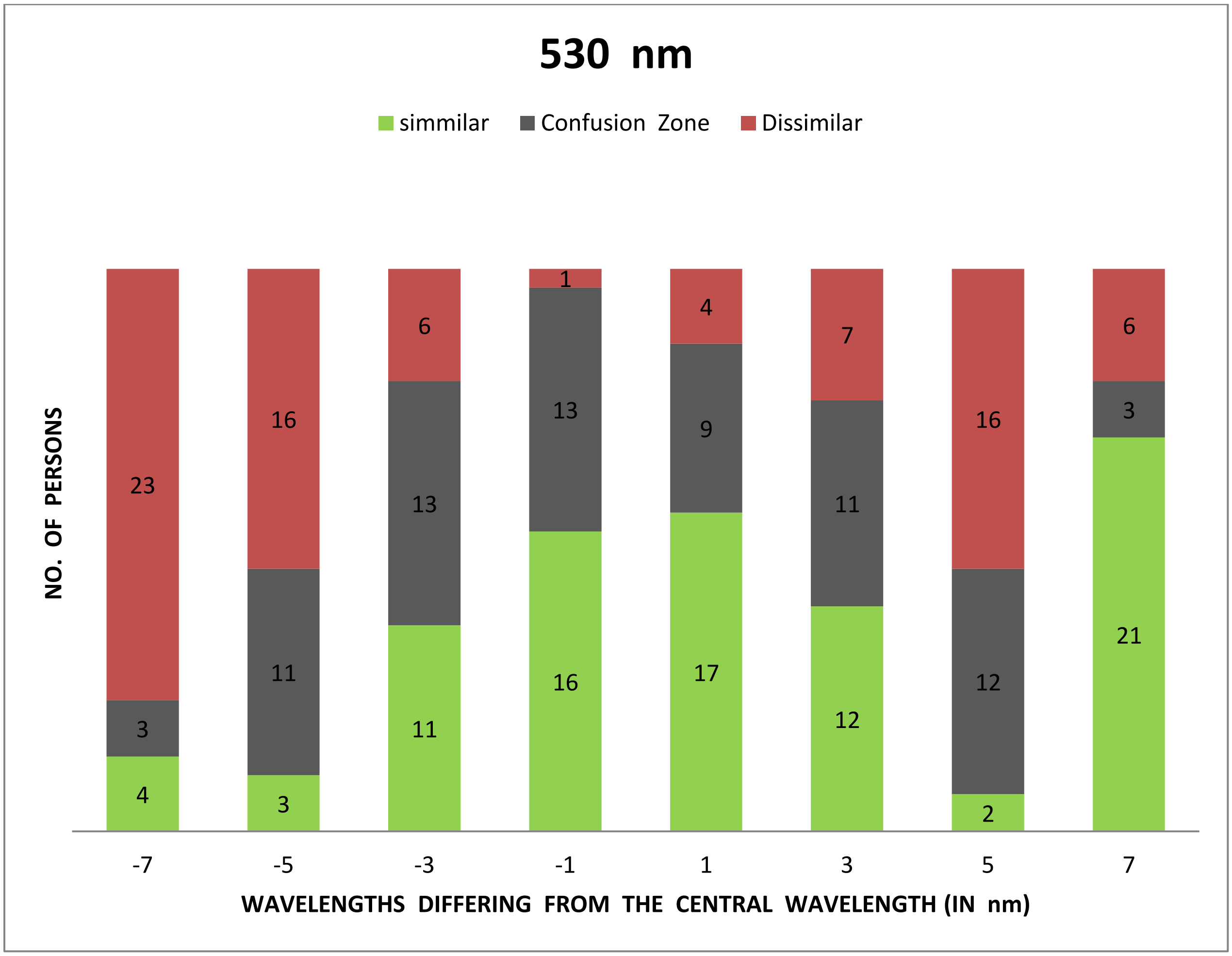
g) For central wavelength = 510 nm



From the graph it is clear that the mode for the similar test is 513 and 515 nm with a frequency of 24 whereas for the dissimilar test is 503 nm with a frequency of 26. The wavelengths on the positive side have massive ‘similar’ frequencies whereas those in the negative side have high ‘dissimilar’ frequencies .

The mean for the similar test was calculated to be 513.28 nm.

h) For central wavelength = 530 nm

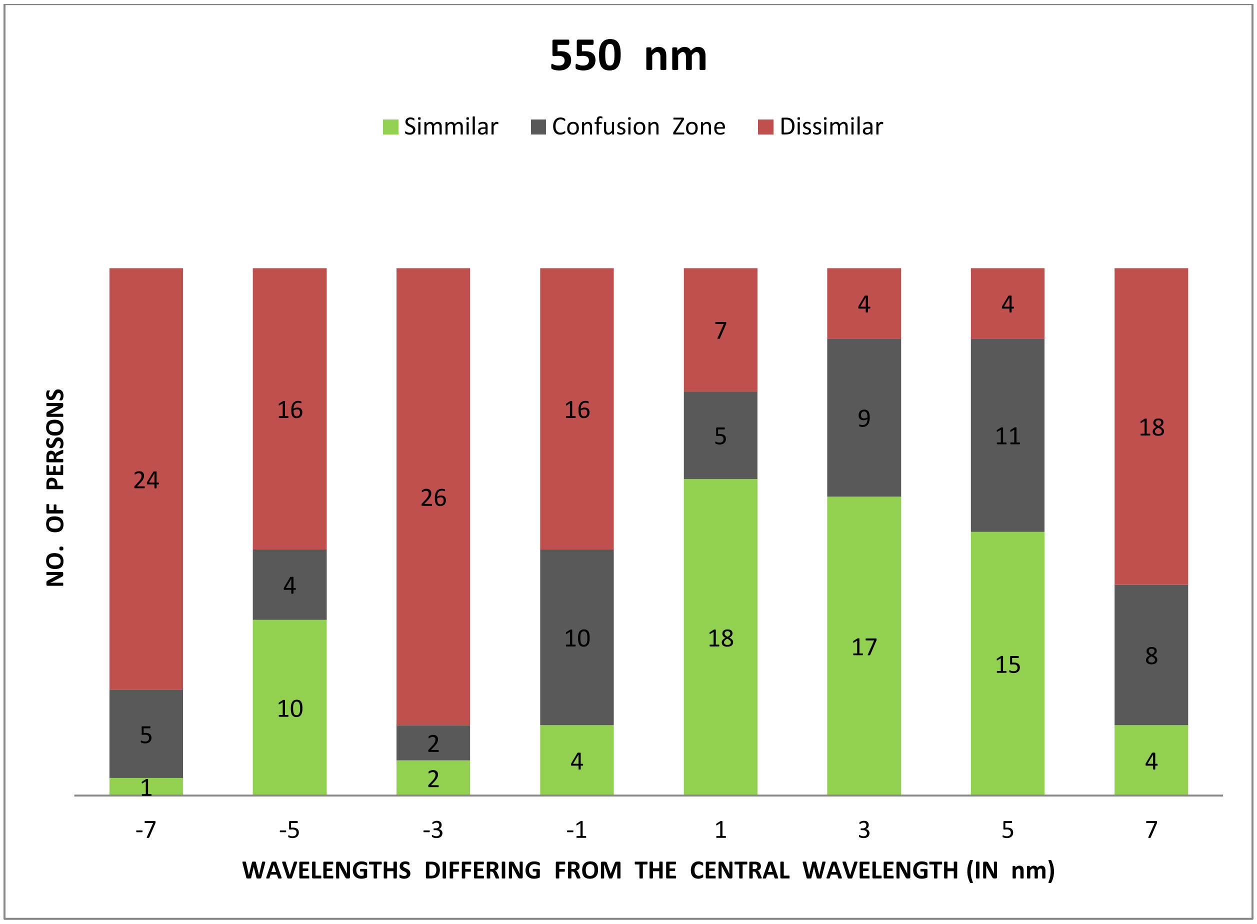


From the graph it is clear that the mode for the similar test is 537 nm with a frequency of 21 though the frequency of the similarity is concentrated within the +/- 3 nm whereas for the dissimilar test is 523 nm with a frequency of 23.

The confusion zone is high along with high similarity.

The mean for the similar test was calculated to be 531.37 nm.

i) For central wavelength = 550 nm

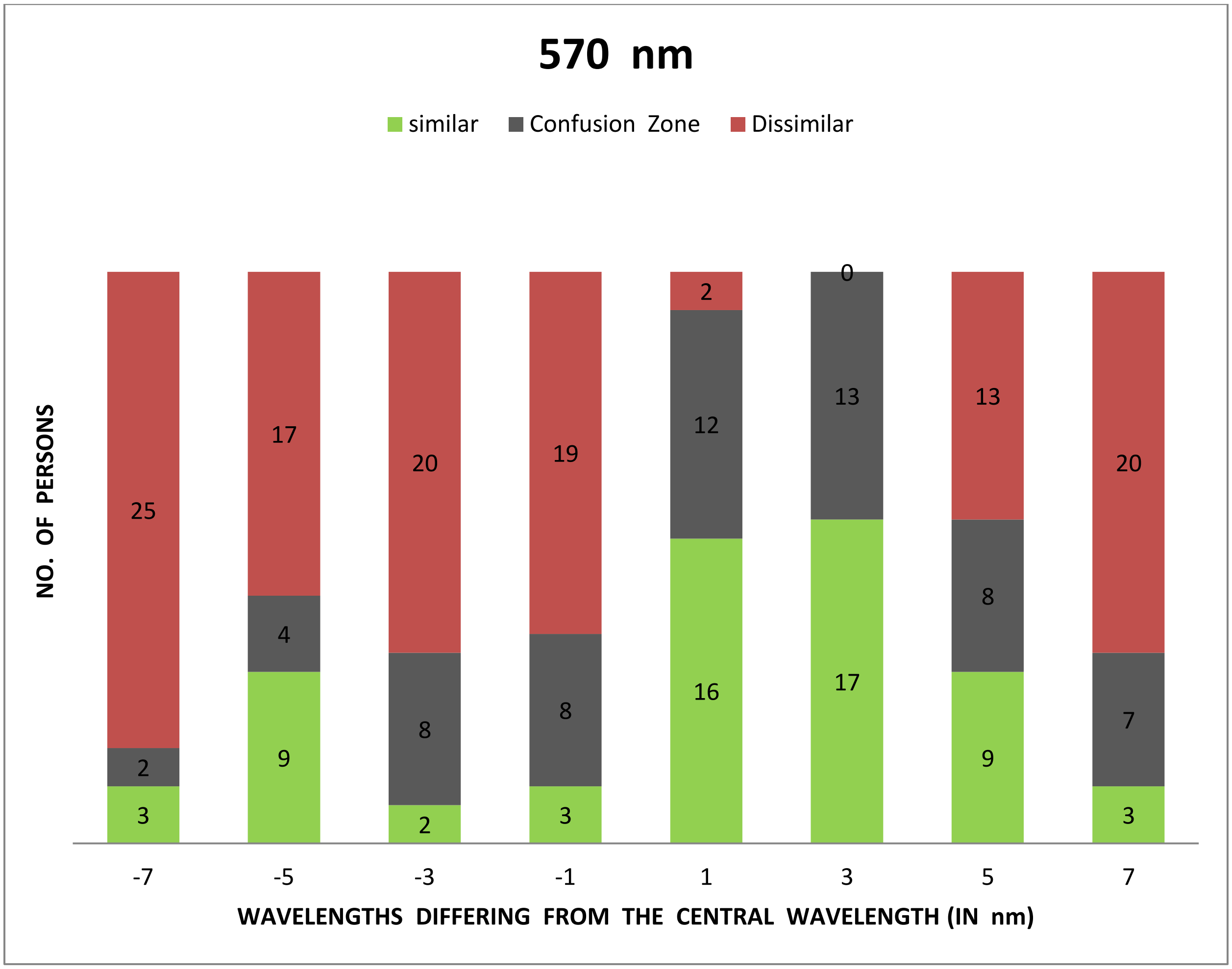


The mode for the similar test is 551 nm with a frequency of 18 whereas for the dissimilar test is 543 nm with a frequency of 24.

The positive side wavelengths show similarity with the central wavelength wheras the negative side show dissimilarity.

The mean for the similar test was calculated to be 551.48 nm.

j) For central wavelength = 570 nm

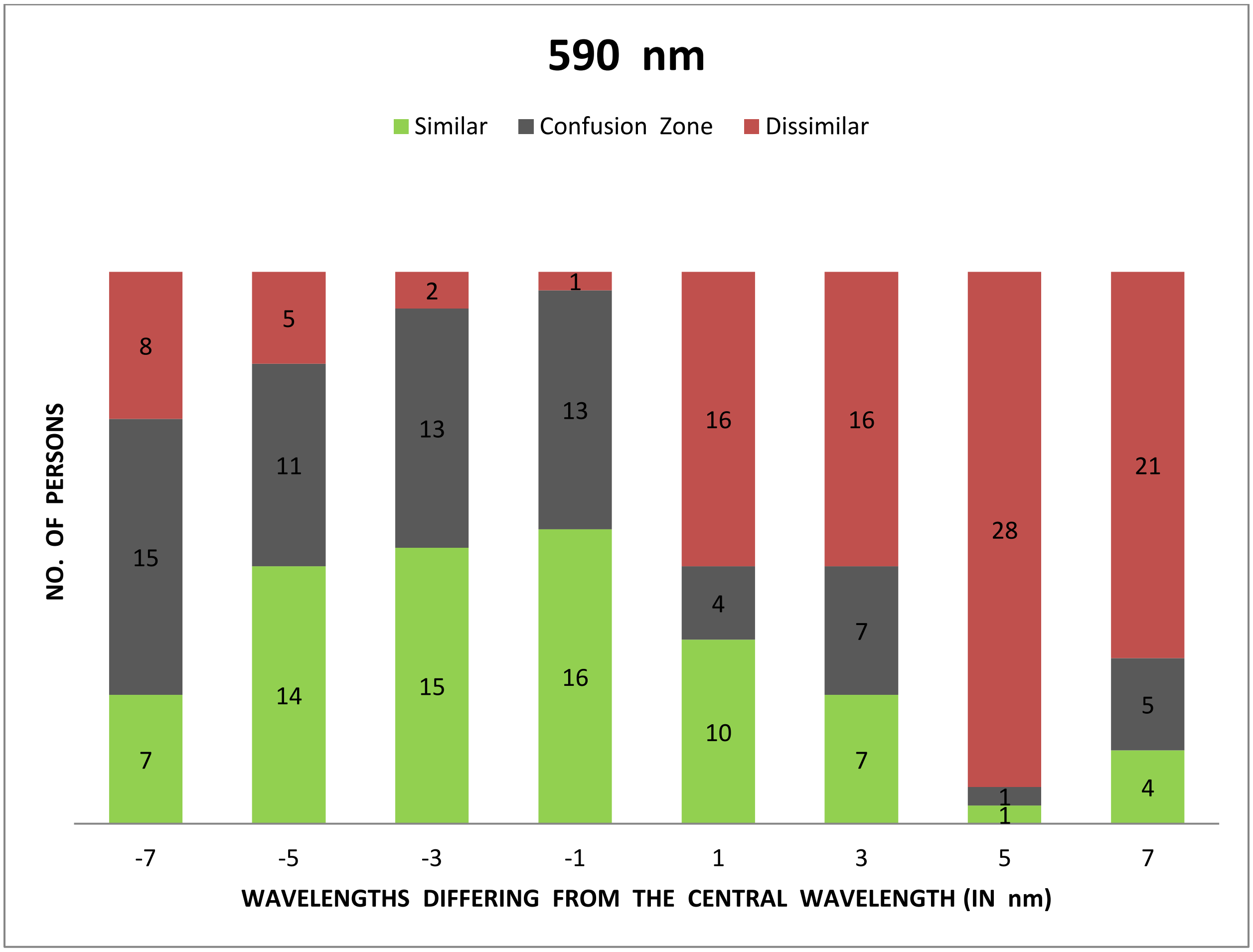


It is found out that the mode for the similar test is 573 nm with a frequency of 17 whereas for the dissimilar test is 563 nm with a frequency of 25.

All the near wavelengths are highly dissimilar except 571 and 573 nm.

The mean for the similar test was calculated to be 570.94 nm.

k) For central wavelength = 590 nm



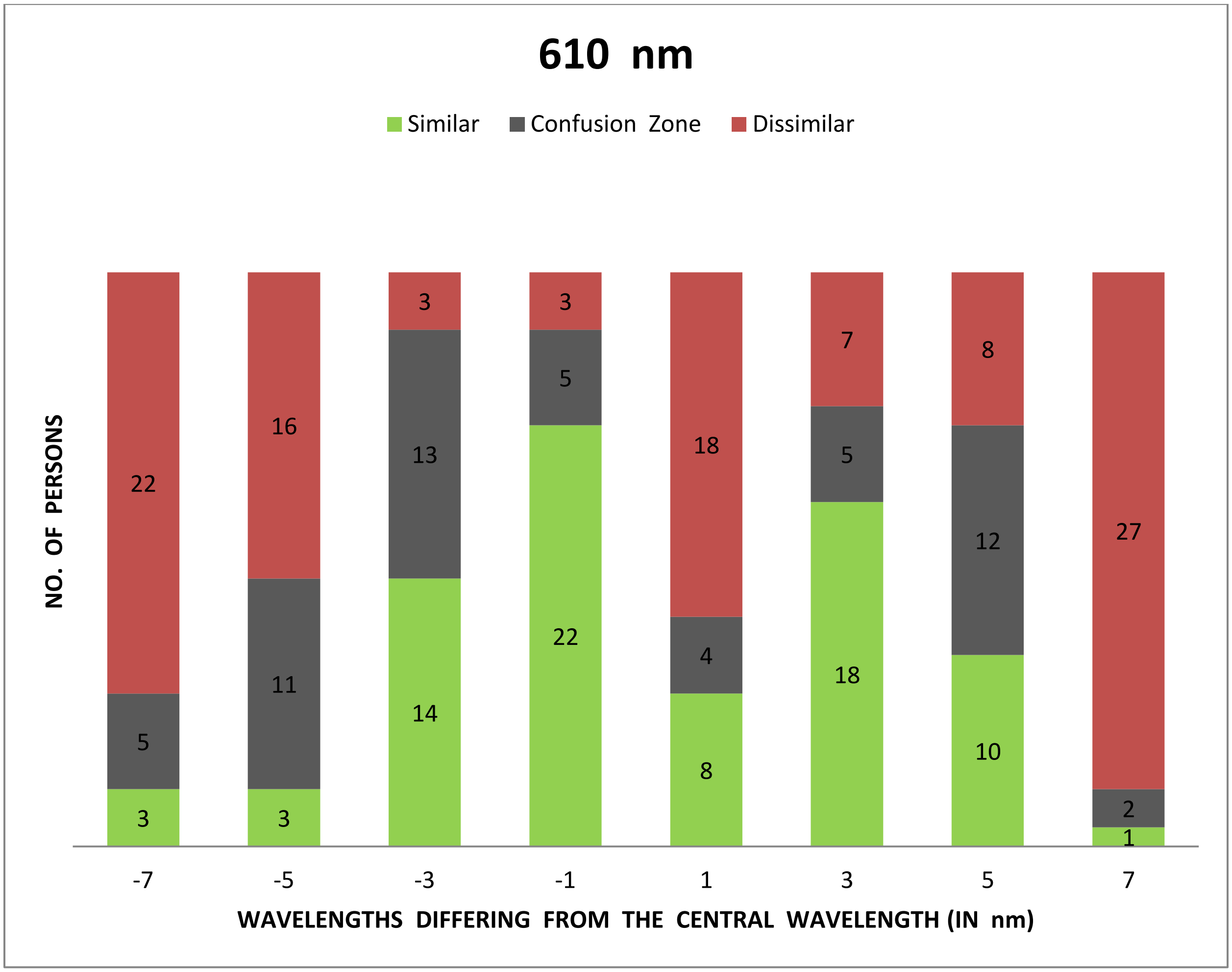
From the graph it is clear that the mode for the similar test is 589 nm with a frequency of 16 whereas for the dissimilar test is 595 nm with a frequency of 28.

The negative side wavelengths show higher similarity with the peak being 589 nm and gradually decreases as we go away from the central wavelength.

Again it was found out that confusion zone is higher among the most similar wavelengths.

The mean for the similar test was calculated to be 588.43 nm.

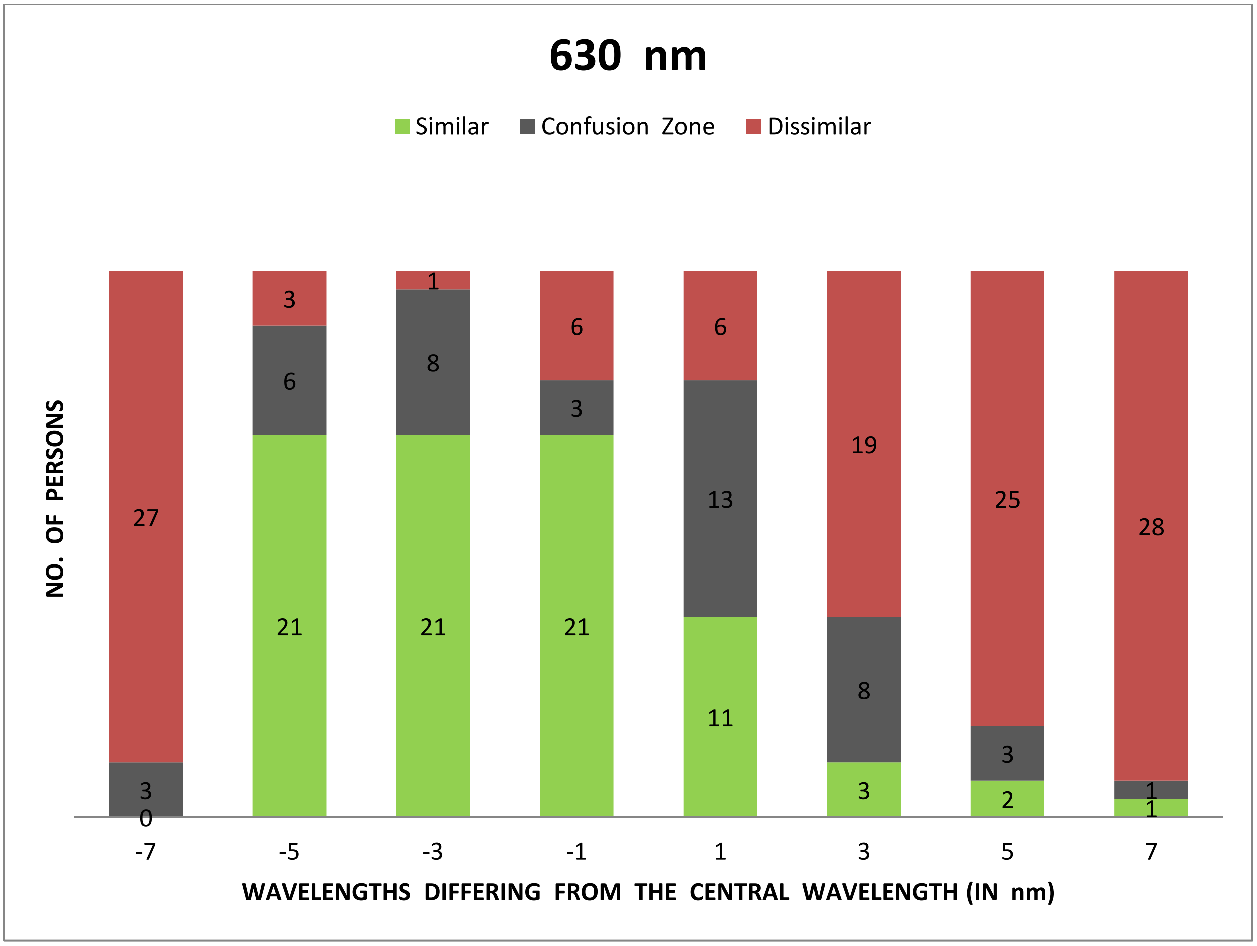
l) For central wavelength = 610 nm



The mode for the similar test is 609 nm with a frequency of 22 whereas for the dissimilar test is 617 nm with a frequency of 27

The mean for the similar test was calculated to be 610.24 nm.

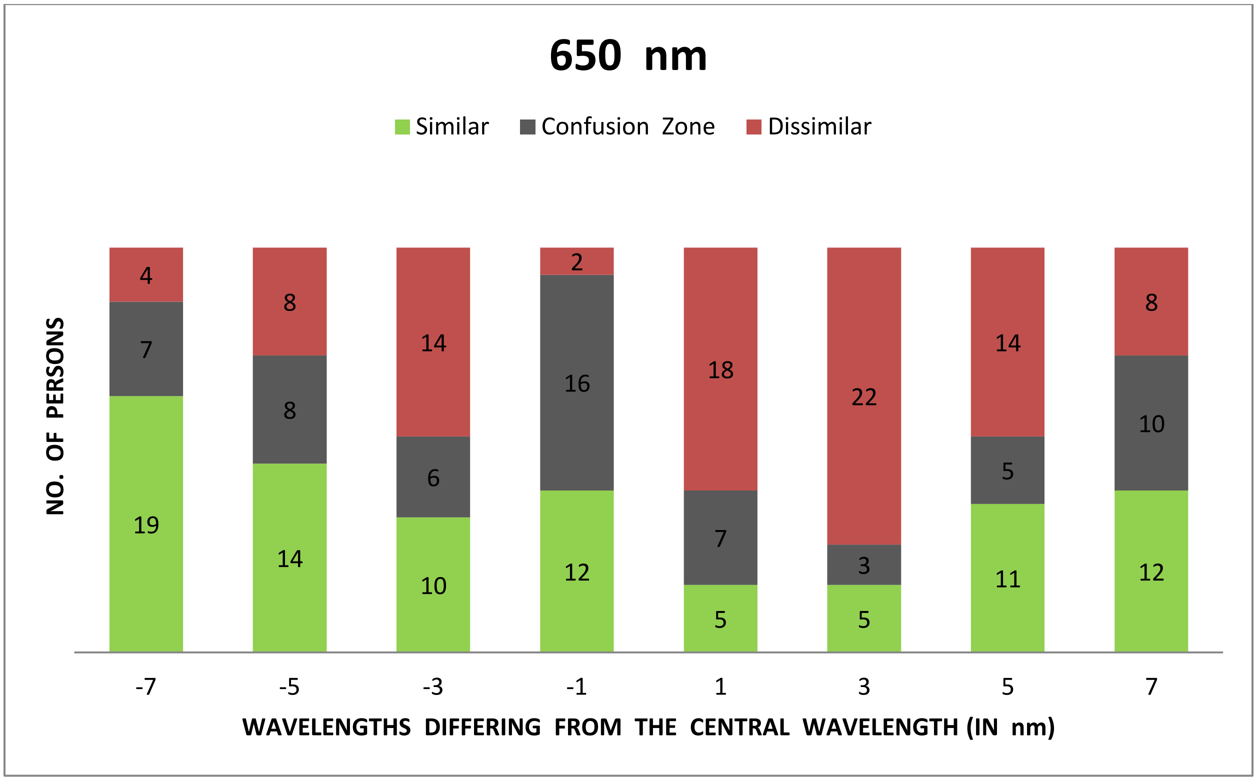
m) For central wavelength = 630 nm

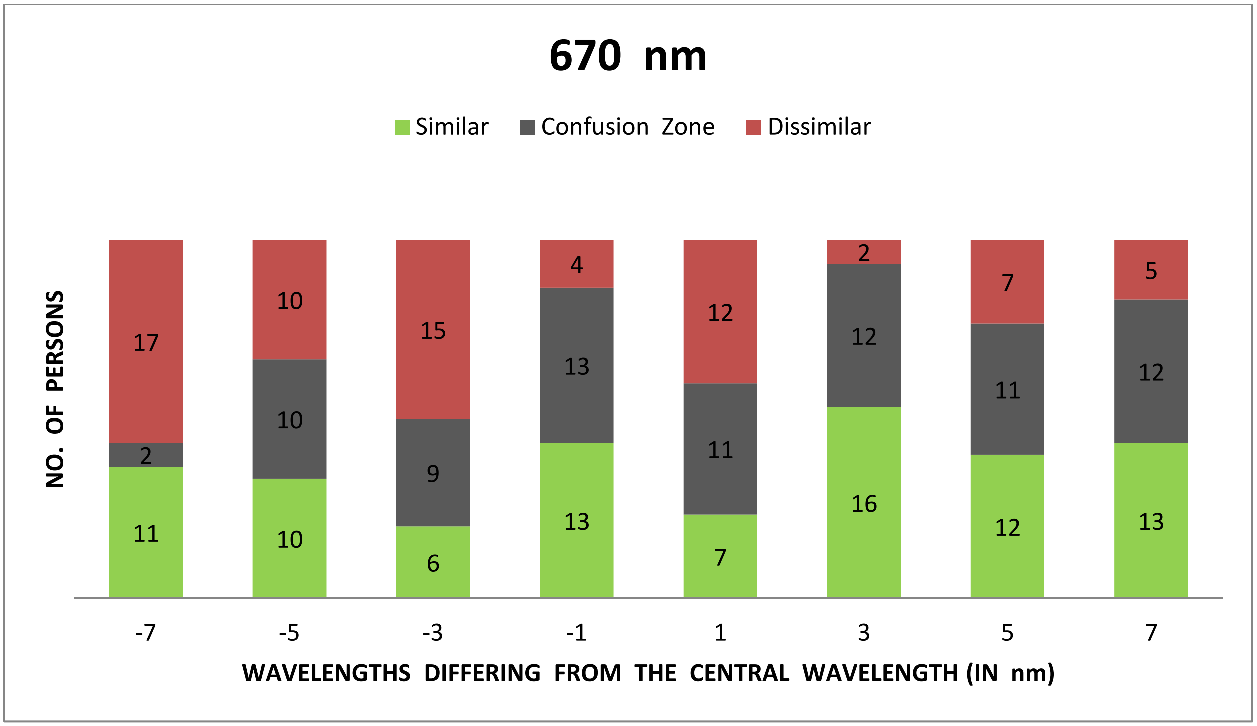


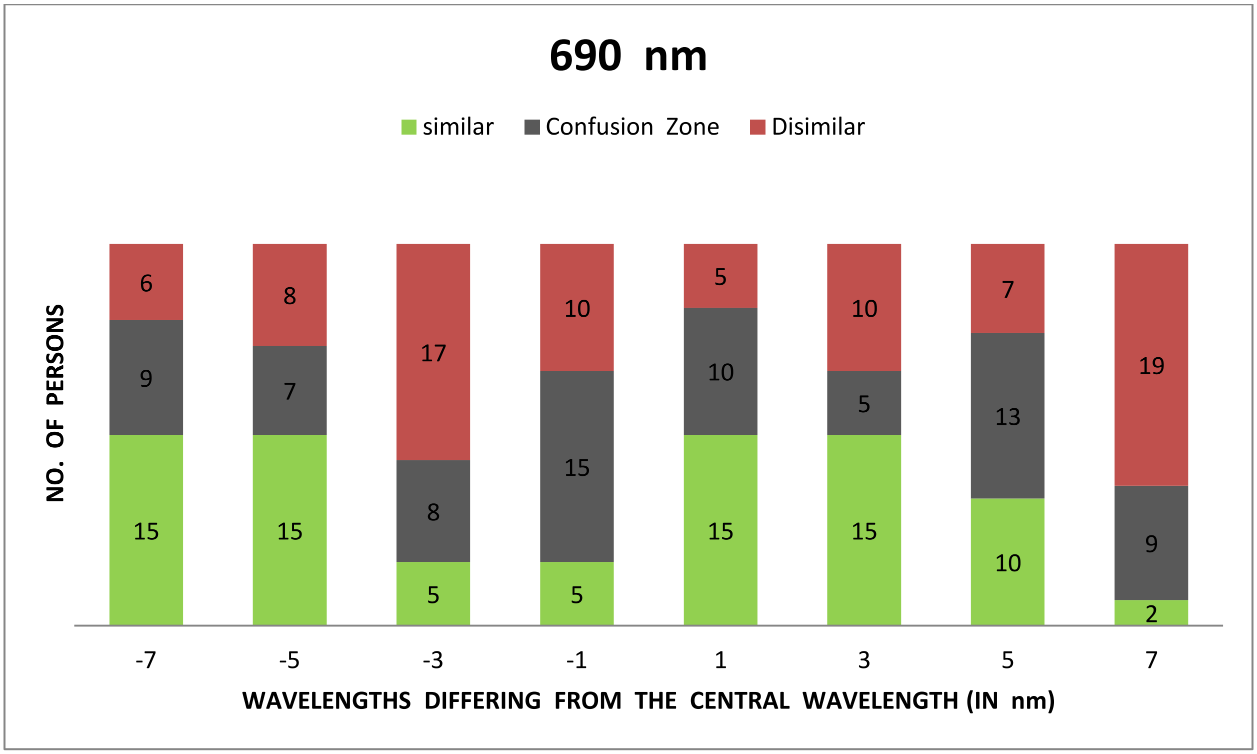
From the graph it is clear that the mode for the similar test is 625 nm, 627 nm, 629 nm with a frequency of 21 each whereas for the dissimilar test is 637 nm with a frequency of 28.

The mean for the similar test was calculated to be 628.1 nm.

n) For central wavelength = 650 nm - 690 nm







The previous three graphs for the central wavelength of 650 nm, 670 nm, 690 nm respectively seem quite erratic.

<u>This erratic behavior of these graphs are due to the fact that the RGB values of all the wavelengths from 645 nm to 700 nm is same i.e.</u>

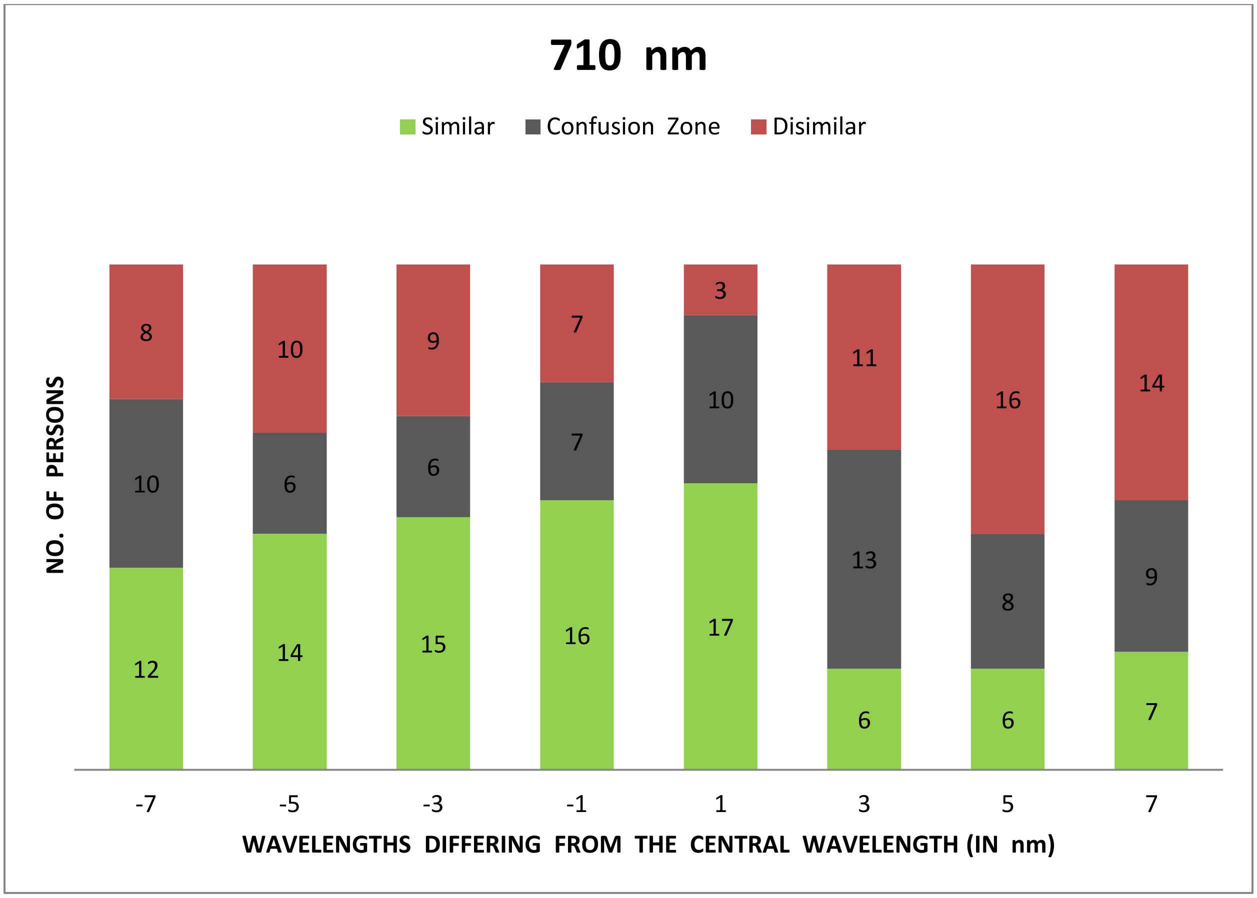
R = 255

G = 0

B = 0

Thus basically they all represent a same color having RGB values of R = 255, G = 0, B = 0.

o) For central wavelength = 710 nm

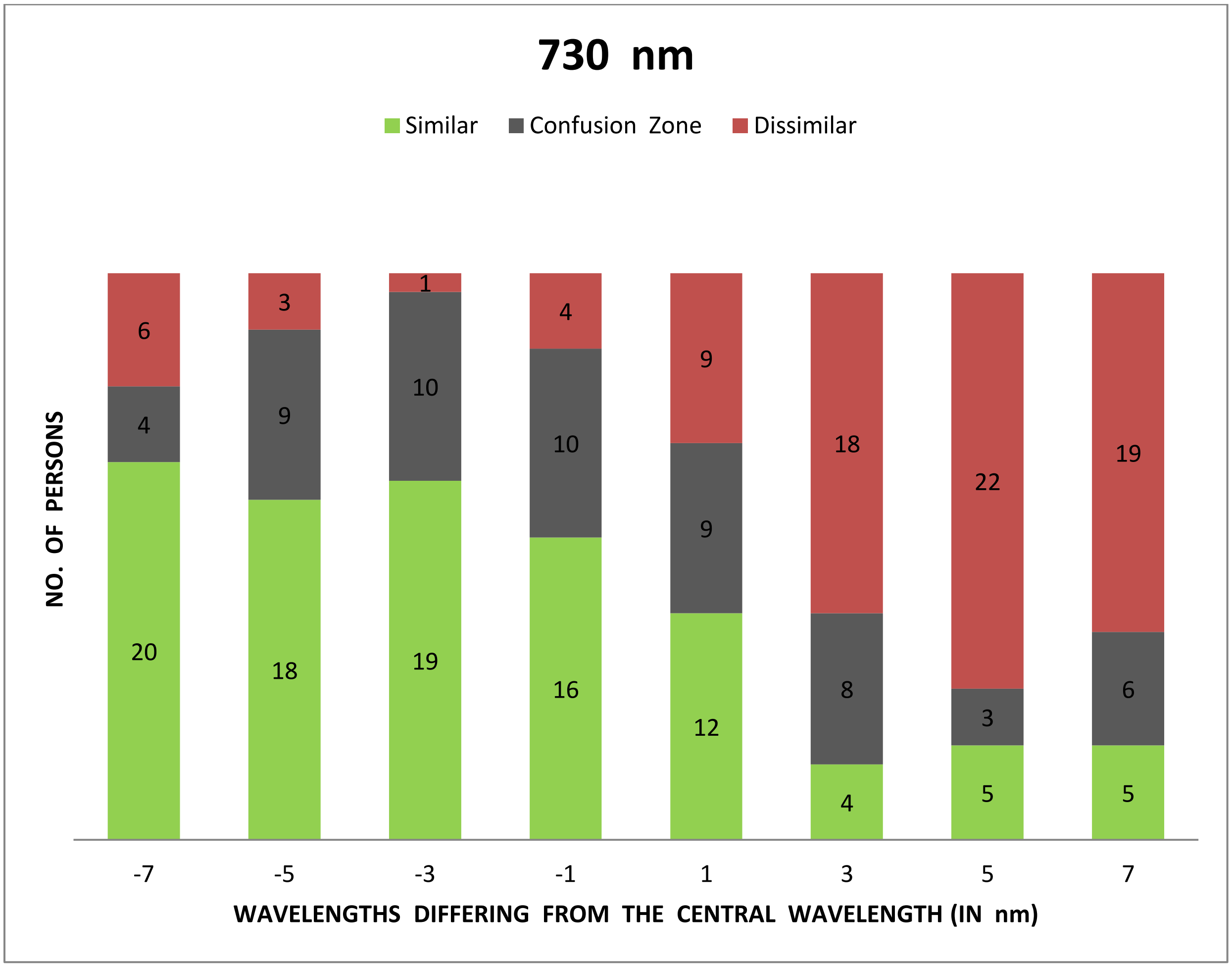


The mode for the similar test is 711 nm with a frequency of 17 whereas for the dissimilar test is 715 nm with a frequency of 16.

The frequency of similarity is highest for 711 nm followed by the wavelengths in the negative side in the order of their proximity to the central wavelength.

The mean for the similar test was calculated to be 708.91 nm.

p) For central wavelength = 730 nm

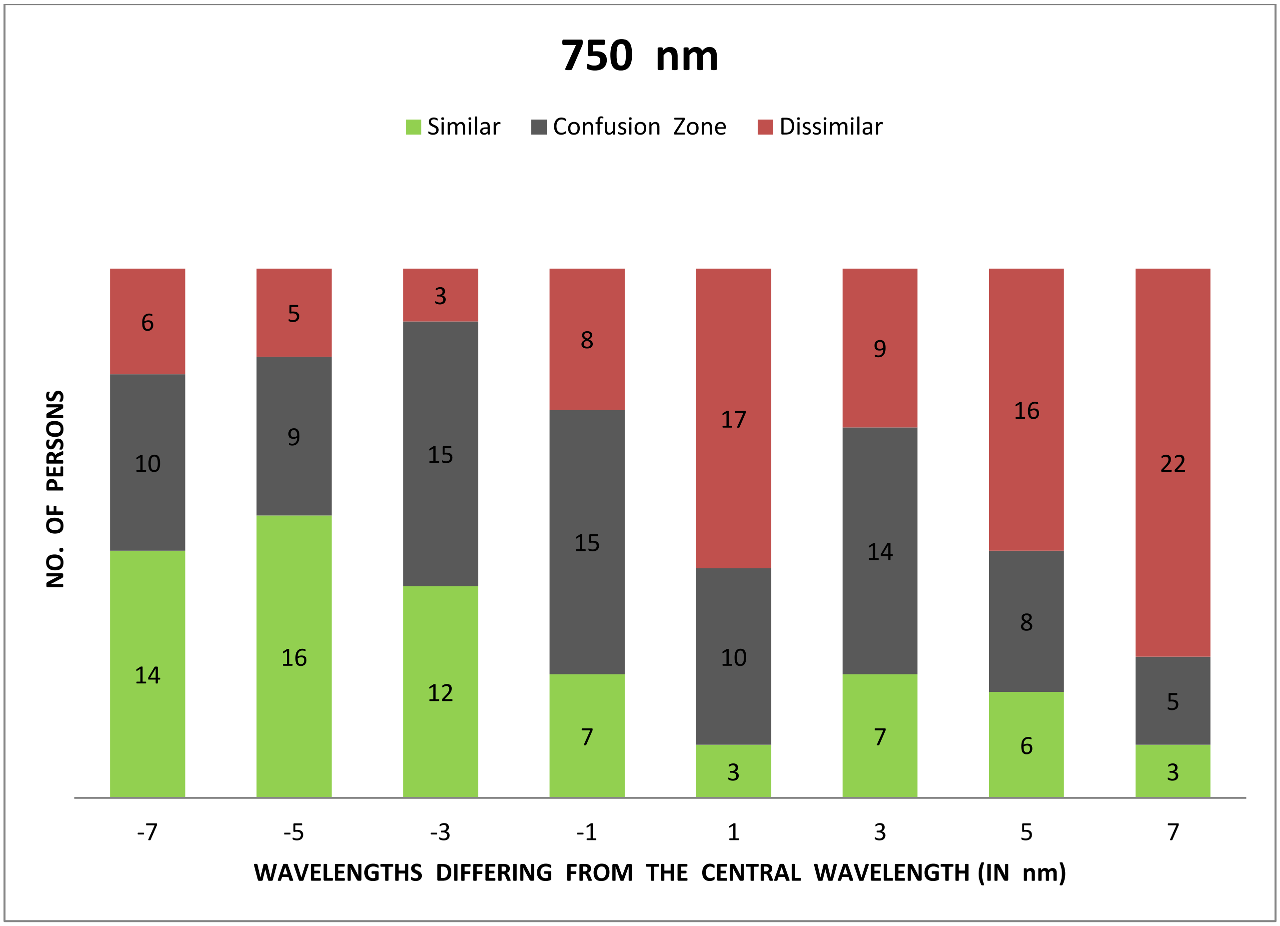


It is found that the mode for the similar test is 723 nm with a frequency of 20 whereas for the dissimilar test is 735 nm with a frequency of 22.

The wavelengths in the negative side have the most resemblance with the central wavelength.

The mean for the similar test was calculated to be 727.79 nm.

q) For central wavelength = 750 nm

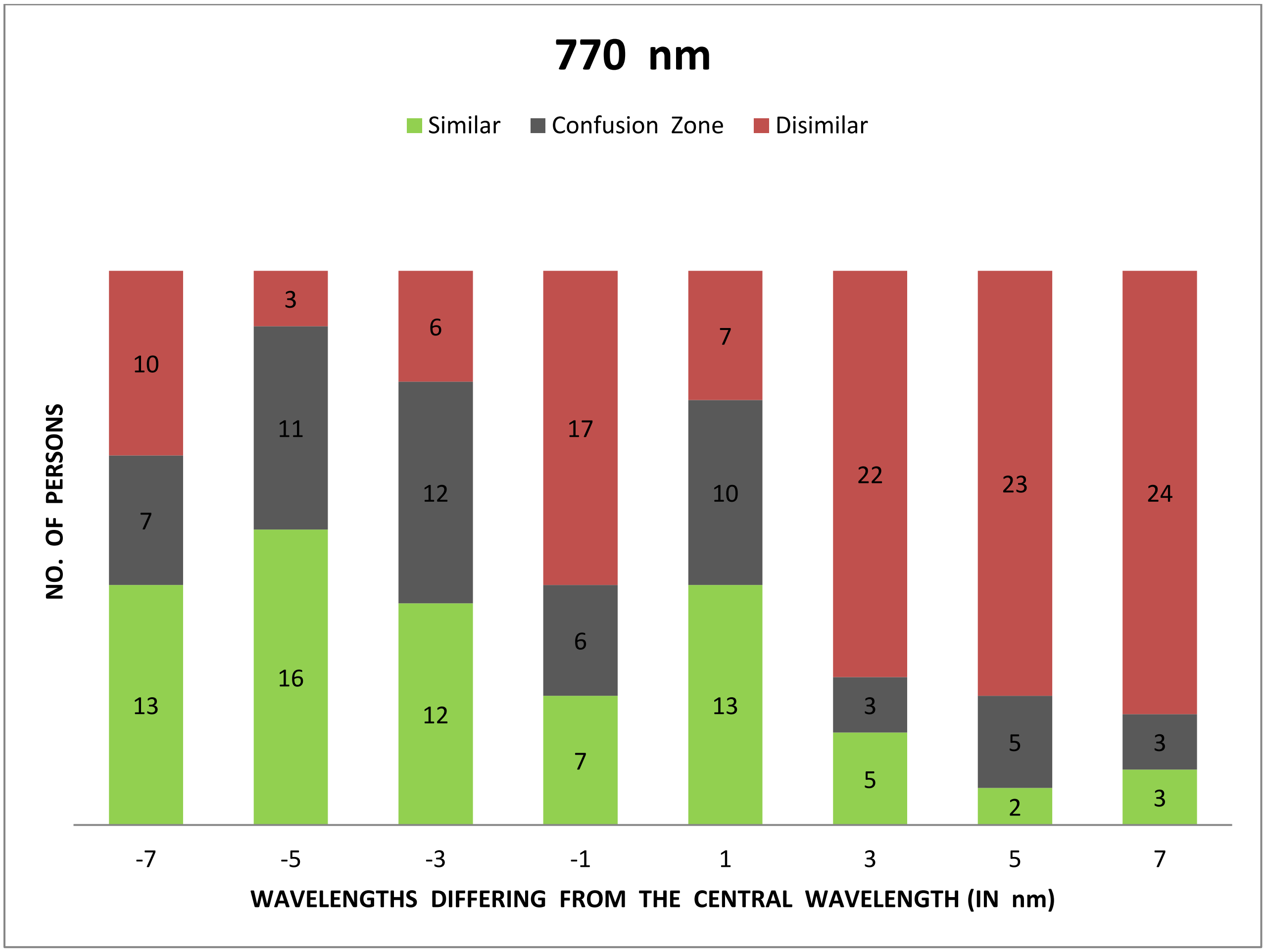


From the graph it is clear that the mode for the similar test is 745 nm with a frequency of 16 whereas for the dissimilar test is 757 nm with a frequency of 22.

Almost all the wavelengths are most of the time neither picked as similar nor dissimilar resulting in a thick confusion zone.

The mean for the similar test was calculated to be 747.85 nm.

r) For central wavelength = 770 nm



From the graph it is clear that the mode for the similar test is 765 nm with a frequency of 16 whereas for the dissimilar test is 757 nm with a frequency of 24.

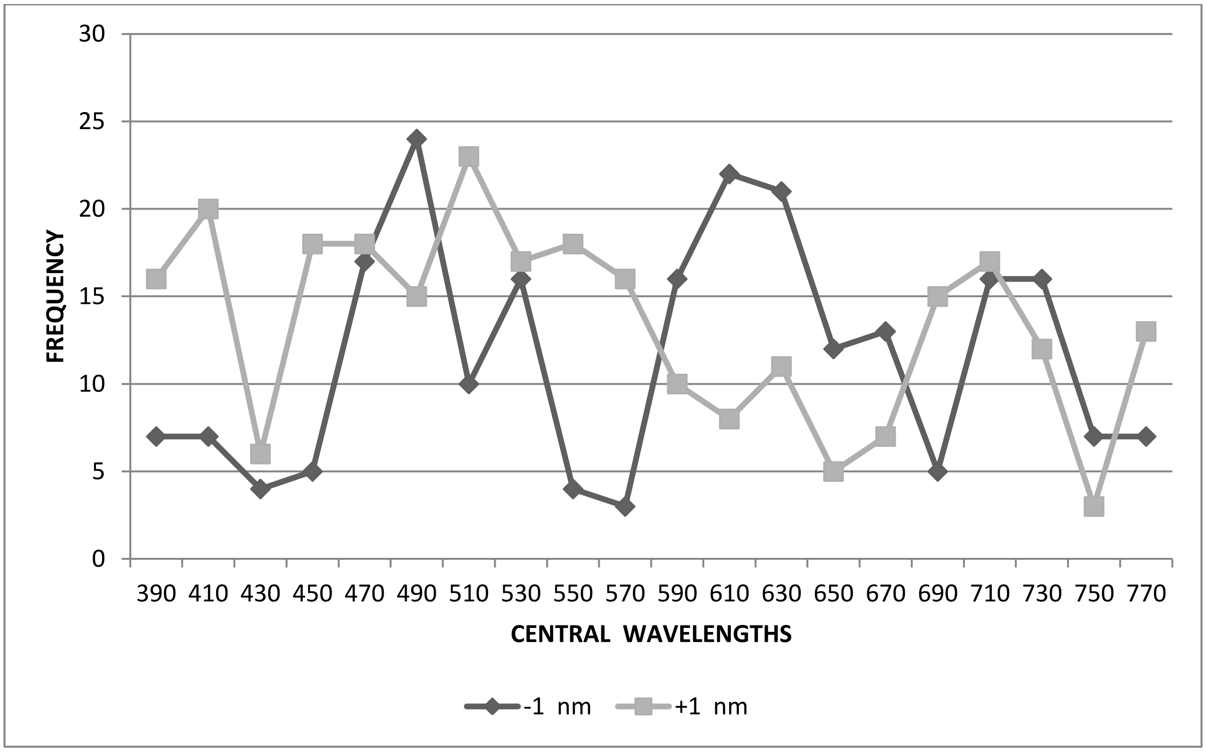
The wavelengths in the extreme left (i.e 763, 765, 767 nm) have the most resemblance with the central wavelength.

The mean for the similar test was calculated to be 767.81 nm.

Central colors and their corresponding ‘most similar’ colors.

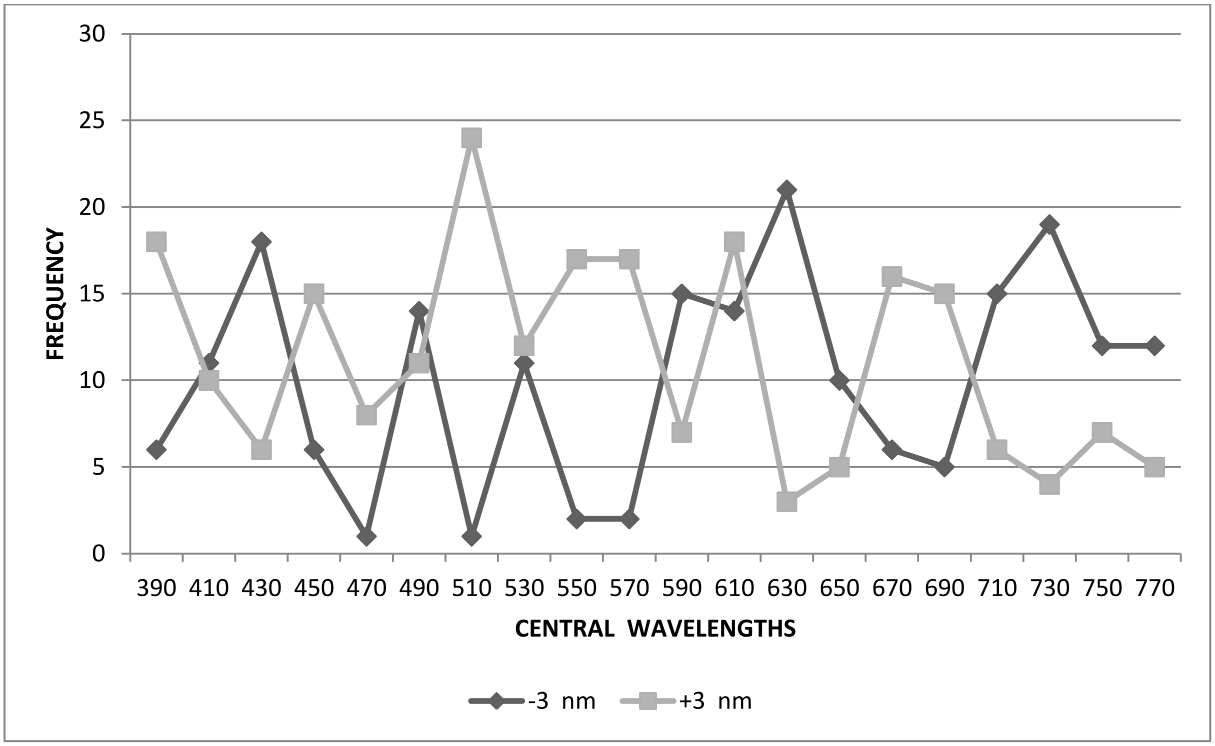
CENTRAL COLOR (In nm)	MOST SIMILAR COLOR (In nm)
390	393
410	411
430	427
450	451
470	471
490	489
510	513,515
530	537
550	551
570	573
590	589
610	609
630	625,627,629
650-690	The colors in the range of 643nm - 700nm are same with RGB values, R=255, G=0, B=0.
710	711
730	723
750	745
770	765

4.2) Comparison between +1nm and -1nm



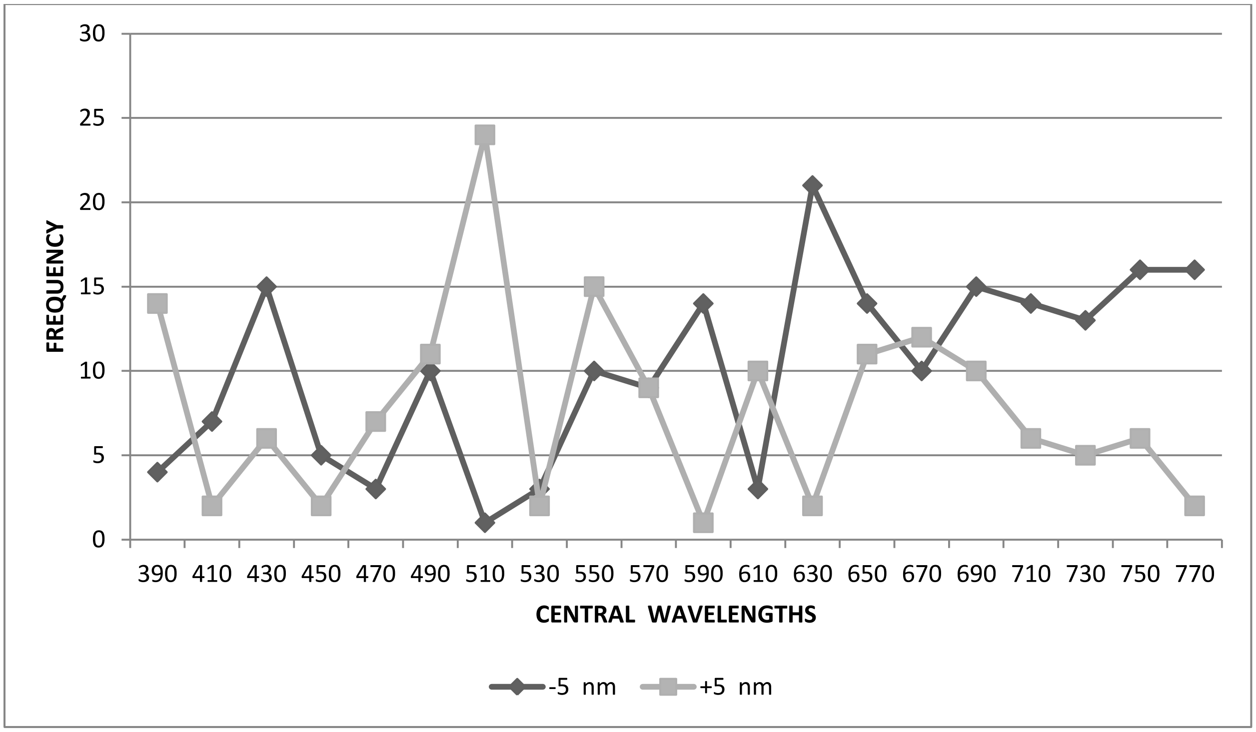
The patttern of rise and fall of frequency is same for -1nm and +1nm towards the either ends of the spectrum and opposite in the mid region.

4.3) Comparison between +3nm and -3nm



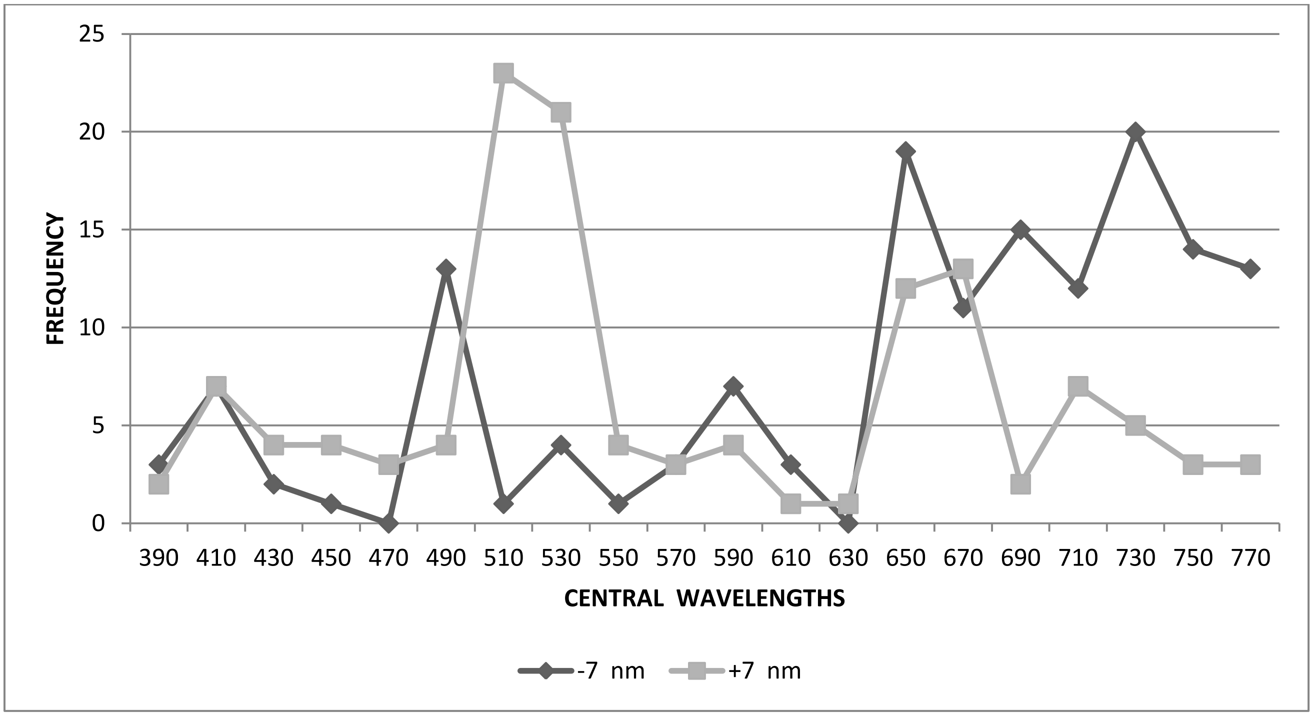
In case of -3nm vs. +3nm we found out whenever there is a rise in frequency of one, the other undergoes a decrease in frequency.

4.4) Comparison between +5nm and -5nm



The trend is opposite except for small packets of same trend observed in the regions of nearest peak wavelength of the three types of cone i.e S-type, M-type and L-type having their peak wavelengths at 420nm - 440nm, 534nm -555 nm and 564nm - 580nm respectively.

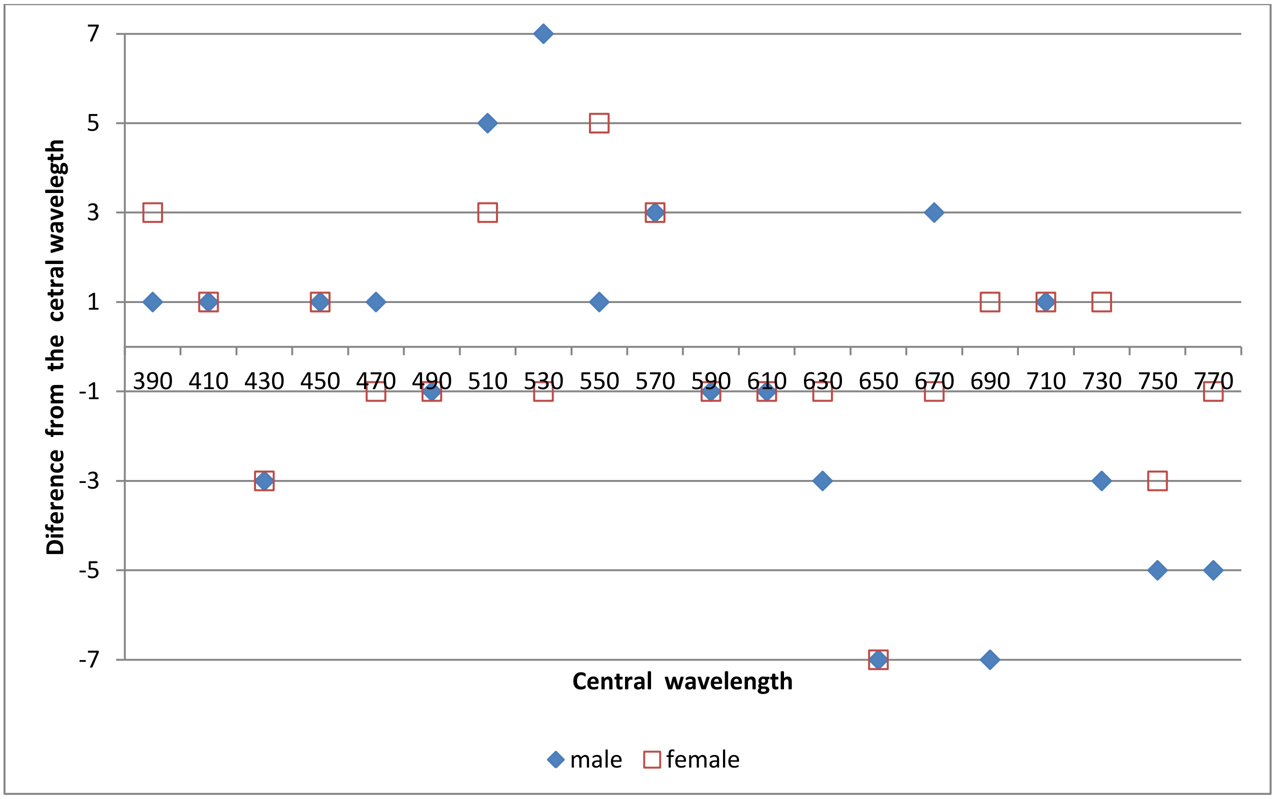
4.5) Comparison between +7nm and -7nm



These two wavelengths are too far from the central wavelength to form a pattern. The frequencies are also too less and abrupt at times

4.6) Comparison between male and female.

When the wavelengths that were selected for most of the times were plotted against their corresponding central wavelength for males and females the following graphs were obtained.



We perform a t-test to check whether the observations obtained from the male and females are statistically different or not. The null hypothesis being the modes of the similar tests for male and female is the same. A two tailed test was performed.

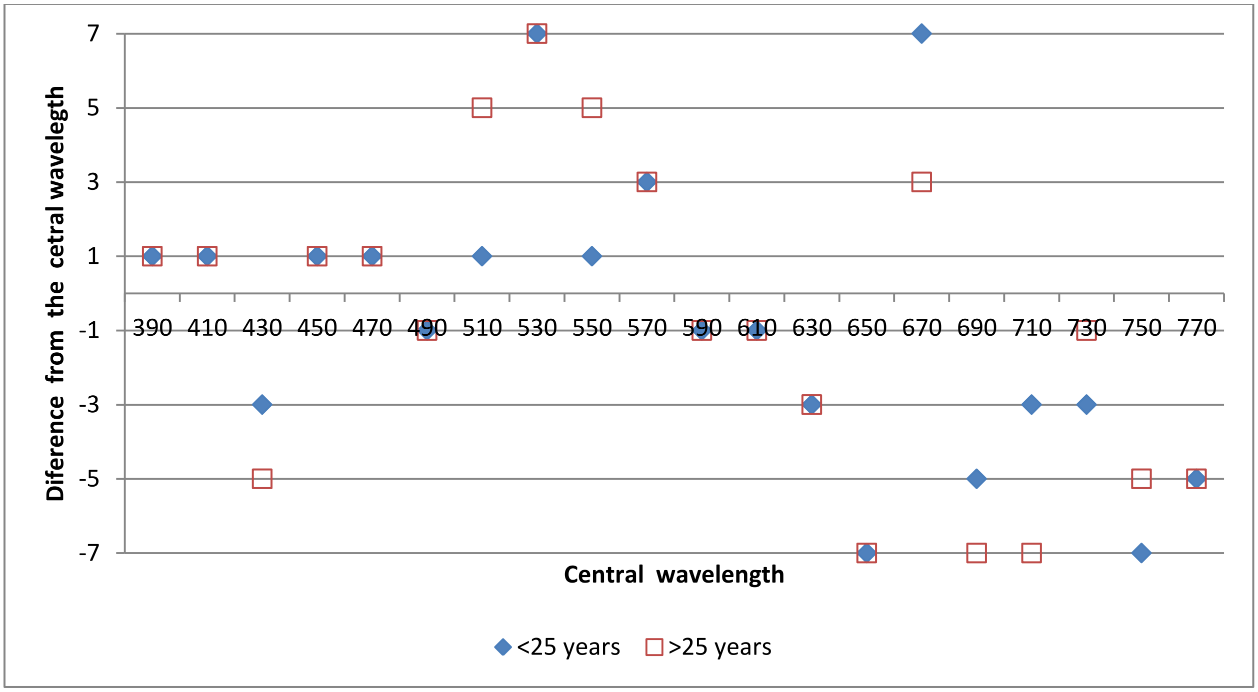
t-Test: Two-Sample Assuming Unequal Variances

	m	*f*
Mean	-0.6	-0.1
Variance	14.14737	6.936842
Observations	20	20
Hypothesized Mean Difference	0	
df	34	
t Stat	-0.48697	
P(T<=t) two-tail	0.629401	
t Critical two-tail	2.032245	

P(T<=t) was found out to be 0.629401 which is greater than 0.05.

Thus there is no statistical difference between the observations of males and females.

4.7) Comparison between <25 years and >25 years



The above graph shows the comparison of the modes of each central wavelengths obtained in the similarity test between the populations aged <25 years and > 25 years.

t-Test: Two-Sample Assuming Unequal Variances

	<25	*>25*
Mean	-0.8	-0.8
Variance	15.11578947	18.06315789
Observations	20	20
Hypothesized Mean Difference	0	
df	38	
t Stat	0	
P(T<=t) two-tail	1	
t Critical two-tail	2.024394164	

The null hypothesis being the modes of the similar tests for populations aged <25 years and > 25 years is the same. A two tailed t-test was performed to check whether the observations obtained from the two age groups are statistically different or not.

P(T<=t) was found out to be 1.0 which is greater than 0.05.

Thus there is no statistical difference between the observations of those aged <25 years and >25 years.

CHAPTER 5 : CONCLUSIONS

- The corresponding most similar colors for each central wavelength was found out from a sample of 30 individuals out of which 8 were females and 12 were aged more than 25 years.

- The similarity of the central colors was more prominent towards the nearest peak wavelength of the three types of cone i.e S-type, M-type and L-type having their peak wavelengths at 420nm - 440nm, 534nm -555 nm and 564nm - 580nm respectively.

- The trend of similarity between equally spaced wavelengths in either sides of the central wavelength was found to be opposite to one another till +/-5nm apart from the central wavelength.

- No statistical difference between the preference of 'most similar frequency' of central wavelength for males and females was found out.

- No statistical difference between the preference of 'most similar frequency' of central wavelength for those aged <25 years and >25 years was found out.

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