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THRESHOLD OF LUMINANCE CONTRAST AND CHROMATICITY CONTRAST FOR SUBJECTS WEARING SIMULATED LOW VISION GLASSES

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จากการรายงานโดย WHO ในปี 2553 มีจำนวนผู้มองเห็นเลือนราง 246 ล้านคนทั่วโลก จากจำนวนประชากรทั้งหมด 6,737 ล้านคน การจัดสิ่งแวดล้อมที่คนกลุ่มนี้ต้องเผชิญจากการทำกิจกรรมในชีวิตประจำวันให้มีความปลอดภัยและสะดวก จะช่วยให้คุณภาพชีวิตของคนกลุ่มนี้ดีขึ้น งานวิจัยนี้จึงได้หาขีดเริ่มเปลี่ยนความเปรียบต่างความส่องสว่างและความเปรียบต่างสีสำหรับผู้สังเกตใส่แว่นจำลองการมองเห็นเลือนราง ทดลองในผู้ที่มีสายตาปกติสวมใส่แว่นจำลองการมองเห็นเลือนรางที่มีช่วงความคมชัดการมองเห็น (visual acuity, VA) 0.05-0.3 ใน 4 กลุ่ม ได้แก่ การมองเห็นแบบลานสายตาแคบ (narrow vision, NV) การมองเห็นแบบตามัว (blur vision, BL) การมองเห็นเลือนรางเนื่องมาจากหลอดเลือดจอประสาทตาอุดตัน (occlusion vision, OLS) และการมองเห็นแบบตามัวร่วมกับการมองเห็นเลือนรางเนื่องมาจากหลอดเลือดจอประสาทตาอุดตัน (combination of blur and occlusion vision, BL-OLS) ทำการทดลองในเชิงไซโคฟิสิกส์โดยใช้สติมูลัสแบบเกรตติงที่มีความถี่เชิงพื้นที่ (spatial frequency) และสีสัน (hue) ที่ต่างกัน หาขีดเริ่มเปลี่ยนความเปรียบต่างความส่องสว่างและความเปรียบต่างสี พบว่าในทุกแว่นจำลองการมองเห็นเลือนรางที่ความถี่เชิงพื้นที่สูง ขีดเริ่มเปลี่ยนความเปรียบต่างความส่องสว่างและความเปรียบต่างสีมีค่าสูงเมื่อเปรียบเทียบกับความถี่เชิงพื้นที่ต่ำ ยกเว้นสีน้ำเงินและสีแดงในแว่นจำลองการมองเห็นแบบลานสายตาแคบระดับมากที่สุด (maxNV) สีเหลืองมีค่าขีดเริ่มเปลี่ยนความเปรียบต่างสีสูงที่สุดอีกทั้งขีดเริ่มเปลี่ยนไม่ต่างกันมากที่ความถี่เชิงพื้นที่ต่ำและสูง ขีดเริ่มเปลี่ยนความเปรียบต่างความส่องสว่างและความเปรียบต่างสีในแว่นจำลองการมองเห็นแบบตามัวระดับกลางร่วมกับการมองเห็นเลือนรางเนื่องมาจากหลอดเลือดจอประสาทตาอุดตันระดับมากที่สุด (medBL-maxOLS) มีค่าสูงสุด และในแว่นจำลองการมองเห็นแบบลานสายตาแคบระดับมากที่สุด (maxNV) มีค่าต่ำสุด

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As reported by WHO in 2010, there are 246 million people with low vision (total population in the world is 6,737 million). The proper environment is important for doing their daily activities not only to be safe and convenient but also to improve the quality of life. This research investigated the threshold of luminance contrast and chromaticity contrast for subjects wearing simulated low vision glasses. The subjests are color normal vision wearing simulated low vision glasses with visual acuity (VA) ranging between 0.05 and 0.3: narrow vision (NV), blur vision (BL), occlusion vision (OLS) and combination of blur and occlusion vision (BL-OLS). They took part in series of psycho-physical experiments. The stimuli are achromatic and chromatic sinusoidal gratings of different spatial frequencies and hues. For all stimulated low vision glasses at higher spatial frequencies, the luminance and chromaticity contrast thresholds were high compared to lower spatial frequencies except for blue and red in maxNV glasses. Yellow showed the highest chromaticity contrast threshold and they were not much different for all spatial frequencies. The medBL-maxOLS glasses showed the highest luminance and chromaticity contrast thresholds while the maxNV glasses showed the lowest ones.

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CHAPTER I
INTRODUCTION

1.1 Statement of the problems

Visual impairment is a major global health issue. The major causes of visual impairment are uncorrected refractive errors (43%) and cataract (33%). As reported by WHO in 2010, there are 246 million people with low vision (total population in the world is 6,737 million) [1]. Low vision means poor visual function at a level that cannot do activities correctly and cannot be corrected with regular glasses. The low vision is a person who has a visual acuity (VA) of less than 20/70 or a visual field less than 10 degrees from the point of fixation [2]. The low vision can be divided into 2 groups: people with eye disease [3, 4] and the elderly without eye disease [5, 6].

Contrast sensitivity, ability to discriminate brightness of adjacent areas, decreases with eye disease [3, 4] and age [6]. Reduced contrast sensitivity affects daily activities such as difficulty in reading [2, 6], mobility performance [7, 8], object recognitions [9] and face recognition [10]. Severe contrast sensitivity also increases a fault vehicle crash [11]. The proper environment is important for doing their daily activities not only to be safe and convenient but also to improve the quality of life without affecting other people. The measurement of the contrast sensitivity of the eye is a more complete assessment of vision than standard VA measurement. The reciprocal of the thresholds of luminance contrast and chromaticity contrast obtained from series of spatial frequency is contrast sensitivity function (CSF) of the individual. We can apply individual CSF to captured scene for obtaining simulated view seen by that person. The application is useful for designing environment supporting people with low vision.

This research investigated the threshold of luminance contrast and chromaticity contrast for subjects wearing simulated low vision glasses. The observers are normal vision wearing simulated low vision glasses: narrow vision (NV), blur vision (BL), occlusion vision (OLS) and combination of blur and occlusion vision (BL-OLS) with VA ranged between 0.05 and 0.3 [2]. They took part in series of psycho-physical experiments. The stimuli are achromatic and chromatic sinusoidal gratings of different spatial frequencies, and hues. We tested the minimum perceptible contrast within the spatial frequency range of 0.1, 0.2, 0.4, 1, 2, 4, 6, 8, 12, and 14 cycle per degrees (cpd). We exploited blue, red, green, and yellow for investigating chromaticity contrast. The luminance contrast threshold (achromatic contrast threshold, AC_{thr}) and chromaticity contrast threshold (CC_{thr}) were calculated by the Michelson equation [12].

1.2 Objective

To investigate threshold of luminance contrast and chromaticity contrast for observers wearing simulated low vision glasses.

1.3 Scope of the research

This research investigated the threshold of luminance contrast and chromaticity contrast for subjects wearing simulated low vision glasses. The scope of the research were as follow:

1.3.1 Three types of glasses: NV, BL and OLS having VA between 0.05 and 0.3 were exploited. The combination of BL and OLS lenses giving the VA of 0.05-0.3 were included.

1.3.2 The stimuli were achromatic and chromatic sinusoidal gratings of different 10 spatial frequencies: 0.1, 0.2, 0.4, 1, 2, 4, 6, 8, 12, and 14 cpd. The achromatic stimuli had 4 hues: blue, red, green and yellow.

1.3.3 There were 8 subjects: 4 males and 4 females. They took part in series of psycho-physical experiments.

1.3.4 The luminance contrast threshold (achromatic contrast threshold, AC_{thr}) and chromaticity contrast threshold (CC_{thr}) were calculated using Michelson's equation.

1.4 Expected outcome

Thresholds of luminance contrast and chromaticity contrast for observers wearing simulated low vision glasses.

This thesis is organized as follows: 1) Chapter 2, we provide related theories and literature reviews; 2) Chapter 3 presents materials, experimental setup, observers and methods; 3) Chapter 4 explains results and discussions of preliminary experiment (PE) and main experiment (ME) for both AC_{thr} and CC_{thr} and 5) Chapter 5 the conclusions are provided.

CHAPTER II

LITERATURE REVIEW

2.1 Theories and related literature reviews

This research investigated the luminance contrast and chromaticity contrast thresholds for subjects wearing simulated low vision glasses. They took part in series of psycho-physical experiments. The stimuli were achromatic and chromatic sinusoidal gratings of different spatial frequencies and hues. The luminance contrast threshold (achromatic contrast threshold, AC_{thr}) and chromaticity contrast threshold (CC_{thr}) were calculated by the Michelson equation. Corresponding theories including low vision, psychophysical methods, contrast, luminance contrast threshold, chromaticity contrast threshold, contrast threshold and spatial contrast sensitivity will be explained.

2.1.1 Low vision

The specific meaning of low vision as defined by WHO was "A person with low vision is one who has impairment of visual functioning even after treatment and/or standard refractive correction, and has a visual acuity of less than 6/18 to light perception, or a visual field of less than 10 degrees from the point of fixation, but who uses, or is potentially able to use, vision for planning and/or execution of a task." Categorization of visual impairment is shown in Table 2.1, WHO classified 3 groups of visual impairment: category 0 for mild or no visual impairment (binocular) with $VA \geq 0.3$, category 1 for moderate visual impairment (binocular) with $0.3 > VA \geq 0.1$ and category 2 severe visual impairment (binocular) with $0.1 > VA \geq 0.05$ [2]. Therefore, visual acuity range of low vision was 0.05-0.3.

Table 2.1 Categories of visual impairment and blindness [2]

Presenting distance visual acuity		
Category	Worse than:	Equal to or better than:
Mild or no visual impairment 0		6/18 3/10 (0.3) 20/70
Moderate visual impairment 1	6/18 3/10 (0.3) 20/70	6/60 1/10 (0.1) 20/200
Severe visual impairment 2	6/60 1/10 (0.1) 20/200	3/60 1/20 (0.05) 20/400
Blindness 3	3/60 1/20 (0.05) 20/400	1/60 1/50 (0.02) 5/300 (20/1200)
Blindness 4	1/60 1/50 (0.02) 5/300 (20/1200)	Light perception
Blindness 5	No light perception	
9	Undetermined or unspecified	

2.1.2 Psychophysical methods

The term "psychophysics" was given by Gustav Theodor Fechner, a physicist and philosopher. He published the research programme of “Psychophysik” in 1860, he wanted to present a scientific method of studying the relations between body and mind or between the physical and phenomenal worlds. The main idea underlying Fechner’s psychophysics was that body and mind are just different reflections of the same reality. His purpose was to make a method that would be able to connect the personal impression or experience of a person to that of the public or external impression [13].

Psychophysics was described as “the scientific study of the relation between stimulus and sensation" [14] or as "the analysis of perceptual processes by studying the effect on a subject's experience or behavior of methodically varying the characteristics of a stimulus along one or more physical dimensions". Psychophysics serves as a merging of psychology and physics in which the physical stimuli and its characteristics connect to one's sensory processes. Because of this, psychophysics may also refer to a group of classical methods that are used to analyze an organism's perception.

The basic anchor of psychophysical method is to use the physical stimuli as a reference system. Stimulus properties are carefully and methodically managed and subjects are asked to record their perception of the stimuli. The art of psychophysics is to generate a question that is precise, clear and simple enough to get an influencing answer. In visual system, the physical stimulus such as light reflected from an object surface stimulates visible and psychological response (see Figure 2.1). Thus the psychological action allows us to know the relation between physical input and psychological response.

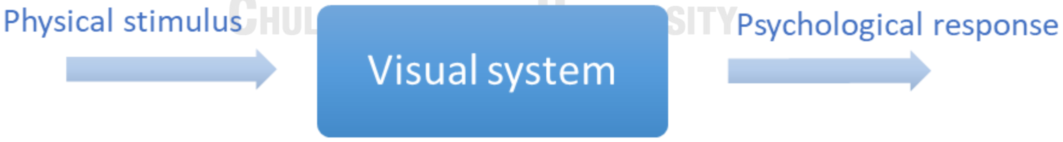


Figure 2.1 Physical stimulus stimulated visible and psychological response.

The experiments of psychophysicists concentrate on using physical stimuli and connecting them to sensation; vision, taste, smell, hearing or touch. The areas of investigation involve in the experiments include thresholds and scaling. A threshold refers to the minimal intensity point where the subject is able to perceive a stimulus.

The most basic function of any sensory system is to perceive energy or changes of energy in the environment. This energy may be composed of chemical (as in taste or smell), electromagnetic (in vision), mechanical (in audition, proprioception and touch) or thermal stimulation. In order to be noticed, the stimulus must create an absolute level of energy. This minimal amount of energy is called the absolute threshold. The absolute threshold is thus the intensity that a subject can just hardly perceive. Another threshold, the difference threshold, is based on stimulus intensities above the absolute threshold. It refers to the minimum intensity by which a variable analogue stimulus must orientate from a constant standard stimulus to create an obviously perceptual difference. There were two groups of psychophysical methods: classical psychophysical and adaptive psychophysical methods [15].

2.1.2.1 Classical psychophysical methods

Psychophysical experiments traditionally include three methods for testing subjects' perception in stimulus detection: the method of adjustment, the method of limits and the method of constant stimuli.

2.1.2.1.1 Method of adjustment

The method of adjustment is the simplest and quickest way to determine absolute and difference thresholds. This method is to let a subject adjust the stimulus intensity until it is just detected or until it is just undetectable (in the case of measurements of the absolute threshold) or appears to be just detected different from, or to just match, some other standard stimulus (to measure a difference threshold). The subject is normally provided with a control of grey filter that can be used to change the luminance level, and then the luminance level is recorded to provide an estimate of the subject’s threshold. The subject can change the luminance from definitely visible to just hardly invisible, and then change the luminance level until it is hardly detectable the light again. They may repeat many times. The luminance level that the subject is able to detect the light was the threshold (see Figure 2.2).

The following methods of threshold determination differ from the adjustment method in that they do not allow the subject to control the stimulus intensity directly. As they trust on the experimenter's rather than on the subject's control, they provide a more standardized method of measurement [15].

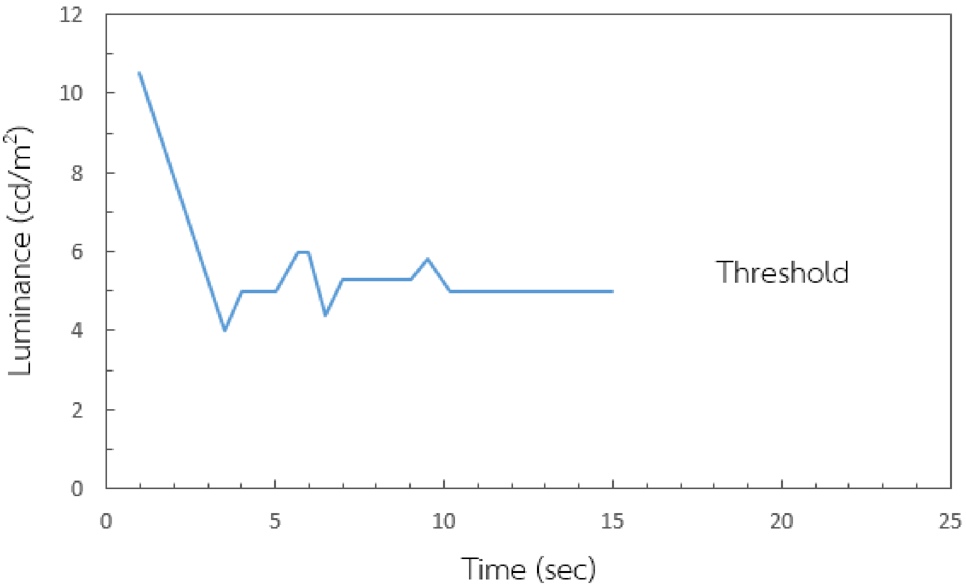


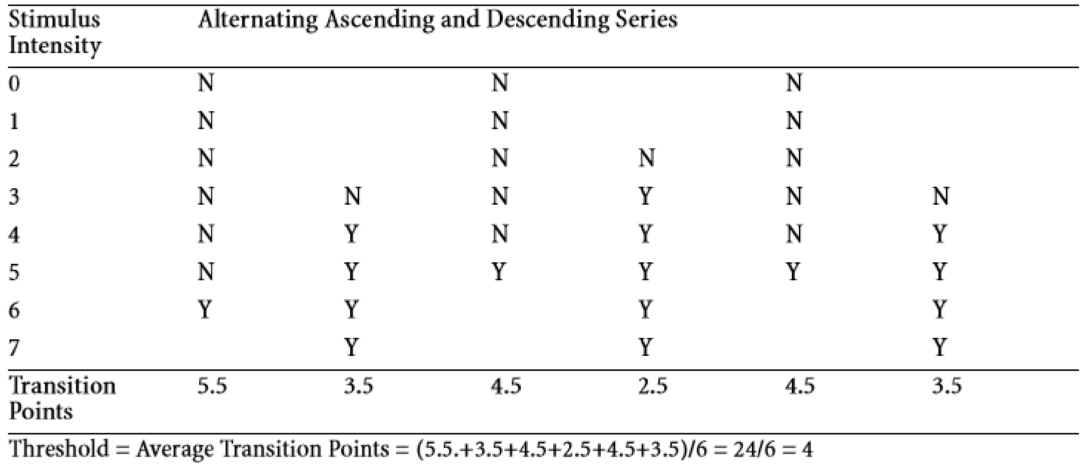
Figure 2.2 Example of results, the luminance levels that were changed by a subject for finding the threshold in the method of adjustment.

2.1.2.1.2 Method of limits

In the method of limits, a single stimulus or a single light is adjusted intensity in respective, discrete steps and the subject's response to each stimulus presentation is recorded. As in the previous method, the stimulus should initially be too hard to be noticed, so that the answer is "not seen"; intensity is then increased in steps until the stimulus becomes visible (ascending series), or it is changed from an obviously visible intensity until it becomes invisible (descending series). The average of the intensity of the last "seen" and the first "not seen" stimuli in the ascending trials, whereas in the descending trials, is recorded as an estimate of the absolute threshold. Ascending and descending series always negligible yield but systematic differences in thresholds (for an example, see Table 2.2). Therefore, the two types of series are commonly used in alternation and the results are averaged to gain the threshold estimate [15].

In experiments, the ascending and descending methods are used alternately and the thresholds are averaged. A drawback of these methods is that the subject may become accustomed to reporting that they perceive a stimulus and may continue recording the same way even beyond the threshold (the error of habituation). Conversely, the subject may also expect that the stimulus about to become detectable or undetectable and may make a premature judgment (the error of anticipation). To avoid these mistakes, Georg von Békésy suggested the staircase method in 1960 in his study of auditory perception. In this method, the sound started out audible and got quiet after each of the subject's responses, until the subject did not report hearing it. At that point, the sound was made louder at each step, until the subject reported hearing it, at which point it was made quiet in steps again. This way the experimenter was able to "zero" on the threshold [13].

Table 2.2 Example of absolute threshold determined by method of limits [15]



Stimulus Intensity	Alternating Ascending and Descending Series					
0	N		N		N	
1	N		N		N	
2	N		N	N	N	
3	N	N	N	Y	N	N
4	N	Y	N	Y	N	Y
5	N	Y	Y	Y	Y	Y
6	Y	Y		Y		Y
7		Y		Y		Y
Transition Points	5.5	3.5	4.5	2.5	4.5	3.5

Threshold = Average Transition Points = (5.5.+3.5+4.5+2.5+4.5+3.5)/6 = 24/6 = 4

2.1.2.1.3 Method of constant stimuli

In the method of constant stimuli the experimenter chooses a number of stimulus values (usually from five to nine) which, on the basis of previous examination, are probably to cover the threshold value. These stimuli are showed several times in a random order that approve each will occur equally often. After each stimulus presentation, the subject records whether or not the stimulus is detected (for the absolute threshold) or whether its intensity is stronger or weaker than that of a standard (for calculating a difference threshold). The proportion of “detected” and “not detected” (or, “stronger” and “weaker”) responses is computed for each stimulus level (for an example, see Table 2.3). The data are plotted with stimulus intensity and percentage of perceived stimuli. This resulting graph is called psychometric function (see Figure 2.3).

Table 2.3 Example of results recorded from the method of constant stimuli (50 presentation for each stimulus intensity) [15]

Stimulus Intensity (arbitrary units)	1	2	3	4	5	6	7
Frequency of Perceived Stimuli	1	3	12	20	37	45	50
Percentage of Perceived Stimuli	2	6	24	40	74	90	100

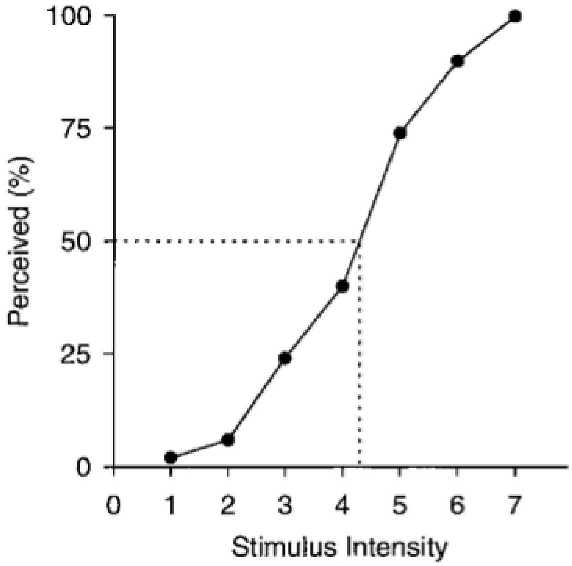


Figure 2.3 Psychometric function which showed the relationship between the percentage of times that a stimulus is perceived and the corresponding stimulus intensity. The threshold is defined as the intensity at which the stimulus is detected 50 percent of the time [15].

A sigmoid curve showing that lower stimulus intensities are detected provisionally and higher values more often, is usually gained. The absolute threshold measured with the method of constant stimuli is defined as the intensity value that “perceived” responses on 50% of the experiments. In case the threshold value of 50% locates between these two points, we can determine the threshold intensity by linear interpolation as shown in Eq 1:

$$T = a + (b - a) \cdot \frac{50 - p_a}{p_b - p_a}, \quad (1)$$

where T is the threshold, a and b are the intensity levels of the stimuli that between 50% detection, and p_a and p_b the respective percentages of detection [15].

In our study, we employed the constant stimuli method for determining AC and CC thresholds by presenting the observers with a set of stimuli of which above the threshold and of which below the threshold in a random order. This method prevented the observers from being able to predict what the next stimulus would be. The 50% amount of stimuli that could be seen as the stripes and 50% amount of stimuli that could not be seen as the stripes were considered to be the contrast threshold. We plotted the “Yes” results in each type of contrast on the probability of seeing curve: luminance level or chroma level was the abscissa and *P(E)* is the ordinate. This method was the most precise threshold estimates but it was time consuming.

2.1.2.2 Adaptive psychophysical methods

The adaptive psychophysical methods are used to keep the test stimuli close to the threshold by adapting the order of stimulus display according to the subject’s response. Since a smaller range of stimuli needed to be showed, adaptive methods are rather proficient. An example of the adaptive psychophysical methods is the staircase method.

The staircase method is adapted from the method of limits. This method is shown in Figure 2.4. Staircases normally begin with a high intensity stimulus (descending set of stimuli) which is easy to detect. Each time the subject can detect the stimulus, and then intensity is reduced by one step until the subject cannot detect the stimulus. This method continues with increasing the intensity if the subject's response is "no" and reducing the intensity if it is "yes". In this way, the stimulus intensity flips back and forth around the threshold value. Usually six to nine reversals in intensity are taken to estimate the threshold, which is defined as the average of all the stimulus intensities at which the subject's responses change. In this method, most of the stimulus values are concentrated in the threshold region, therefore, it is a more efficient method than the method of limits. A problem with this single staircase method is that a subject might speculate the pattern of stimulus presentation, which may guide the subject to forecast the approach of threshold and change the response before the threshold is really reached. This problem can be fixed by adding more staircases as shown in Figure 2.5. On trial 1, staircase A starts with a high threshold intensity. On trial 2, staircase B starts with a low threshold stimulus. On trial 3, the next stimulus of staircase A is displayed, on trial 4, the next stimulus from staircase B, and so on. Both staircases gather at the threshold intensity. The two staircases might also be interleaved in a random to protect the subject from finding out which staircase to forecast from trial to trial [16].

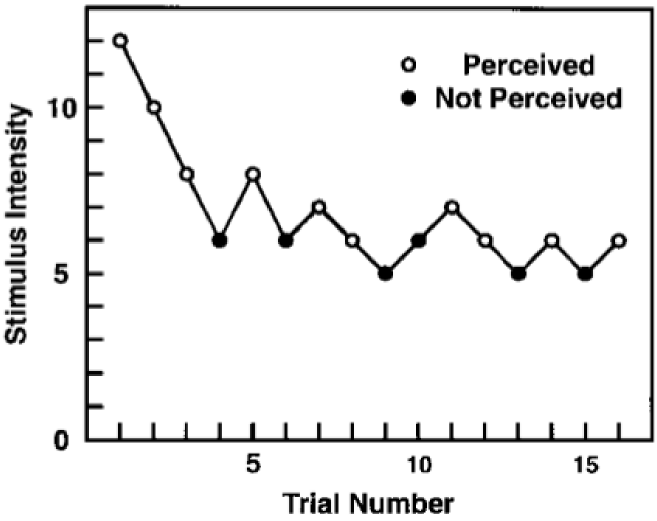


Figure 2.4 Adaptive testing using single staircase method. This example shows a descending staircase for which stimulus intensity decreases when the stimulus is perceived and increases when it is not perceived [15].

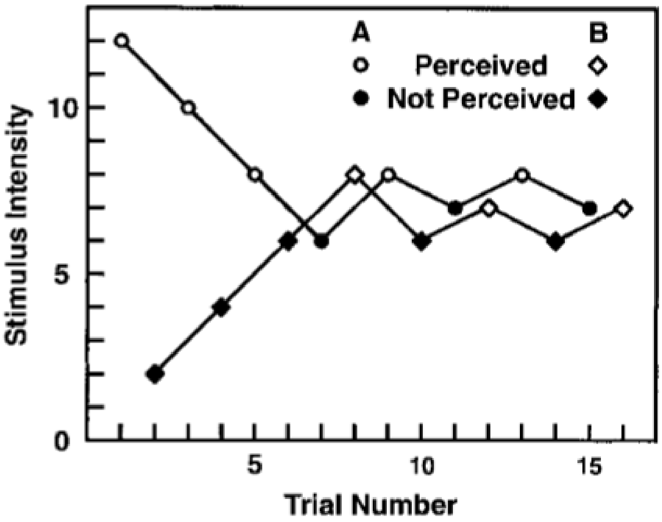


Figure 2.5 Example of using two staircases. Stimuli from the respective descending and ascending staircases are displayed alternate trails [15].

2.1.3 Contrasts

Contrast is the difference in luminance or colour that made an object or image in display distinguishable. In visual perception of the real world, contrast is determined by the difference in the colour and brightness of the object and other objects within the same visual field. There are many definitions of contrast. Various definitions of contrast are used in different conditions. Two definitions that have been normally used for measuring the contrast of test stimuli are Weber contrast and Michelson contrast [12].

2.1.3.1 Weber contrast

Weber contrast is commonly used in cases where small features are presented on a large uniform background, i.e., where the average luminance is approximately equal to the background luminance. Weber contrast is preferred for letter stimuli and is defined by Eq 2:

$$C = \frac{L_{max}-L_{min}}{L_{background}}, \tag{2}$$

where L_{max}, L_{min} and $L_{background}$ represent the maximum, minimum, and background luminance, respectively, in the letter stimuli [12].

2.1.3.2 Michelson contrast

Michelson contrast is commonly used for patterns where both bright and dark features are equivalent and take up similar fractions of the area. Michelson contrast is preferred for grating such as a sinusoidal grating. Michelson contrast is defined by Eq 3:

$$C = \frac{L_{max}-L_{min}}{L_{max}+L_{min}}, \tag{3}$$

where L_{max} and L_{min} represent the maximum and minimum luminance values, respectively, in the grating stimuli [12, 17].

2.1.4 Luminance contrast and chromaticity contrast thresholds

In previous research [18] the luminance contrast threshold or achromatic contrast threshold, AC_{thr}, and chromaticity contrast threshold, CC_{thr}, were determined respectively by Eqs 4 and 5, referred as Michelson equation. The sinusoidal grating stimuli as presented in Figure 2.6 was employed.

$$AC_{thr} = \frac{L_{max}-L_{min}}{L_{max}+L_{min}} \cdot 100\%, \tag{4}$$

where L_{max} and L_{min} represented the maximum and minimum luminance of sinusoidal achromatic stimuli.

$$CC_{thr} = \frac{C^*_{max} - C^*_{min}}{C^*_{max}+C^*_{min}} \cdot 100\%, \tag{5}$$

where C^*_{max} and C^*_{min} were the maximum and minimum CIE C* of the sinusoidal chromatic stimulus.

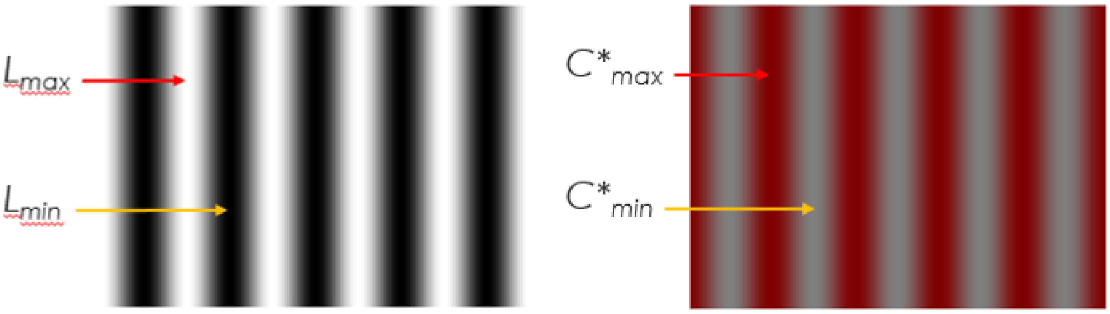


Figure 2.6 Sinusoidal grating stimuli for determining luminance contrast (left) and chromaticity contrast (right).

In our study, CIE L*u*v* (CIELUV) 1976 colour space was introduced to obtain C^*_{uv} through Eq 6.

$$C^*_{uv} = \{(u^*)^2 + (v^*)^2\}^{1/2}, \tag{6}$$

where u^* and v^* could be determined by Eqs 7 and 8.

$$u^* = 13L^* \cdot (u' - u'_n), \tag{7}$$

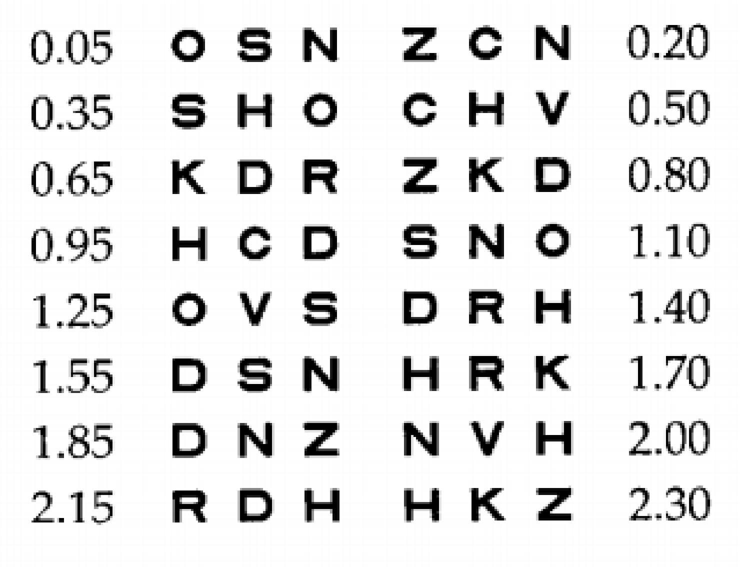
$$v^* = 13L^* \cdot (v' - v'_n), \tag{8}$$

where u' and v' represented the CIE $u'v'$ chromaticity coordinates of the sinusoidal chromaticity stimuli and u'_n and v'_n were the u' and v' chromaticity coordinates of the perfect reflecting diffuser under D65 illuminant which was termed the white point [18].

2.1.5 Contrast threshold and spatial contrast sensitivity

The spatial and temporal characteristics of the human visual system is commonly explored through measurement of contrast sensitivity function. The contrast sensitivity function is defined by the threshold response to contrast as a function of spatial or temporal frequency. Contrast is normally defined as the difference between maximum and minimum luminance in a stimulus that is divided by the summation of the maximum and minimum luminance. The contrast sensitivity function is regularly measured with sinusoidal stimuli that is varied frequencies across space or time [19].

The contrast sensitivity can be tested by using the Pelli-Robson chart (see Figure 2.7) for a clinical test. The Pelli-Robson chart is a letter chart which consists of uniform-sized but reduces in contrast on a white background. The letters are arranged in groups of three; every groups reduce in contrast by a factor of 1/√2 from a high contrast down to a contrast below the threshold of normal subjects. The numbers show the log contrast sensitivity in group of three letters. For example, if the subject starts to see H R K, the log contrast sensitivity of observer is 1.70 [20].



0.05	O S N	Z C N	0.20
0.35	S H O	C H V	0.50
0.65	K D R	Z K D	0.80
0.95	H C D	S N O	1.10
1.25	O V S	D R H	1.40
1.55	D S N	H R K	1.70
1.85	D N Z	N V H	2.00
2.15	R D H	H K Z	2.30

Figure 2.7 Pelli-Robson chart used for scoring an observer’s contrast sensitivity [20].

In addition, the measurement of contrast threshold could use a variety of grating patterns such as sine, square, rectangular and saw-tooth waves as shown in Figure 2.8 [21].

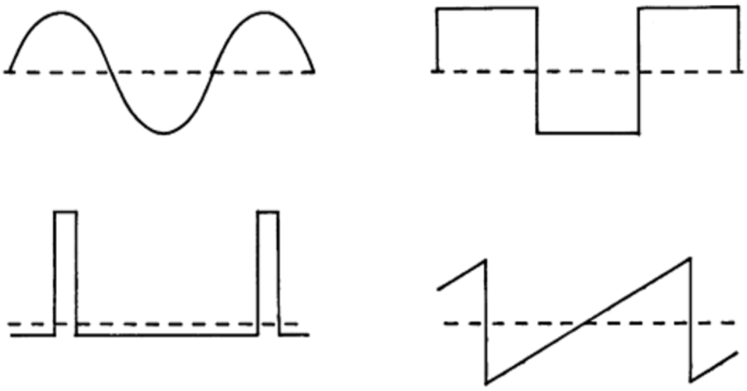


Figure 2.8 Sine-wave or sinusoidal wave grating (top left), square-wave grating (top right), rectangular-wave grating (bottom left) and saw-tooth-wave grating (bottom right) [22]

In the study of visual perception, sinusoidal gratings are frequently used to examine the visual abilities. The spatial frequency of these stimuli is expressed as the number of cycles per degree of visual angle. Sinusoidal gratings also differ from one another in amplitude (the magnitude of difference in intensity between light and dark stripes), and angle. The spatial frequency is a measure of how often sinusoidal components of the structure repeated per unit of distance, measured in cycles per degree (c/deg or cpd).

The results of a contrast sensitivity test, a contrast sensitivity curve could be plotted, with spatial frequency (cpd) as the abscissa, and contrast sensitivity as the ordinate, known as contrast sensitivity function (CSF). The shape of contrast sensitivity function in normal vision rises in lower spatial frequencies, and then abates in higher spatial frequencies as shown in Figure 2.9 [22].

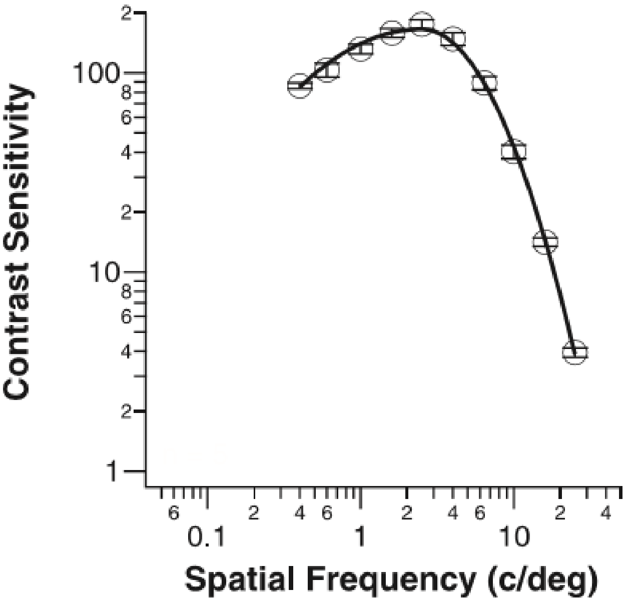


Figure 2.9 Contrast sensitivity function for normal-vision observers [22].

Figure 2.10 shows common spatial contrast sensitivity function for luminance (black–white) and chromaticity (red-green and yellow-blue at constant luminance) contrasts [19]. As described by Fairchild, the luminance contrast sensitivity function was band-pass in nature, it was increasing up to around 3-5 cpd and then decreasing in high spatial frequencies [19, 23]. For about 40 cpd (corresponding to a visual object of about 1 arcmin) or above, contrast sensitivity was equal to zero. If the object was smaller than about 1 arcmin, it was no use in increasing the contrast because this was the absolute limit of (foveal) VA [24]. The band-pass contrast sensitivity function correlated with the concept of center-surround antagonistic receptive fields that would be most sensitive to an intermediate range of spatial frequency.

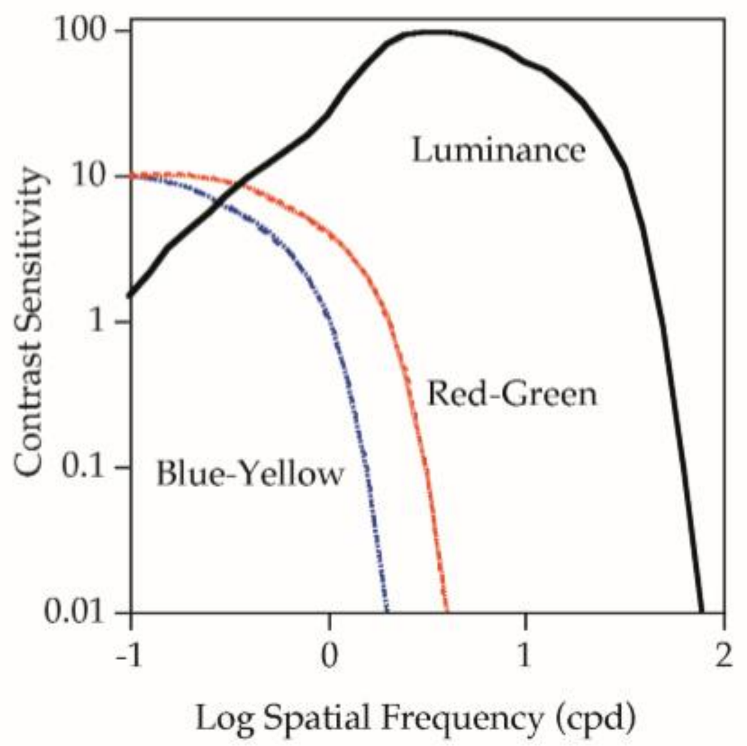


Figure 2.10 Spatial contrast sensitivity functions for luminance and chromatic contrasts [19]

The chromatic contrast sensitivity is of a low-pass nature and has significantly lower cut-off frequencies. This shows the reduced availability of chromatic information for fine details (high spatial frequencies). The blue-yellow chromatic contrast sensitivity has a lower cut-off frequency than the red-green chromatic contrast sensitivity because the scarcity of S cones in the retina. Moreover, the luminance contrast sensitivity is significantly higher than the chromatic contrast sensitivity, indicating that the visual system was more sensitive to small changes in luminance contrast compared with chromatic contrast [19].

2.2 Literature reviews

Kutas G. et al. studied luminance contrast and chromaticity contrast preference on the display for young and elderly users. Spatial contrast sensitivity dramatically decreased as age increased especially in high spatial frequencies. In the elderly, it was found that achromatic contrast sensitivity and chromatic contrast sensitivity declined. The reduced contrast of print limited text accessibility for many people. Presenting text in a high-contrast format would increase the number of people to be able to access the information, such as black laser printed on white paper, text displayed on LED computer monitor [25]. Chung S.T.L. and Legge G.E. studied the shape of CSF of 20 low vision observers with eye diseases: age-related macular degeneration (AMD) disease, glaucoma, Stargardt disease, optic neuropathy, toxoplasmic chorioretinitis and oculocutaneous albinism and compared it with CSF of older adults having normal vision. CSFs of the observers with low vision have similar shape to the normal vision observers' but differ in two points: the spatial frequency and contrast sensitivity at the peak of the curve. In clinical terms, measuring of VA and contrast sensitivity from patient with low vision can guide more information about the patient's pattern vision [22]. Mullen K.T. studied the contrast sensitivity of human colour vision in people with normal vision to red-green and blue-yellow iso-luminance chromatic gratings. Both blue-yellow and red-green contrast sensitivity functions were similar at low frequencies below 0.1 cpd and decreased in high spatial frequencies [26]. Owsley C. et al. studied spatial contrast sensitivity in 91 adults, age ranged from 19 to 87. Contrast sensitivities at low spatial frequency were the same throughout adults. In higher spatial frequencies, the contrast sensitivity slightly reduced with age around 40 to 50 years old. Reduced retinal illuminance characteristics of the aged eye, cause it effected to an older adult deficit in spatial vision [27].

Moreover, interactions among the spatial frequency, the age of the observer and the psychophysical method recommended that the method of adjustment should be avoided for age-related studies of vision [28]. In researches about chromatic contrast [26, 29-31], iso-luminance chromatic gratings were used for test and iso-luminance opponent colour pairs (e.g. red text on green background) should be avoided because chromatic aberrations might occur. In addition, chromatic aberrations created the luminance artifacts at spatial frequencies above 3 cpd and they could distort the chromatic contrast results [32].

CHAPTER III

EXPERIMENT

3.1 Stimuli

For investigating the luminance contrast and chromaticity contrast thresholds, stimuli of sinusoidal grating of different spatial frequencies (Figure 3.1) were presented to the observers. The spatial frequency and contrast of the sinusoidal grating of each stimulus were constant. All stimuli, with the size of 12.6 × 12.6 cm^2, were generated using MATLAB.

3.1.1 Achromatic stimulus

In the achromatic contrast (AC) experiment, the amplitude of the sine wave is peak white and black (Figure 3.1 left). The maximum luminance of the grating was 127.3 cd/m^2 (white peak) and the minimum was 1.1 cd/m^2 (black). In preliminary experiment (PE) of AC, we generated the sinusoidal gratings with 10 luminance levels: 2.2, 5.4, 11.0, 19.2, 30.7, 44.1, 60.8, 80.6, 103.3 and 127.3 cd/m^2 for 10 spatial frequencies: 0.1, 0.2, 0.4, 1, 2, 4, 6, 8, 12 and 14 cpd (Figure 3.2). Due to the limitation of the monitor resolution, we could not generate the stimuli with spatial frequency greater than 14 cpd. After the PE, the luminance level could be reduced down to 5 levels with finer steps.

3.1.1.1 PE. Achromatic sinusoidal gratings were generated with 10 luminance levels. There were 10 spatial frequencies in each luminance level and the experiment was repeated 3 times.

3.1.1.2 ME. Achromatic sinusoidal gratings were generated with 5 luminance levels, covered the possible range in 10 spatial frequencies. Each stimulus was observed with 5 repetitions.

3.1.2 Chromaticity stimulus (4 hues: red, green, blue and yellow)

In the chromatic contrast (CC) experiment, chromatic stimuli were sinusoidal grating with a fixed luminance of 25.2 cd/m^2. The amplitude of the sine wave is CIELUV chroma ($C^* = C^*_{uv}$) of the constant hue and achromatic grey (Figure 3.1 right). In PE of CC, chroma was varied with 10 steps for 10 spatial frequencies as in AC preliminary experiment. After the CC preliminary experiment, chroma level could be reduced down to 5 steps. The white point of the display was referred as reference white with the CIE 1931 xy chromaticity coordinates of x_0: 0.327, y_0: 0.339. The CIE 1931 xy chromaticity coordinates of 4 hues were blue (0.172, 0.095), red (0.511, 0.308), green (0.290, 0.441) and yellow (0.395, 0.437) [33].

3.1.2.1 PE. Ten chroma levels of chromatic sinusoidal gratings with 10 spatial frequencies were generated for 4 hues: blue (9.2, 16.9, 25.3, 33.5, 40.8, 47.8, 53.5, 56.4, 56.6 and 57.2), red (6.1, 13.3, 20.7, 28.1, 35.9, 43.6, 50.5, 55.7, 59.0 and 59.4), green (5.1, 10.8, 16.1, 21.4, 25.5, 29.2, 32.2, 35.1, 37.7 and 38.9), and yellow (6.1, 13.7, 20.4, 25.3, 30.6, 33.4, 36.6, 37.5, 37.6 and 38.0). The observation was carried out with 3 repetitions for each stimulus.

3.1.2.2 ME. Five chroma levels of chromatic sinusoidal gratings covered the possible range with 10 spatial frequencies were generated for 4 hues. The observation was repeated 5 times for each stimulus.

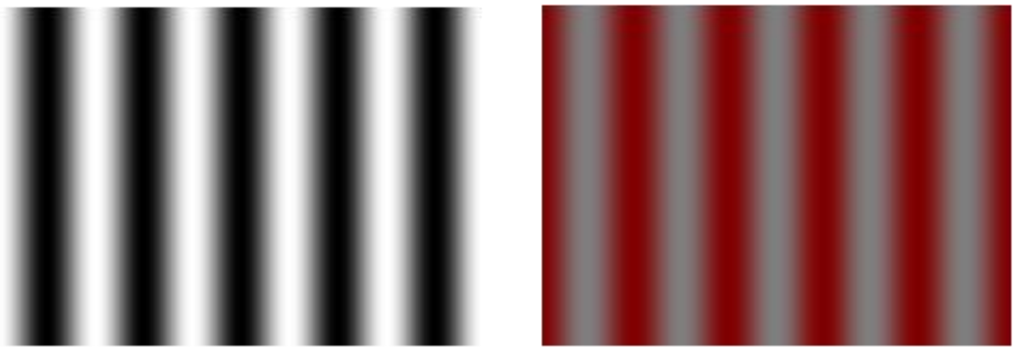


Figure 3.1 Stimuli used in the experiment. The spatial frequency of achromatic stimulus (left) is the same as that of chromaticity stimulus (right), 2 cpd.

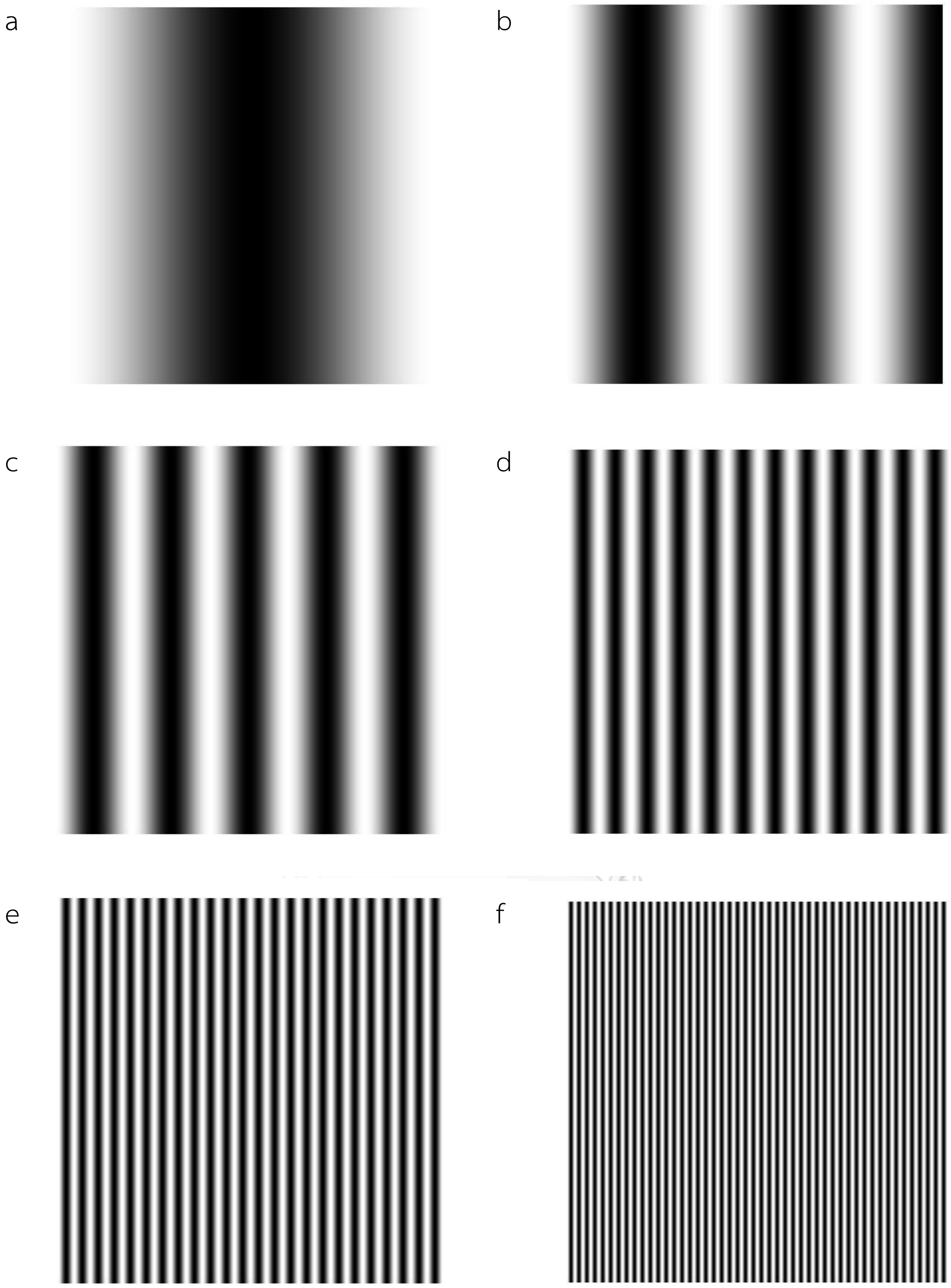


Figure 3.2 Ten spatial frequencies: 0.1 (a), 0.2 (b), 0.4 (c), 1 (d), 2 (e), 4 (f), 6 (g), 8 (h), 12 (i) and 14 cpd (j) (High spatial frequency may not be presented correctly on the printed thesis format due to the limitation of printing.)

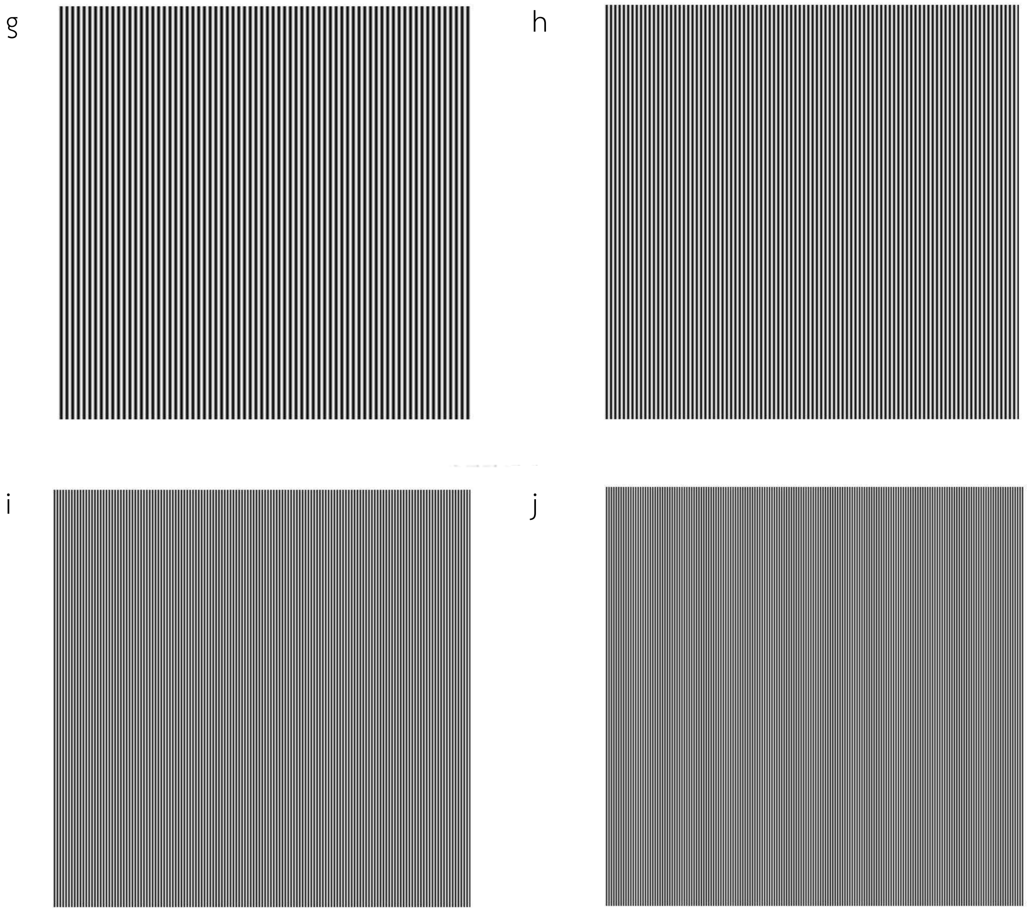


Figure 3.2 (continued) Ten spatial frequencies: 0.1 (a), 0.2 (b), 0.4 (c), 1 (d), 2 (e), 4 (f), 6 (g), 8 (h), 12 (i) and 14 cpd (j) (High spatial frequency may not be presented correctly on the printed thesis format due to the limitation of printing.)

3.2 Stimulated low vision glasses

The simulated low vision glasses (see Figure 3.3) in this experiment were made by M. Takata Optical Company Limited. We used three types of lenses in VA ranges of 0.05-0.3: narrow vision (NV), blur vision (BL) and occlusion (OLS) making four groups of stimulated low vision glasses: NV, BL, OLS and BL-OLS. In PE, we initially investigated luminance contrast threshold through BL-OLS glasses with VA various combinations using the BL with VA 0.01 and the OLS with VA 0.02. We found that the contrast threshold could be determined only in three spatial frequencies: 0.1, 0.2 and 0.4 cpd, which were not sufficient for the contrast threshold curve. We then narrowed down the range of VA to 0.05-0.3 according to the adjacent available level of VA lenses. In this experiment, we investigated AC and CC by using 4 groups of simulated low vision glasses.

3.2.1 Narrow vision (NV)

3.2.1.1 Maximum NV (maxNV): 3 degrees of visual angle (see Figure 3.5 (left)).

3.2.2 Blur vision (BL)

3.2.2.1 Maximum BL (maxBL): VA 0.06 (see Figure 3.4 (left)).

3.2.2.2 Medium BL (medBL): VA 0.1 (see Figure 3.4 (middle)).

3.2.2.3 Minimum BL (minBL): VA 0.3 (see Figure 3.4 (right)).

3.2.3 Occlusion vision (OLS)

3.2.3.1 Maximum OLS (maxOLS): VA 0.08 (see Figure 3.5 (middle)).

3.2.3.2 Minimum OLS (minOLS): VA 0.2 (see Figure 3.5 (right)).

Figure 3.3 The glasses were lenses changeable.

Figure 3.4 MaxBL (left), medBL (middle) and minBL (right)

Figure 3.5 MaxNV (left), maxOLS (middle) and minOLS (right)

3.2.4 Combination of blur and occlusion vision (BL-OLS)

The VA of BL and OLS lenses have been specified by the manufacturer. The VA through the combination of these two lenses were tested using the Snellen chart to obtain the valid combination giving the VA between 0.05 and 0.3. The results are shown in Table 3.1. We could obtain 6 combinations of the BL to the OLS lenses and only 4 combinations were valid for the experiments: medBL-maxOLS, medBL-minOLS, minBL-maxOLS and minBL-minOLS.

Table 3.1 Visual acuity of 6 BL-OLS lenses tested using Snellen chart.

Types of BL-OLS lens	Visual acuity (VA)
maxBL-maxOLS	0.03
maxBL-minOLS	0.04
medBL-maxOLS	0.06*
medBL-minOLS	0.07*
minBL-maxOLS	0.08*
minBL-minOLS	0.09*

* Type of BL-OLS lenses giving VA in the ranges of 0.05-0.3.

We initially intended to use 10 glasses as shown in Table 3.2 and we started the preliminary experiment by using 4 glasses, 3 having lowest VA in the low vision range and 1 with lowest visual angle. Subsequently, the glasses with higher VA were employed and the results were the same as the previous 4 glasses, we then used the 4 glasses having lowest VA and lowest visual angle in the main experiment.

Table 3.2 Ten glasses having VA in the low vision range and 4 selected glasses used in main experiment.

Type	Visual acuity (VA)			
NV	3 [a]			
BL	0.06 [b]	0.1	0.3	
OLS	0.08 [b]	0.2		
BL-OLS	0.06 [b]	0.07	0.08	0.09

[a] Visual angle (degree)

[b] Four selected glasses used in main experiment.

3.3 Tools

3.3.1 Display

ASUS K555L laptop 15.6 inches monitor was used for presenting stimuli. The resolution of the monitor was set to 1366 × 768 pixels (at 60 Hz), 8 bits per colour channel.

3.3.2 Spectroradiometer

Konica Minolta CS1000a spectroradiometer was used for measuring luminance, L^*, CIE u' and CIE v'.

3.3.3 Calibration

i1Profiler was used for calibrating display before experiment. The luminance of display was 131 cd/m^2 and white point was at correlated colour temperature (CCT): 6503K (x_0: 0.313, y_0: 0.329).

3.4 Experimental setup

We used ASUS K555L 15.6 inches monitor for presenting all stimuli and it was located in the black box (70W × 70L × 60H cm). The resolution of the monitor was set to 1366 × 768 pixels (at 60 Hz), 8 bits per colour channel. The monitor was calibrated with i1Profiler (luminance: 131 cd/m^2), white point: correlated colour temperature (CCT): 6503K (x_0: 0.313, y_0: 0.329), black luminance: 1.07 cd/m^2, contrast ratio: 113:1).

The experiment was carried out in the black box located on a table, one side of the box was covered with black fabric. We set up the stand for chin resting, in front of an observer chair, for relatively precise position. The center of monitor, where the stimuli were presented, was 60 cm far from observer's eyes. We covered the surround of stimuli with black paper and allowed only stimulus to be seen by the observers. The MATLAB was used for showing stimuli in the experiment (see Figure 3.6).

Figure 3.6 Experimental box with black fabric and chin rest stand.

3.5 Observers

Eight young observers aged between 20-28 years old with the average of 24 years old participated in the experiments: 4 males and 4 females. All of them had normal vision with VA ≥ 20/20, tested by Snellen chart (Figure 3.7 (left)), and normal colour vision, tested by FM 100-hue colour vision test (Figure 3.7 (right)). In the experiments, all observers were permitted to wear corrective contact lenses for adjusting to normal vision. We performed the AC and CC experiments on different days. The stimuli were presented randomly and allowed observers to adapt 10 seconds to the grey background after finishing each stimulus. We tested 2 spatial frequencies per day.

3.6 Methods

This experiment was carried out in the dark environment. The observers sat in front of the monitor, wore simulated low vision glasses, located chin on the chin rest and were covered by black curtain of the experimental box (Figure 3.8). The light in the experimental room was turned off. The stimuli were presented in the center of the monitor. The observers judged the stimuli by observing the luminance or chromatic contrasts depending on types of stimulus. If they could see the contrast of the vertical strip of sinusoidal stimulus, they answered "Yes, I see". If they could not see the vertical stripes, but homogenous image, the answer was "No, I cannot see." We recorded the result in the programme, stimulus disappeared automatically and, during adapting stage, a homogenous mid-grey was presented, then the next stimulus of a different contrast was shown (Figure 3.9).

Figure 3.7 Snellen chart (left) and FM 100-hue color vision test (right).

Figure 3.8 Before an observer is covered with black fabric, she/he sat in front of the display and located chin on the chin rest.

3.7 Achromatic contrast and chromaticity contrast thresholds investigation

Both “Yes” and “No” results of the stimuli were recorded and saved for each of the observers by the MATLAB. We plotted the “Yes” results in each contrast on the probability of seeing curve: AC or CC in percentage is the abscissa and *P(E)* is the ordinate. The 50% amount of “Yes” responded to stimuli, detected the stripes, and 50% amount of “No” responded to stimuli, could not detect the stripes, were considered to be the contrast thresholds.

In AC, we measured maximum and minimum luminance at luminance levels that contrast threshold could be determined in each spatial frequency by the Konica Minolta cs1000 spectroradiometer and determined luminance contrasts by Michelson equation (Eq 4).

In CC, we measured maximum and minimum CIE u' and CIE v' at chroma levels that contrast threshold could be determined in each spatial frequency by the Konica Minolta cs1000 spectroradiometer and determined u^*, v^* by Eq 7 and 8. Subsequently, maximum and minimum CIE C^*_{uv} could be determined by Eq 6 before being determined chromaticity contrasts by Eq 5.

Finally, we plotted the average luminance contrast and chromaticity contrast threshold for all 10 spatial frequencies from 8 observers in contrast threshold curves.

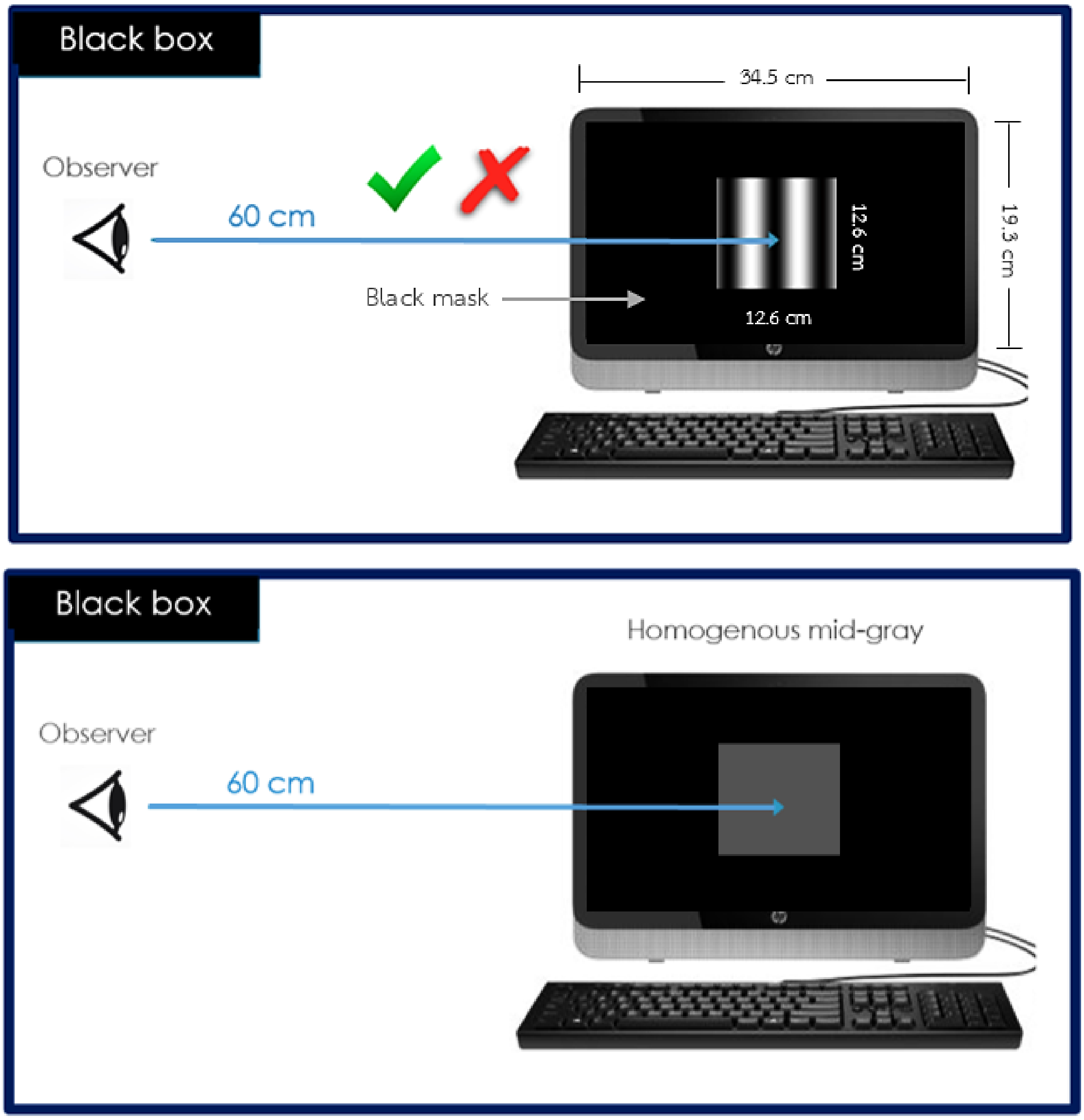


Figure 3.9 Observers judged the stimuli by observing the luminance or chromatic contrasts (top) and during adapting stage, a homogenous mid-grey was presented (bottom).

CHAPTER IV

RESULTS AND DISCUSSIONS

4.1 Preliminary Experiments

4.1.1 Preliminary experiment of achromatic contrast thresholds

We started the PE with the lowest visual acuity in each type of glasses: maxNV, maxBL, maxOLS and medBL-maxOLS.

In PE of AC, we investigated 10 spatial frequencies using 4 simulated low vision glasses with 2 observers: 1 male and 1 female, 3 repetitions, for investigation of contrast thresholds that could be determined. Table 4.1 shows the results for 4 types of glasses. For maxNV glasses, when the luminance was less than 2.2 cd/m^2, the contrast threshold could be determined for all 10 spatial frequencies. For maxBL glasses, when the luminance less than 2.2 cd/m^2, the contrast thresholds of stimuli with spatial frequencies of 0.2, 0.4, 1, 2, and 4 cpd could be determined. The stimuli of 0.1 cpd and 6 cpd could be done at 2.2 cd/m^2. The rest stimuli were at 2.2 and 5.4 cd/m^2. The PE results of the maxOLS and medBL-maxOLS were similar to maxNV and maxBL except for 14 cpd the contrast threshold could be determined from 5.4 to 11.0 cd/m^2 and from 11.0-19.2 cd/m^2 respectively.

4.1.2 Preliminary experiment of chromatic contrast thresholds

In PE of CC, we varied 10 steps of chroma levels with a constant luminance level. The results of PE for determining chromaticity contrast threshold of 4 types of low vision glasses were shown in Table 4.2, 4.3, 4.4 and 4.5 for blue, red, green and yellow respectively. The CIE C^*_{uv} values of the stimuli that could be used to determine the contrast thresholds at most spatial frequencies are shown in the Tables.

These values, subsequently, were used as a guideline for obtaining narrower range for luminance and chroma resulting in lesser number of stimuli in the main experiment.

Table 4.1 Luminance levels of PE of AC that contrast threshold could be determined.

Spatial frequency (cpd)	Luminance (cd/m^2)			
	maxNV	maxBL	maxOLS	medBL-maxOLS
0.1	< 2.2	2.2	< 2.2	< 2.2
0.2	< 2.2	< 2.2	< 2.2	< 2.2
0.4	< 2.2	< 2.2	< 2.2	< 2.2
1	< 2.2	< 2.2	< 2.2	< 2.2
2	< 2.2	< 2.2	< 2.2	< 2.2
4	< 2.2	< 2.2	-[a]	-[a]
6	< 2.2	2.2	< 2.2	2.2
8	< 2.2	2.2-5.4	< 2.2	2.2
12	< 2.2	2.2-5.4	-[a]	-[a]
14	< 2.2	2.2-5.4	5.4-11.0	11.0-19.2

[a] could not find the contrast threshold because of the limitation of glasses.

Table 4.2 CIE C^*_{uv} of blue that chromaticity contrast threshold could be determined at different spatial frequencies.

Spatial frequency (cpd)	CIE C^*_{uv}			
	maxNV	maxBL	maxOLS	medBL-maxOLS
0.1	< 9.2	< 9.2	< 9.2	< 9.2
0.2	< 9.2	< 9.2	< 9.2	< 9.2
0.4	< 9.2	< 9.2	< 9.2	< 9.2
1	< 9.2	< 9.2	< 9.2	< 9.2
2	< 9.2	< 9.2	< 9.2	9.2
4	< 9.2	< 9.2	-[a]	-[a]
6	< 9.2	< 9.2	< 9.2	9.2
8	< 9.2	< 9.2	< 9.2	< 9.2

[a] could not find the contrast threshold because of limitation of glasses.

Table 4.2 CIE C^*_{uv} of blue that chromaticity contrast threshold could be determined at different spatial frequencies. (continued)

Spatial frequency (cpd)	CIE C^*_{uv}			
	maxNV	maxBL	maxOLS	medBL-maxOLS
12	< 9.2	9.2-16.9	-[a]	-[a]
14	< 9.2	9.2	16.9-25.3	16.9-25.3

[a] could not find the contrast threshold because of limitation of glasses.

Table 4.3 CIE C^*_{uv} of red that chromaticity contrast threshold could be determined at different spatial frequencies.

Spatial frequency (cpd)	CIE C^*_{uv}			
	maxNV	maxBL	maxOLS	medBL-maxOLS
0.1	< 6.1	< 6.1	< 6.1	< 6.1
0.2	< 6.1	< 6.1	< 6.1	< 6.1
0.4	< 6.1	< 6.1	< 6.1	< 6.1
1	< 6.1	< 6.1	< 6.1	< 6.1
2	< 6.1	< 6.1	< 6.1	< 6.1
4	< 6.1	< 6.1	-[a]	-[a]
6	< 6.1	< 6.1	< 6.1	13.3
8	< 6.1	< 6.1	< 6.1	6.1-13.3
12	< 6.1	6.1-13.3	-[a]	-[a]
14	< 6.1	6.1	6.1-13.3	28.1

[a] could not find the contrast threshold because of limitation of glasses.

Table 4.4 CIE C^*_{uv} of green that chromaticity contrast threshold could be determined at different spatial frequencies.

Spatial frequency (cpd)	CIE C^*_{uv}			
	maxNV	maxBL	maxOLS	medBL-maxOLS
0.1	< 5.1	< 5.1	< 5.1	< 5.1
0.2	< 5.1	< 5.1	< 5.1	< 5.1
0.4	< 5.1	< 5.1	< 5.1	< 5.1
1	< 5.1	< 5.1	< 5.1	< 5.1
2	< 5.1	< 5.1	5.1-10.8	5.1-10.8
4	< 5.1	< 5.1	-[a]	-[a]
6	< 5.1	5.1	5.1-10.8	5.1
8	< 5.1	5.1	5.1-10.8	10.8
12	5.1	10.8-16.1	-[a]	-[a]
14	5.1	5.1-10.8	21.4	25.5

[a] could not find the contrast threshold because of limitation of glasses.

Table 4.5 CIE C^*_{uv} of yellow that chromaticity contrast threshold could be determined at different spatial frequencies.

Spatial frequency (cpd)	CIE C^*_{uv}			
	maxNV	maxBL	maxOLS	medBL-maxOLS
0.1	< 6.1	< 6.1	< 6.1	< 6.1
0.2	< 6.1	< 6.1	< 6.1	< 6.1
0.4	< 6.1	< 6.1	< 6.1	< 6.1
1	< 6.1	< 6.1	< 6.1	< 6.1
2	< 6.1	< 6.1	6.1	13.7-20.4
4	< 6.1	6.1-13.7	-[a]	-[a]

[a] could not find the contrast threshold because of limitation of glasses.

[b] could not find the contrast threshold because of limitation of display colour gamut.

Table 4.5 CIE C^*_{uv} of yellow that chromaticity contrast threshold could be determined at different spatial frequencies. (continued)

Spatial frequency (cpd)	CIE C^*_{uv}			
	maxNV	maxBL	maxOLS	medBL-maxOLS
6	< 6.1	13.7	20.4	33.4-36.6
8	< 6.1	6.1-13.7	6.1-13.7	30.6
12	6.1-13.7	13.7-20.4	-[a]	-[a]
14	6.1	20.4	-[b]	37.6-38.0

[a] could not find the contrast threshold because of limitation of glasses.

[b] could not find the contrast threshold because of limitation of display colour gamut.

After ranges of luminance and chroma levels were obtained, the method of adjustment was used to narrow down the ranges. Subsequently, we could decrease the number of stimuli to 5.

4.2 Main experiments

The purpose of this experiment was to investigate the threshold of luminance contrast and chromaticity contrast for subjects wearing simulated low vision glasses with visual acuity range between 0.05 and 0.3.

In both AC and CC experiment, we investigated 10 spatial frequencies using maxNV and maxBL, and 8 spatial frequencies using maxOLS and medBL-maxOLS glasses (dissected 4 and 12 cpd due to the limitation of the OLS glasses) with 8 observers: 4 males and 4 females. We decreased number of stimuli and used only specific range in each spatial frequency and in each glasses. The luminance levels were varied 5 steps with 5 repetitions in each spatial frequency.

4.2.1 Achromatic contrast (AC)

The average of achromatic contrast threshold (AC_{thr}) values for all glasses were determined by Eq 4 and plotted in Figure 4.1 as a function of spatial frequency (cpd).

For all glasses, the AC_{thr} started to decrease from the 0.1 cpd until 1 cpd and then increased. This pattern was similar to the contrast threshold of the elderly determined by Kutas G. et al. [34] Almost all spatial frequencies in maxNV glasses showed the lowest luminance contrast threshold except for 0.1 and 0.2 cpd. At 0.2, 0.4 and 1 cpd, all glasses were found to have similar contrast threshold. At 0.1 cpd the AC_{thr} for maxNV and maxBL glasses were higher than maxOLS and medBL-maxOLS glasses. Wearing maxNV glasses, the observers could see the stimuli rather similar to normal vision person but the visual field was narrower. This resulted in low contrast threshold compared to other glasses. At high spatial frequency, around 4 cpd onward, the AC_{thr} of all glasses were higher than low spatial frequency. This means that image with high resolution required higher luminance contrast compared to low resolution.

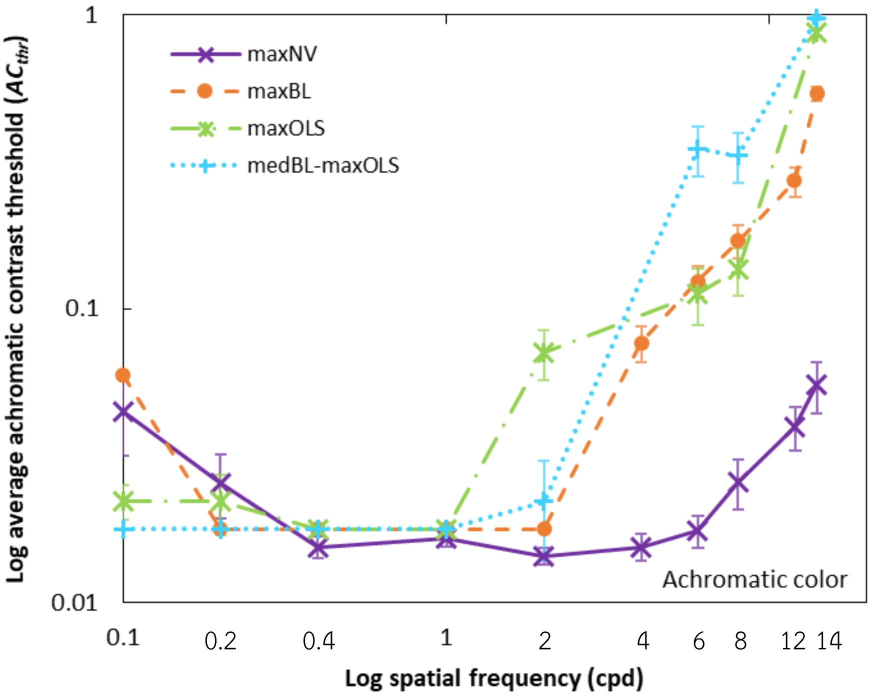


Figure 4.1 Average achromatic contrast threshold (AC_{thr}) for all glasses as a function of spatial frequency (cpd) (log-log axes). The value of 1 in the ordinate corresponds to 100% contrast. Error bars represented 95% confidence intervals of the mean values calculated from 8 observers × 5 repetitions.

4.2.2 Chromaticity contrast (CC)

The average of chromaticity contrast threshold (CC_{thr}) values for all glasses were determined by Eq 5 and plotted in Figures 4.2, 4.3, 4.4 and 4.5 for blue, red, green and yellow, respectively as a function of spatial frequency (cpd).

4.2.2.1 Blue

Similar to AC_{thr}, the CC_{thr} obtained from maxNV glasses were high at low spatial frequencies, 0.1 and 0.2 cpd, compared to other glasses showing similar threshold at these frequencies (Figure 4.2). When the spatial frequency increased, the CC_{thr} obtained from maxNV decreased gradually and started to increase slightly at 8, 12 and 14 cpd and the thresholds at these last 3 spatial frequencies were lower than at the 0.1 and 0.2 cpd. For the other three types of glasses, the CC_{thr} decreased slightly from the 0.1 cpd until 1 cpd and then increased quickly. This pattern was similar to the luminance contrast threshold. At high spatial frequencies, 2 to 12 cpd, the CC_{thr} of medBL-maxOLS were higher than that of other glasses.

4.2.2.2 Red

The curves of red CC_{thr} in all glasses were similar to blue but the CC_{thr} for all spatial frequencies with all glasses were slightly higher than the blue CC_{thr} (Figure 4.3). We found that, for red, the CC_{thr} of maxBL were closer to maxOLS glasses at high spatial frequencies compared to blue. At 14 cpd, with medBL-maxOLS glasses, the observers could not determine the CC_{thr} due to the limitation of display colour gamut (*P(E)* was less than 0.5). We may say, from these plots, that the image with red required higher contrast for medBL-maxOLS vision (VA = 0.06) compared to maxOLS (VA = 0.08), maxBL (VA = 0.06) and maxNV vision at high resolution to enhance the vision of people having similar vision.

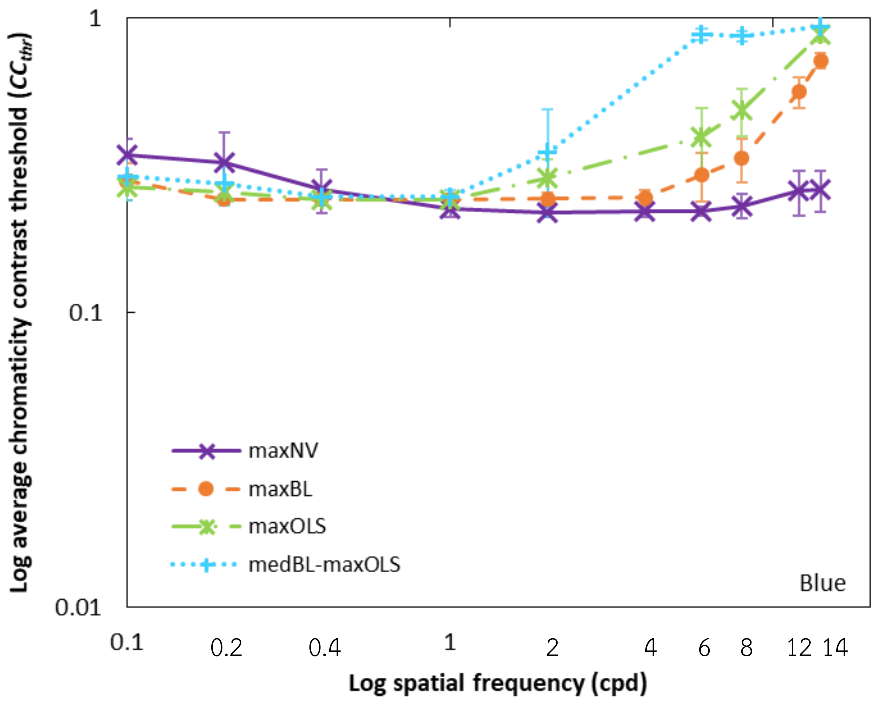


Figure 4.2 Average chromaticity contrast threshold (CC_{thr}) of blue for all glasses as a function of spatial frequency (cpd) (log-log axes). The value of 1 corresponds to 100% contrast. Error bars represented 95% confidence intervals of the mean values calculated from 8 observers × 5 repetitions.

4.2.2.3 Green

The CC_{thr} curves of green in all glasses were slightly difference from blue and red. The threshold were higher than the CC_{thr} of blue (Figure 4.2). The CC_{thr} of maxOLS were almost the same to that of medBL-maxOLS at high spatial frequencies. At 14 cpd, the CC_{thr} through maxOLS and medBL-maxOLS glasses could not be investigated due to the limitation of display colour gamut (*P(E)* was less than 0.5). Again we may say that the image with green in maxOLS and medBL-maxOLS vision required higher contrast compared to maxBL and maxNV at higher resolution.

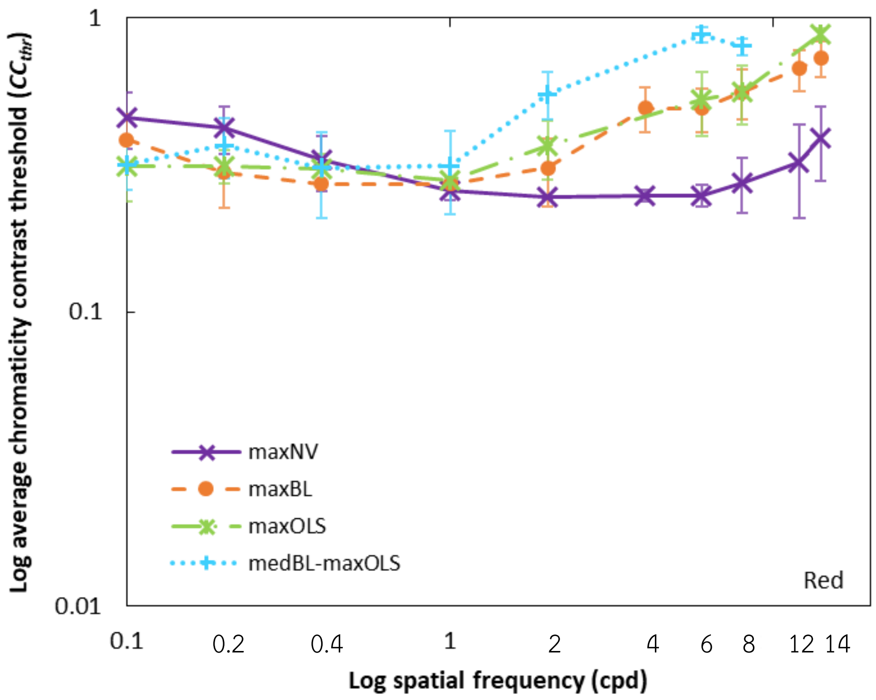


Figure 4.3 Average chromaticity contrast threshold (CC_{thr}) of red for all glasses as a function of spatial frequency (cpd) (log-log axes). The value of 1 in the ordinate corresponds to 100% contrast. Error bars represented 95% confidence intervals of the mean values calculated from 8 observers × 5 repetitions.

4.2.2.4 Yellow

The curves of yellow CC_{thr}, for all glasses, were close to each other and higher than those of blue, red and green (Figure 4.5). The CC_{thr} at 6, 8 and 14 cpd for medBL-maxOLS, and at 14 cpd in maxOLS glasses could not be investigated due to the limitation of display colour gamut (*P(E)* was less than 0.5).

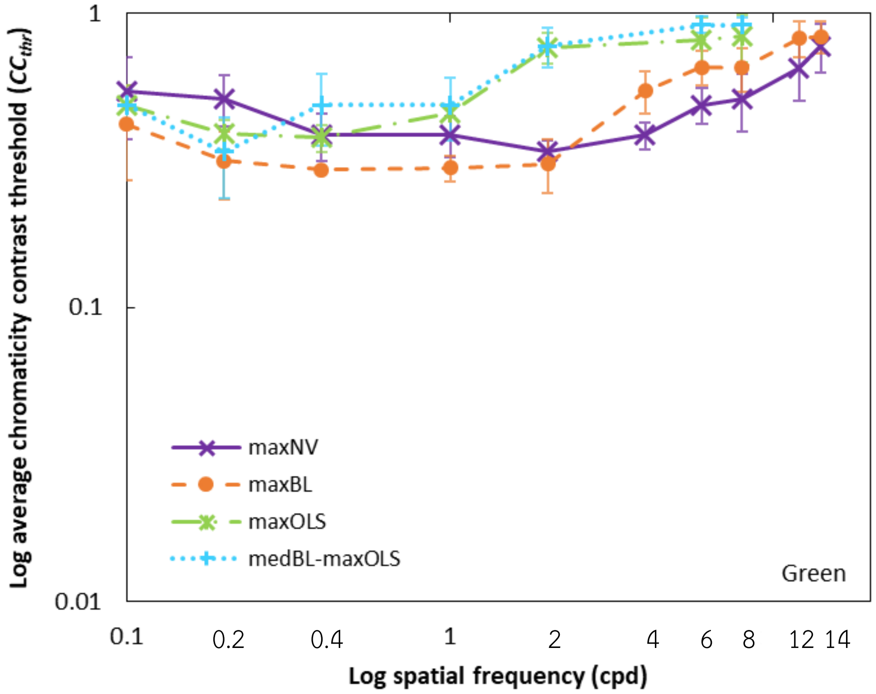


Figure 4.4 Average chromaticity contrast threshold (CC_{thr}) of green for all glasses as a function of spatial frequency (cpd) (log-log axes). The value of 1 corresponds to 100% contrast. Error bars represented 95% confidence intervals of the mean values calculated from 8 observers × 5 repetitions.

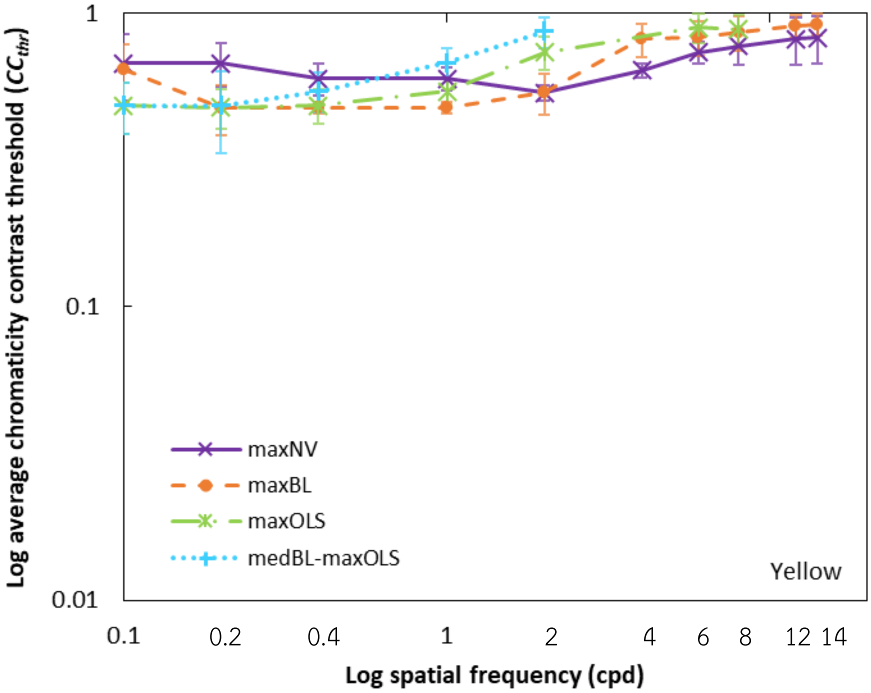


Figure 4.5 Average chromaticity contrast threshold (CC_{thr}) of yellow for all glasses as a function of spatial frequency (cpd) (log-log axes). The value of 1 corresponds to 100% contrast. Error bars represented 95% confidence intervals of the mean values calculated from 8 observers × 5 repetitions.

We compared the average chromaticity contrast threshold (CC_{thr}) values for all glasses. The plots of thresholds are presented in Figure 4.6 to Figure 4.9 as a function of spatial frequency (cpd) for maxNV, maxBL, maxOLS and medBL-maxOLS respectively. In all glasses, the CC_{thr} of yellow was the highest one compared to green, red and blue respectively. This means that image with yellow requires higher contrast compared to green, red and blue. In maxBL glasses, the CC_{thr} of red and green were very close to each other. The CC_{thr} obtained from the combination glasses, medBL-maxOLS were highest at high spatial frequencies: 8, 12 and 14 cpd, compared to other glasses although medBL-maxOLS had VA the same as maxBL.

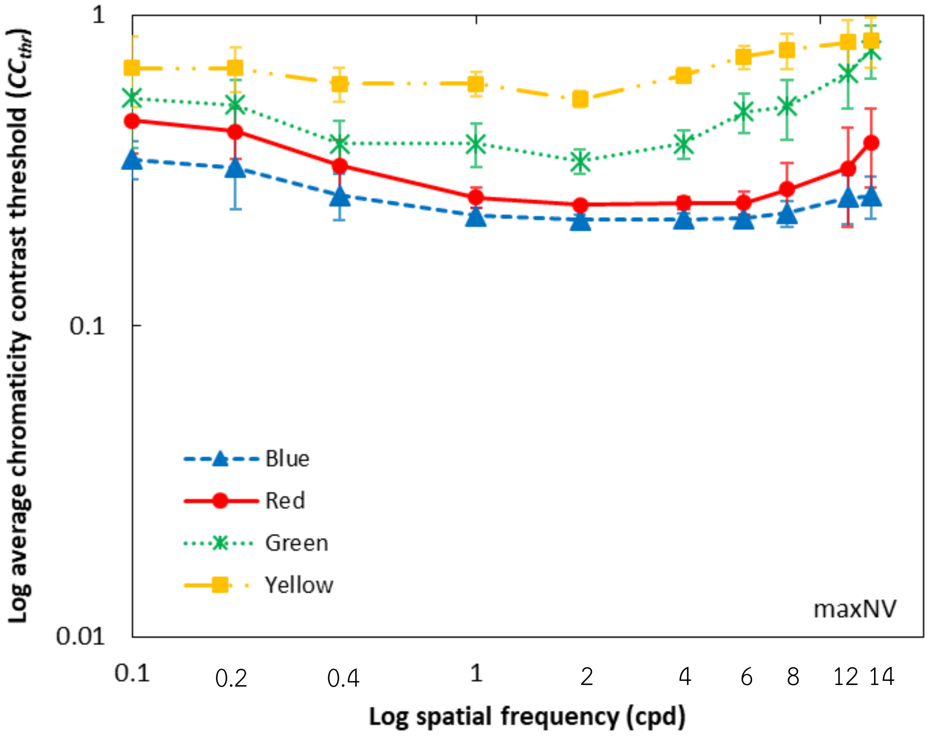


Figure 4.6 Average chromaticity contrast threshold (CC_{thr}) of maxNV glasses as a function of spatial frequency (cpd) (log-log axes). The value of 1 at the ordinate corresponds to 100% contrast. Error bars represented 95% confidence intervals of the mean values calculated from 8 observers × 5 repetitions.

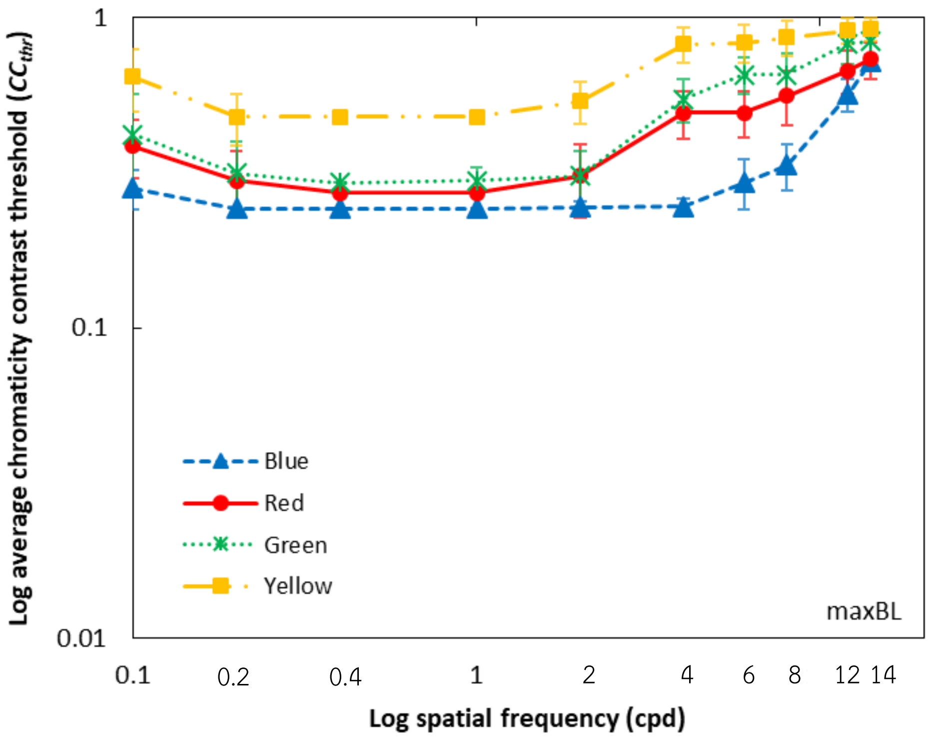


Figure 4.7 Average chromaticity contrast threshold (CC_{thr}) of maxBL glasses as a function of spatial frequency (cpd) (log-log axes). The value of 1 at the ordinate corresponds to 100% contrast. Error bars represented 95% confidence intervals of the mean values calculated from 8 observers × 5 repetitions.

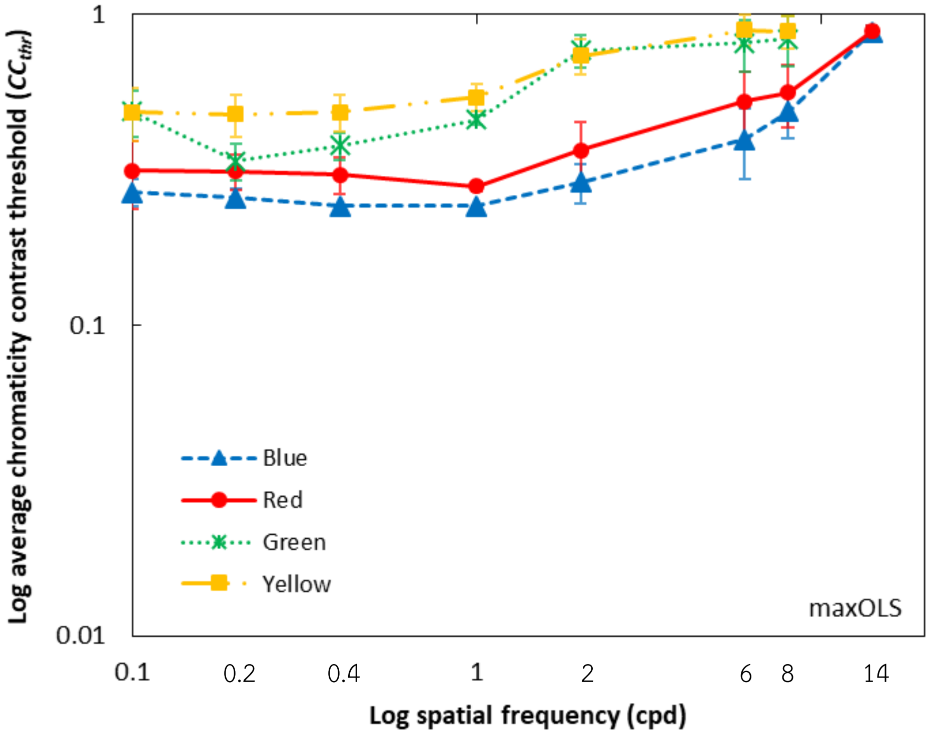


Figure 4.8 Average chromaticity contrast threshold (CC_{thr}) of maxOLS glasses as a function of spatial frequency (cpd) (log-log axes). The value of 1 at the ordinate corresponds to 100% contrast. Error bars represented 95% confidence intervals of the mean values calculated from 8 observers × 5 repetitions.

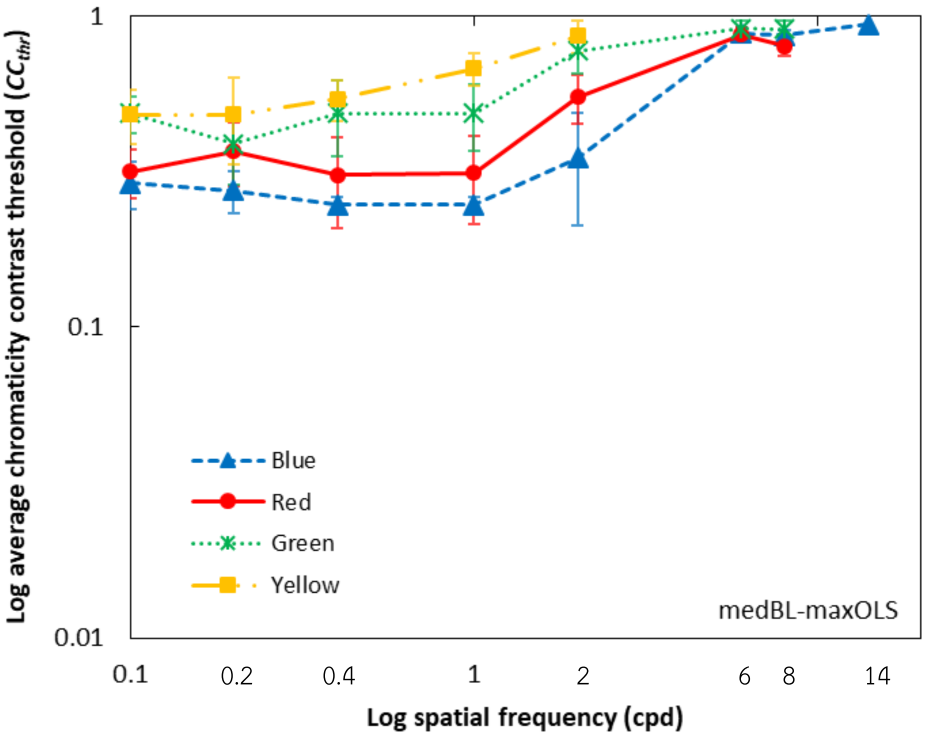


Figure 4.9 Average chromaticity contrast threshold (CC_{thr}) of medBL-maxOLS glasses as a function of spatial frequency (cpd) (log-log axes). The value of 1 at the ordinate corresponds to 100% contrast. Error bars represented 95% confidence intervals of the mean values calculated from 8 observers × 5 repetitions.

When we finished investigating the luminance and chromaticity contrast thresholds for first four low vision glasses: maxNV, maxBL, maxOLS and med-BL-maxOLS that were the lowest visual acuity in each glasses type included in our research scope, we used the medBL, minOLS and medBL-minOLS glasses and found that the contrast thresholds were the same as the previous results. Therefore, finally, we carried out the investigation of thresholds using only four types of glasses.

4.3 Discussions

The experiment carried out by Kutas G. et al. [34] demonstrated that the luminance contrast threshold of the elderly, at 8 cd/m^2, gave the minimum threshold at 1 cpd while the young was at 2 cpd, 1 step to higher cpd direction. In our experiment, the simulated low vision maxOLS was at 0.4 cpd, 1 step shift to lower cpd direction, and the threshold at 1 cpd was equal to 0.4 cpd as shown in Figure 4.10. The maxBL had the lowest threshold at 0.2 cpd, 2 steps shift, and the medBL-maxOLS gave the lowest threshold at 0.1 cpd, 3 steps shift as shown in Figure 4.1. We may say that the maximum contrast sensitivity in low vision shift to lower spatial frequency than the elderly. Our results are also in agreement Chung S.T.L. and Legge G.E. [22], who did the experiment with the real low vision observers: central field loss and intact central field, in that the peak of constant sensitivity of low vision shifted to the lower spatial frequency as shown in Figure 4.11. Low vision is individual. This is confirmed by Chung S.T.L. and Legge G.E.'s results [22], showing the contrast sensitivity curves of 16 observers with central field loss and with intact central field. Some of their contrast sensitivity curves somewhat match with our reciprocal of threshold although the type of low vision is different.

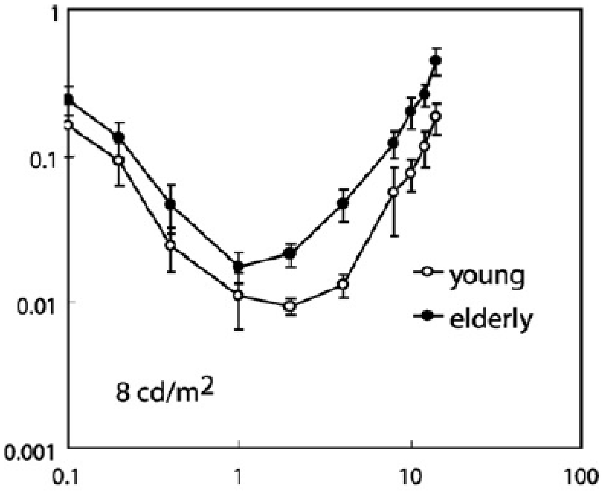


Figure 4.10 Average achromatic contrast threshold (AC_{thr}) as a function of spatial frequency (log–log axes): values comparing the mean of young (open dots) and elderly (filled dots) at 8 cd/m^2. The value of 1 at the ordinate corresponds to 100% contrast. Error bars represented 95% confidence intervals of the mean values calculated from 5 observers x 5 repetitions of both age groups [34].

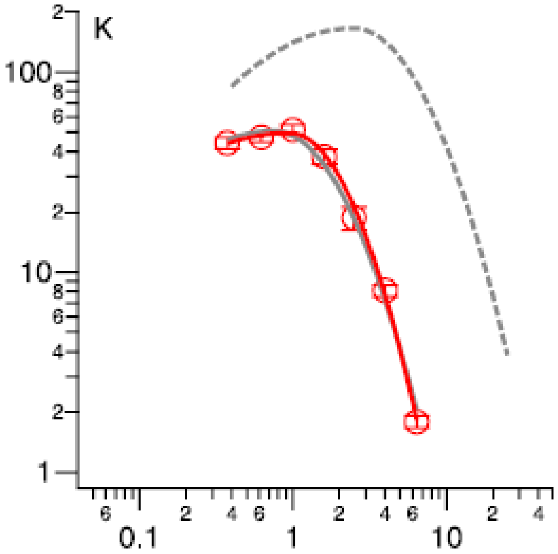


Figure 4.11 Contrast sensitivity of low vision with central field loss (red curve). Error bars represent the SD of the mean sensitivity based on 1000 bootstrap resamplings. The normal-vision CSF is also given in each panel as the gray dashed curve [22].

The result also demonstrated that the threshold of medBL-maxOLS vision are constant at 0.1-0.4 cpds, which is similar to that of some of observers in Chung S.T.L. and Legge G.E. [22]. This character of curve is different from the elderly and normal observers.

For blue and green CC_{thr}, the minimum threshold was shifted to lower cpd in the elderly compare to the young [34]. Our blue, green, red and yellow, CC_{thr} curves shows shifting in threshold to lower cpd compare to elderly in Kutas G. et al.'s experiment [34].

CHAPTER V

CONCLUSION

5.1 Conclusion

5.1.1 Luminance contrast threshold (AC_{thr})

The minimum luminance contrast thresholds of three simulated glasses: maxOLS (VA=0.08), maxBL (VA=0.06) and medBL-maxOLS (0.06) are at lower spatial frequencies: 0.4 to 1, 0.2 to 2 and 0.1 to 1 cpd respectively. At higher spatial frequencies in all simulated low vision glasses, the luminance contrast thresholds are high compared to lower spatial frequencies. The maxNV glasses give different threshold curve compared maxOLS, maxBL and medBL-maxOLS. The threshold of maxNV curve at higher spatial frequency is not as high as the other three low vision glasses.

5.1.2 Chromaticity contrast threshold (CC_{thr})

For 3 low vision glasses: maxOLS, maxBL and medBL-maxOLS, the minimum chromaticity contrast threshold of red, green, yellow and blue are at lower spatial frequency and the contrast thresholds at lower cpd (0.1-1.0) are not much different. Yellow CC thresholds, obtained from all glasses, are the highest. The curves of yellow are similar to those of green, and the curves of blue are similar to red. At higher spatial frequency the medBL-maxOLS glasses showed the highest threshold and the maxNV glasses showed the lowest contrast thresholds, for all 4 colors.

The simulated low vision glasses are specific for their types and stable which differ from individual low vision people who may give different threshold although they have the same type of low vision.

5.2 Suggestion

The luminance in experiment of luminance and chromaticity contrast thresholds should be equal therefore the thresholds can be compared. The reciprocal of the thresholds of luminance contrast and chromaticity contrast obtained from series of spatial frequency is contrast sensitivity function (CSF) of the individual. We can apply individual CSF to captured scene for obtaining simulated view seen by that person. The application is useful for designing environment supporting people with low vision.

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